

**PROCEEDINGS
OF THE
INTERNATIONAL
POLAR DIVING WORKSHOP**



NY-ÅLESUND, SVALBARD

MARCH 15-21, 2007



Smithsonian



Lang, M.A. and M.D.J. Sayer (eds.) 2007. *Proceedings of the International Polar Diving Workshop*. Svalbard, March 15-21, 2007. Smithsonian Institution, Washington, DC. 213 pp.

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Cover:
Emperor penguin tracks heading South in Antarctica (left)
Polar bear tracks heading North in Svalbard (right)
Cover photo provided courtesy of Langdon B. Quetin

Ultimate IPDW quote:

“It’s better to finish your dive before you finish your gas...” Roberto “Bob” Palozzi

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ACKNOWLEDGEMENTS

I wish to acknowledge and extend sincere appreciation to the International Polar Diving Workshop co-sponsors: Dr. Ira Rubinoff (Smithsonian Institution), Dr. Michael Montopoli (National Science Foundation), Dr. Martin D.J. Sayer (NERC Facility for Scientific Diving), Mr. Dick Long and Ms. Susan Long (Diving Unlimited International, Inc.). This international scientific diving workshop would not have been possible without their combined support.

Workshop participants are thanked for their presentations and submission of manuscripts in a timely fashion. The short production time of these proceedings could not have happened without the full cooperation of the authors. The Workshop Co-Chairs take satisfaction in having assembled this expert panel of professionals who contributed their expertise in polar diving. The international, interdisciplinary nature of this project was evidenced by participation of colleagues from the military, commercial, recreational and scientific diving communities and the papers they presented. Participation from Scotland, Norway, Germany, Canada, Finland, New Zealand, Australia, Italy, Switzerland and the United States provided an international perspective in science, medicine, equipment engineering and manufacturing and polar scientific diving operational and safety considerations.

The Workshop organizers are grateful for the assistance and support of many individuals, including: Hugh Brown and Simon Thurston (NFSD), Christian McDonald (Scripps Institution of Oceanography) and Rob Robbins (Raytheon Polar Services Company) for diving support; Dr. Peter H.J. Mueller (GTÜM e.V.) for diving medical support; Dr. Sergio Angelini and Emmanuel Glauser (UWATEC) for dive computer support; and, Arvid Påsche, Brit Gulvag, Bård Holand (Thelma, AS), Alf Brubakk (NUST), KingsBay staff, and Laurie Penland, Shelly Cole and Stacy Cavanagh (Smithsonian Institution) for administrative and logistical support.

Finally, I thank my Workshop Co-Chair Martin Sayer. I enjoyed our collaboration, mutual interest in advancing the practice of polar scientific diving and his spirit(s) from Oban. All indications are that we succeeded in accomplishing our workshop objectives. However, we both agreed not to put ourselves in the position of leading another contribution from the scientific diving community during the next International Polar Year.

Michael A. Lang
Smithsonian Institution
Workshop Co-Chair

WELCOME

We are pleased welcome all participants and open the 2007 International Polar Diving Workshop here at the new Arctic Marine Laboratory in Ny-Ålesund, Svalbard. Generous support has been provided for this re-assessment of polar scientific diving operations by the NSF Office of Polar Programs, the Smithsonian Institution, the NERC Facility for Scientific Diving and Diving Unlimited International, Inc.

Approximately four decades ago scientists were first able to enter the undersea polar environment to make biological observations for a nominal period of time. Since those first ice dives in wetsuits without buoyancy compensators and double-hose regulators without submersible pressure gauges technology has advanced. Today's scientific ice divers have the potential of extending their observational and experimental depths and times to limits never before available. Novel ice diving techniques have expanded the working envelope based on scientific need to include use of dive computers, oxygen-enriched air, rebreather units, blue-water diving and drysuit systems. With the advent of new technology greater scientific productivity is achieved while maintaining the scientific diving community's exemplary safety record. The precursor to this diving safety research project is the 1991 Polar Diving Workshop (Lang and Stewart, eds., 1992, available online at www.si.edu/dive). Fifteen years of experience later we confront the need to re-evaluate and update those polar diving recommendations through the combined expertise of polar diving scientists, manufacturers of drysuits and dive computers, medical and decompression experts and diving safety officers. During this International Polar Year (March 2007-2009) an increased level of attention will be focused on the Arctic and Antarctica and this project constitutes a contribution from the international polar scientific diving community.

In order to avoid working in isolation and re-inventing procedures this project is interdisciplinary in nature and international in scope including participants from the U.K., New Zealand, Australia, Canada, Norway, Germany, Switzerland, Italy, Finland, Panama and the United States.

Workshop agenda topics we will address include advances in: equipment technology for ice diving (*e.g.*, thermal protection and regulator design, surface-supplied diving and dive computers), physiological knowledge of cold-water effects on decompression strategies, methods and techniques of under-ice research and operational and diver training procedures specific to the polar environments.

Michael A. Lang
Workshop Co-Chair
Smithsonian Institution
U.S.A.

Martin D.J. Sayer
Workshop Co-Chair
NERC Facility for Scientific Diving
Scotland

DRYSUIT DIVING

Michael A. Lang

Smithsonian Institution
Office of the Under Secretary for Science
PO Box 37012, MRC 009
Washington, DC 20013-7012 U.S.A.

The theoretical knowledge a drysuit diver must master involves several interrelated topics: physics (water properties, pressure, density, buoyancy effects); physiology (thermal effects, hypothermia); and equipment (diving suits, undergarment insulation, weight systems, maintenance.) Practical skills include drysuit diving procedures (pre-dive, suit donning, entry, leak check, buoyancy control, trim, ascent, descent, doffing, post-dive and emergency). Drysuit diving courses within the scientific diving community encompass much of the material outlined in this paper.

Physics and Buoyancy

Water

Water exhibits a high specific heat value and conductivity. It absorbs body heat approximately 3500 times greater than air of the same volume and heat conduction is 25 times faster than air at the same temperature. Thus, body heat loss is faster than heat production even in 80°F water. Warmer water next to the skin flows away and is replaced by cold water. There is forced convection caused by currents or from moving through this water.

Water is incompressible (approximately 800 times denser than air.) Sea water weighs 64 lbs/ft³ and fresh water 62.4 lbs/ft³. When under water, vision, hearing, heat retention and movement are affected. At all depths the diver must compensate for the pressure exerted by the atmosphere, the water and the gases breathed under water.

Pressure

Atmospheric pressure (air) exerted at sea level by the Earth's atmosphere and hydrostatic pressure (water) constitute absolute pressure (atm). At sea level, the weight of a 1 inch x 1 inch column of air (extended to the edge of the atmosphere) = 14.7 lbs (or 1 atmospheres) or 1 cm by 1 cm = 1 kg. Hydrostatic pressure is the constant weight of the accumulated water above the diver that increases at a rate of 0.445 psi/ft in sea water (or 14.7psi/33 fsw) and 0.432 psi/ft in fresh water (or 14.7psi/34 ffw).

Density is mass per unit volume leading to Archimedes' Principle: "An object wholly or partially immersed in a fluid is buoyed upward by a force equal to the weight of the fluid displaced." Therein lies the crux of drysuit diving: the issue of buoyancy and its control.

Buoyancy

There are three states of buoyancy: positive, neutral and negative. Drysuit divers strive for a neutral state of buoyancy throughout the dive. A diver controls buoyancy primarily by the amount of weight worn (including diver's body weight and dive gear) and the amount of air in the buoyancy compensator. The volume of buoyancy required depends on the diver's body size, thickness of suit, and dive gear.

Factors affecting buoyancy

Weighted neutral for salt water, the diver sinks in fresh water with the same amount of weight. Therefore, a buoyancy check is standard operating procedure if changing diving environments and is also affected by the amount of insulation or gear that is worn. Neutral buoyancy beneath the surface is necessary for scientific diving efficiency and safety stops. Diving without proper buoyancy control is ill-advised and a leading proximate cause of drysuit diving incidents.

Boyle's Law

Boyle's Law describes the pressure/air volume relationship, which most directly affects buoyancy. "For any gas at a constant temperature, the volume of the gas is inversely proportional to the pressure." Thus, for a constant temperature: $P_1V_1 = P_2V_2$.

Pressure and buoyancy

A drysuit diver is surrounded by air, the volume of which changes as ambient water pressure changes. When the diver descends, the pressure increases, the air compresses, the volume gets smaller, the buoyancy decreases and the diver sinks even faster through the water column. As the diver ascends, the pressure decreases, the air expands, the volume gets larger, the buoyancy increases and the diver rises even faster. Therefore, either sinking too fast or ascending too fast because of lack of buoyancy control presents the drysuit diver with a significant safety issue.

Cold water physiology

Hypothermia

The average body temperature is 98.6°F. Hypothermia can occur when body heat is lost faster than it is produced, lowering the core body temperature below 95°F. Hypothermia is the result of prolonged chilling, which can progressively incapacitate a diver without ever becoming hypothermic as an end result.

Chilling

Chilling increases fatigue, affects short-term memory and the ability to think clearly, increases air consumption (a diver's metabolism increases as the body burns more calories in an effort to maintain temperature) and may increase the risk of decompression sickness (Mueller, 2007). Operationally, chilling reduces hand dexterity, creating difficulties working buckles, valves, removing fins and even holding onto exit ladders. The goal is to keep the diver warm during the dive, paying particular attention to the hands (Stinton, 2007).

Thermal protection

Dive suits provide protection against cold, abrasions or stings, and sunburn. The amount of insulation required depends on the water temperature, activity level and the diver's physiology.

Dive skins are thin, one-piece suits made from Lycra or Polartec and are used in tropical waters as a protection against marine injuries and sunburn. Wetsuits are made from neoprene and must fit snugly so that a thin layer of water is trapped between the suit and skin, where it is warmed by the body. Drysuits are made from neoprene, crushed neoprene, urethane-coated nylon, trilaminate or vulcanized rubber. They are necessary for diving in colder water and designed to keep the diver dry by using a combination of wrist seals, a neck seal, and a waterproof zipper. Drysuits are more expensive than wetsuits but last longer.

Suit selection guidelines recommend a dive skin (80°F/27°C and warmer water), a 2 to 3 mm full wetsuit or shorty (75°F/23°C to 85°F/30°C waters), a 5 to 7 mm full wetsuit or semi-dry wetsuit (55°F/13°C to 80°F/27°C waters), and a drysuit (35°F/2°C to 60°F/16°C waters). Special training and equipment (*e.g.*, dry gloves) are needed for drysuit diving in 35°F (2°C) and colder waters.

Wetsuit

A wetsuit is made from foam neoprene with thousands of closed cells containing nitrogen that provide insulation. Wetsuits trap a thin layer of water next to the diver's skin, which is warmed by the diver. Thicknesses are from 1 – 7 mm, which determines its insulating capacity at the surface. Wetsuits have good thermal, abrasion and sting protection in shallow, temperate to warm waters, are relatively inexpensive and easy to learn to use. Disadvantages include loss of warmth and buoyancy at depth, loosening of the weight belt and wrist-mounted gauges at depth, the need for careful fitment, a pronounced immersion diuresis effect and they are wholly inappropriate for ice diving.

Drysuit

This one-piece suit has a waterproof zipper, attached boots and seals at the diver's wrists and neck, which do not allow water to enter the suit. The type and amount of undergarments worn determine the level of insulation. Inflator and exhaust valves are installed to allow for inflation/deflation of the suit (Fig. 1).

Drysuits provide superior thermal protection regardless of depth, can isolate the diver from pollutants and evoke a lessened diuresis effect. They are, however, more expensive, have increased weight and maintenance requirements, present difficulties in answering "nature's call", are bulkier than wetsuits, increase drag, require an inflator hose and larger fin pocket sizes, and their use mandates critical buoyancy control proficiency.

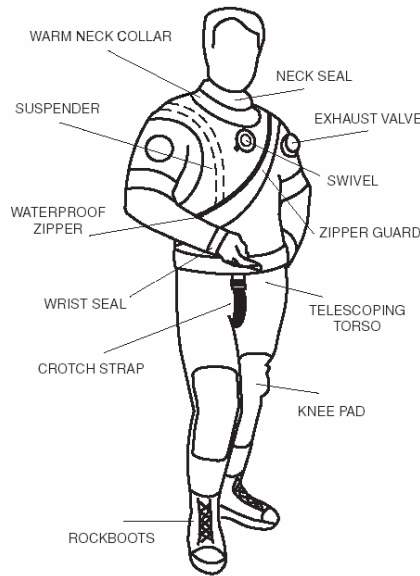


Figure 1. Drysuit components.

Drysuit materials

Neoprene stretches well and can be tailored to closely fit the body. It has good insulating properties, may require less or even no undergarments and is beneficial in the event of a leak. It is the only type of drysuit material that is inherently buoyant and is the most inexpensive type of suit. However, this suit loses buoyancy and insulation value as depth increases. It tends to develop leaks over time as cracks develop in the bubble layers and water migrates through the material making it difficult to patch and repair. This suit may not last as long as other types of drysuits. Crushed neoprene is very tough yet flexible and can be tailored into a suit of outstanding fit. It is good for swimming, has high insulation value and is long lasting. Crushed neoprene may be difficult to repair, may be heavier than suits made of other materials and is more expensive than foam neoprene. Urethane-coated nylon is composed of nylon to which urethane has been laminated to create a waterproof barrier. It is of light weight and low cost construction. There is minimal stretch and the suit's fit is loose and baggy. It is furthermore not as durable and is easily punctured. Trilaminate (TLS) drysuits are composed of two layers of tightly woven nylon with a layer of rubber in between. This is a light weight yet very strong suit of flexible material with little stretch and is easily repaired. TLS suits provide a great range of motion. Vulcanized rubber is available in several thicknesses (*e.g.*, Viking Sport, Pro, Commercial). It is easily repaired with a tire innertube-type patch and the exterior dries quickly resulting in the least amount of evaporative cooling. This suit is excellent for diving in polluted waters because of its relative ease of decontamination. However, this suit is heavy and not as form-fitting or flexible as other suits.

Zipper location

The shoulder-entry suit has the zipper located horizontally across the shoulders on the back, requires assistance to zip in, but is the least expensive to manufacture. The self-donning front diagonal suit requires no assistance in dressing, its telescoping torso allows easier entry into the neck seal and it improves flexibility and zipper durability. The wraparound between legs is an outdated 'Unisuit' style, originally developed for the Swedish military to allow toilet function

without having to remove the suit, but assistance is required in closing the zipper. The wrap around torso zipper is also an antiquated design because of the high stress it places on the zipper when the diver bends over.

Seals

Latex seals stretch easily, are more comfortable by putting less constrictive pressure on neck and wrists and are less likely to leak. However, latex is more easily punctured or torn by fingernails during dressing/undressing (all jewelry should be removed), are susceptible to deterioration from oils, U/V, ozone and have a 1-2 year service life. Some divers may be allergic to latex. Neoprene seals are rugged, harder to tear and longer lasting. They are difficult to repair, do not stretch as well and may feel uncomfortable. Neoprene becomes permanently stretched and will thus fit loosely over time. Individuals with skinny necks may have difficulty getting a proper seal because of the stretch required to pull the seal over the head.

Valves

Inflator valves are operated via push-button activation, are connected to a low pressure inflator hose connected to the first-stage regulator, and are typically located on the center of the chest. Most can swivel to allow flexibility in hose direction. The valve must be accessible while diving (other equipment configuration is important) and be easily disconnected with heavy gloves.

Most exhaust valves are “automatic exhaust valves” that will vent automatically when positioned at the highest point on the drysuit, but can also be vented manually. Valves are generally located on the upper left arm and are rotated clockwise to close and counterclockwise to open. Generally, drysuit exhaust valves do not vent air as rapidly as a buoyancy compensator.

Gloves

Neoprene wetsuit gloves are wet gloves that are pulled over the tops of wrist seals and do not provide ideal insulation. Rubber dry gloves are by far the warmest and connect to the suit with cuff rings or zip seals. Insulation is provided by liner gloves worn underneath.

Hoods

Wet hoods are most common and can be attached to the suit or worn separately. Most hoods have one-way perforations at the crown to vent any excess air in the hood (“cone-head effect”) coming from an incorrectly fitting neck seal or mask. Semi-dry hoods are also made of neoprene, attach to the suit and seal around face. Warm neck rings are neoprene collars attached to the drysuit into which the hood skirt is tucked. This option keeps the neck warmer as it reduces water flow on the cold latex seal and keeps the long hood skirt from folding up during the dive. Dry hoods are the warmest, but add difficulty in donning the suit. The latex hood is attached to the suit and seals around face. This system requires a separate insulating hood worn underneath the latex hood and will not work well with a beard. Care must be taken to avoid external ear squeeze.

Accessories

Relief zippers can be installed that may be useful for urinary relief if dressed for long periods but this adds another potential source of leaks and expense. Pockets are offered in many styles and multiple attachment points are available but create additional drag under water.

Argon inflation systems

Argon inflation systems require a separate inflation bottle and first stage regulator. Argon is denser than Helium or air. Its insulating qualities are discussed by Stinton (2007).

Weight systems

Weight belts

Standard scuba weight belts are less effective than weight harnesses for use with drysuits. The extra weight needed can cause the buckle to fail, lead to lower back or hip pain in females and can slide off male hips. A harness with shoulder straps is more secure. Many modern BCs come with integrated weight systems that may not be able to hold the entire amount of weight needed. Regardless of the weight system, the weights must be capable of being easily ditched in an emergency.

Ankle weights

Ankle weights are nylon fabric-covered rubber sleeves filled with lead shot secured with special buckles. They are usually 1 lb. weights attached to each ankle that help to keep the feet down and retain trim underwater, especially in new drysuit divers or with the use of floating fins.

Buoyancy compensator (BC)

Use of a BC with drysuits is mandatory as it provides secure flotation at the surface in the event of a catastrophic zipper failure or flooding of the suit. Excess air in the drysuit at the surface can put too much pressure on the neck and/or unexpectedly vent through the neck seal, causing a water leak and possible loss of buoyancy. BCs are not used for normal buoyancy control under water. Air must be added to the drysuit anyway to maintain insulation and prevent suit squeeze. There is added difficulty in controlling both BC and drysuit buoyancy simultaneously during the ascent. Of particular importance is that the BC must not cover the inflation valve on the chest.

Undergarments

Undergarments increase insulation by trapping air against the body and directly affect buoyancy, flexibility, mobility, and comfort. Layering garments can add insulation but can affect mobility and the effective migration of air within the suit. Cotton is not ideal because it readily absorbs moisture and loses insulation qualities. Materials that pill or shed fibers may clog valves.

Open-cell foam is, in cross-section, similar to a sponge. It is loose fitting, baggy and bulky yet fairly resistant to compression. Some insulating properties are maintained when damp, but not when soaked, and it will lose all of its buoyancy should the suit flood. This material is less popular today than competing synthetics. Thinsulate consists of many tissue-thin layers of polypropylene sheets covered by nylon fabric, is light weight and quick drying. It has excellent insulating properties, repels water and does not compress at depth. It is certainly the most desirable undergarment to be wearing in the event of a drysuit completely flooding. Thinsulate is not easily machine washable and any detergent not rinsed away will reduce insulation

Lang: *Drysuit diving*

properties. Synthetic pile is also known as “woolly bears,” a polyester fiber woven through a cloth backing and clipped to give a fuzzy appearance. This material has a tendency to form lint, which may block exhaust valves. It is also very buoyant and loses insulation properties when wet. Polartec provides good insulating characteristics with little bulk. It has lots of stretch, is easy to don and swim in but does not retain its insulation capabilities once wet. There are many other undergarments on the market with numerous different ways of providing insulation.

Regardless of the main undergarment that is used, it is recommended to wear a one-piece thin polypropylene layer next to the skin, which emits water vapor. Polypropylene is hydrophobic and ‘wicks’ moisture away from skin, preventing a ‘clammy’ feeling. It further keeps the main undergarment clean.

Drysuit Operation

Because of the added mass of wearing a drysuit with undersuit, it is important to ensure that fins must be large enough to fit over drysuit boots and the BC large enough to fit over the drysuit. A drysuit low-pressure inflator hose must be installed onto the regulator first stage and connected to the drysuit inflator valve. A pre-dive checklist should be followed (Table 1.)

Table 1. Pre-dive procedures checklist.

- Remove drysuit from storage bag and unroll;
- Inspect body of suit for obvious cuts or damage;
- Inspect zippers for corrosion, frayed or cracked rubber sealing surface, or missing teeth;
- Inspect seals for deterioration (cracking or gummy spots on latex), cuts, and other damage. If using Zip Seals, ensure security of cuff/seal interface;
- Check inflator button function; if using swivel type valve, make sure it moves smoothly;
- Check that exhaust valve rotates smoothly and depress the button to check proper function;
- Lightly rub wax onto the outside surface of the zipper;
- Lubricate the seals with pure talcum powder (do not use scented talcs that contain oils that can damage seals) or soapy water to enable easy placement; and,
- Remove watch and all jewelry including earrings, necklaces, bracelets and rings that may tear a drysuit seal.

Standard buddy checks should be performed and dive plan and emergency procedures discussed. The BC should be used for surface flotation as minimal air in the suit is desirable because of the suit’s compression against the feet and legs, squeezing air upwards around the neck.

Drysuits should not leak. Upon entering the water, check for leaks and fix the problem if water is entering the suit. A small trickle at the surface may get worse at depth and will certainly continue throughout the dive. Once the suit is zipped up, the humidity inside rises to 100%. A moderate degree of dampness is acceptable as long as the diver is warm. Even when not perspiring, moisture is constantly coming from the skin’s pores. Body heat moves the moisture to the cool inside surface of the suit where it condenses. It is common to find moisture on the inside of the suit after a dive. Flexing the wrists and turning the head allows water to enter around pronounced tendons. This is normal and can be avoided with knowledge and practice.

The goal of proper buoyancy control is to dive with the minimum amount of weight possible and the minimum volume of air inside the drysuit. A diver with excess weight needs a lot of air in the suit to achieve neutral buoyancy. As the air shifts in the suit, it creates buoyancy control issues. Only enough weight should be worn to allow for a safety stop at the end of the dive (usually 5m/15 fsw) with 500 psi left in the cylinder. Control of the suit's buoyancy is accomplished by inflating on descent to avoid squeeze and slow the descent rate and by venting air on ascent to slow the ascent rate. Loss of buoyancy control is problematic during both descent and ascent, increasing both rates if not immediately corrected. The largest pressure, and thus buoyancy, changes occur in the top 33-34 fsw.

Weighting considerations include the type of drysuit, the amount and type of undergarments, personal buoyancy characteristics, diver volume and total weight, cylinder type (all cylinders become more buoyant as the compressed air is used) and whether diving in a fresh or salt water environment. During the surface buoyancy check, ensure that the BC and drysuit are empty with 500 psi in the cylinder. Assume a motionless, upright position in the water. Holding a deep breath should allow flotation at eye level. By exhaling completely, a slow descent should begin.

Drag is the water's force of resistance to movement and it acts opposite to the direction of travel. Lift is the upward or downward force that results from drag when the diver swims at an angle to the direction of movement. Both drag and lift can be significant, especially in divers who are over weighted or have poor diving skills. The more the diver and equipment are streamlined, the easier it is to move through the water. The greater the surface area presented, the greater the force resisting forward propulsion, hence the importance of proper trim. The normal underwater swimming position is horizontal to minimize drag and increase propulsion.

Table 2. The descent.

- Vent all the air from the BC;
- Open the automatic exhaust valve by rotating it counterclockwise and leave it open throughout the dive;
- Lift the left shoulder (thereby making the exhaust valve the highest part of the suit) while keeping the arm bent and the hand pointed towards the bottom. You will see air bubbling out of the valve;
- Exhale, and with proper weighting, begin to sink;
- Sinking through the water column, the body will feel the "squeeze." Add just enough air to relieve the pressure and control the descent using short bursts;
- Be aware of the exhaust valve function by lowering the left shoulder to retain air and raising it to vent; and,
- Shift to a horizontal position when nearing the bottom to avoid stirring up sediment.

It is always advisable to maintain a minimum volume of air inside the suit. There should not be a large bubble of air, nor should a massive air shift be noticed when changing position in the water. Particular care must be taken to ensure that excessive volumes of air do not move to and become trapped in the feet of the drysuit. Drysuit legs and boots do not have pressure release valves. If air becomes trapped there it may become difficult to control if it expands. This can result in inversions and rapid ascents. If air does become trapped there it is advisable to hold onto something and bring the legs down below the waist. Buoyancy control at depth should be achieved using only the drysuit, without adding air to the BC, as it becomes difficult to control

Lang: *Drysuit diving*

buoyancy in two separate compartments simultaneously, particularly on ascent. A constant awareness of buoyancy status should be maintained.

Table 3. The ascent.

- Ensure that the automatic exhaust valve is open before ascending;
- Dump some of the air from the drysuit in anticipation of the ascent;
- As positive buoyancy is gained during the ascent, raise the left shoulder so that the valve is higher than rest of suit. Keep the lower arm pointed down. Do not extend the rest of the left arm higher than the valve or air will rise to the wrist, bypassing the valve;
- Control buoyancy by raising and lowering the exhaust valve position. The ability to stop and hover at any time during the ascent is important; and,
- If the ascent is faster than it should be, raise the valve higher to vent faster. If air still isn't venting fast enough, depress the valve manually.

Upon reaching the surface, close the exhaust valve by completely rotating it clockwise. Inflate the BC rather than the drysuit to provide more comfort when moving at the surface. If using a DUI Weight and Trim System or weight-integrated BC when diving from small boats, pull each lanyard and hand the weights up, or hook a snap from a boat lanyard and remove the entire system. Always remove weights before removing cylinder or the BC system. Once in the boat, or on land, inflating the drysuit with air can improve comfort and increase warmth.

Table 4. Post-dive procedures.

- Rinse all equipment in fresh, warm (if available) water as normal;
- Operate valves as you run water over them - rotate automatic valves and push the inflator button several times;
- It is usually easier to hose the zipper while wearing the suit, but if you remove the suit before washing, close the zipper, and the seals with rubber bands, first to prevent water entry;
- If the suit or seals have been contaminated by oil, gently wash with mild soapy water;
- Hang the suit over a large diameter roller in a dry location away from direct sunlight, ozone, high heat, etc;
- Remember also to turn the suit inside out to dry (keeps the mold and smell down); and,
- When fully dry, roll as per owner's manual instructions and store in drysuit bag.

Leak location is accomplished by closing the zipper and also the seals with rubber bands. Assemble the regulator and cylinder with the drysuit inflator attached. Turn the air on, attach the inflator to the suit and depress the button just enough to lightly inflate it. Brush soapy water on the suit and observe any bubbles. Minor leaks can be repaired with Aquaseal and Cotol once completely dry. The suit should be returned to a dealer or the factory to repair major leaks or damage.

Drysuit Emergencies

Never lift heavy weights by inflating the drysuit or BC. If the weight drops, dangerous positive buoyancy ensues. Proper procedures, such as the use of lift bags or lift lines must be used to raise heavy objects.

Compressed air released from low pressure inflator valves is cold because of adiabatic cooling. The colder the water, the more readily ice forms from moisture-saturated air in the

drysuit that freezes on the valve mechanism. Ice crystals then form, preventing the valve from seating and creating a free-flow, which in turn increases cooling, resulting in more ice formation and an uncontrolled free-flow. Both BC inflator valves and regulator second stages are susceptible to freezing. Prevention includes completely drying the inflator valve between dives and inflating the BC and drysuit using only short bursts of air.

Should the inflator valve stick open, immediately attempt to disconnect the inflator hose while remaining aware of depth in the water column. Assume a vertical position and vent excess air through the exhaust valve. If severe enough, pull the wrist seal open allowing water to enter the suit. If air cannot be vented, extend arms and legs in a horizontal position to create drag (*i.e.*, flare position.) An inflator valve stuck in the closed position should be caught during pre-dive inspection or immediately stop the descent and terminate the dive. Use the BC as needed to control buoyancy and return to the surface venting expanding air as normal

For an exhaust valve stuck closed or clogged, failing to exhaust air, immediately stop the ascent, if possible. Rotate or manually operate the automatic exhaust valve to attempt to get it to work. If the valve still does not function properly, pull wrist seal open to vent. Attempt to ascend along a fixed object or down line.

If weights are accidentally dropped at depth and their recovery is unsuccessful, a buoyant, rapid ascent will follow. If an anchor line or fixed object is in close proximity, hold on and try to shimmy up. Do not drag the dive buddy to the surface, rather, attempt to exhaust expanding air as rapidly as possible. If ascending rapidly, exhale and use the flare position to slow the ascent by increasing drag. The flare position slows the ascent dramatically by holding the ankles rigid with fins parallel to the bottom, acting as “water brakes”, arching the back, and holding the arms outstretched. Another technique for slowing a rapid ascent is to swim horizontally, so the body presents a greater surface area. It is possible for excess air to move to the feet of the drysuit, making it difficult to return to an upright position and invariably, swim fins will pop off the feet. Attempt to tuck the body into a ball, kick, and roll to an upright position. Once upright, immediately vent the suit through the exhaust valve to regain control.

Drysuit flooding can occur from the complete failure of a zipper, blow out of a neck seal, or the destruction of a valve and may cause immediate negative buoyancy depending on the kind of undergarments worn. Neutral or positive buoyancy must be achieved by inflating the BC or dropping partial weights. Drysuit divers should not only be concerned with an uncontrolled rapid ascent and the concomitant danger of gas embolism or decompression sickness, but also with an uncontrolled rapid descent caused by overweighting or loss of buoyancy. Fins that provide adequate thrust are essential for drysuit diving.

Suit Maintenance and Storage

The zipper should be lubricated either before or after the dive with a thin film of bees wax or paraffin wax. Silicone spray or grease should not be used on the drysuit zipper. Excess paraffin wax should be removed to not cause deterioration of the latex seals if left in contact with them for long periods of time. The zipper should be closed and only lubricated on the outside (lubrication on the inside causes dirt to collect and the zipper to fail.) Depending on availability

Lang: *Drysuit diving*

of fresh water, rinse suits and hang to dry on wide hangers. Carefully inspect latex drysuit seals, zipper and valve operation and cover the valve stem.

Store the suit in a cool, dry, dark place away from heat, direct sun light, chemicals, petroleum, solvents, electric motors and other producers of ozone that can deteriorate latex. Store the suit rolled up in a drysuit bag or flat, but never folded (to avoid permanent creases) or on a thin metal hanger (creases and rust). Leave the zipper open to avoid creating a permanent compression set on the sealing surface and reducing the life of the zipper.

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A REVIEW OF DIVER PASSIVE THERMAL PROTECTION STRATEGIES FOR POLAR DIVING: PRESENT AND FUTURE

Robert T. Stinton

Diving Unlimited International, Inc.
1148 Delevan Drive
San Diego, CALIFORNIA 92102 U.S.A.

Introduction

Dr. Ted DeLaca, a 20-year veteran of polar diving, summed up the requirements for successful underwater polar science as, “A diver with fully functional hands, eyeballs and brain.” Inadequate thermal protection can quickly strip the diver of functional hands and, with time, cognitive functions. While the impact on the hands is noticeable to the diver, the loss of cognitive functions such as problem solving, recall, memory, perception, and recognition, slips away without notice.

This is of particular importance in the case of scientific diving operations as thermal stress can not only impact the quality of science during the dive, but its residual effects can also impact the quality of science following the dive. For example, in many cases, the scientific diver’s work continues post dive with data analysis, specimen preparation and recording observations. Therefore, when planning diving operations it is important to consider the impact of residual effects of thermal stress such as unearned fatigue, impaired cognitive function and impaired tactical function, all of which individually or collectively can impact the dive and post-dive performance (DeLaca, 1985).

The key to effective planning is a good understanding of the impact of cold stressors on the diver and the limitations of thermal protective choices. Armed with this knowledge the planner needs to consider thermal protection strategies for four separate regions of the body (hands, feet, trunk and limbs, and head), each of which have specific requirements.

This paper reviews diver thermal protection strategies available to individuals planning polar diving operations, with particular emphasis on diver passive thermal protection strategies built around drysuit-based systems. When compared with active heating systems, such as surface supplied hot water systems commonly used in commercial diving, drysuit-based systems are versatile, easy to transport and require a minimum of surface support.

Requirements

The General Thermal State

One step in selecting the thermal protection strategy is definition of the level of performance needed to safely complete planned underwater tasks. Weinberger and Thalmann (1990) broke

diver performance into three categories (fully functional, adequately functional and barely functional) based on the individual's thermal state. Table 1 provides the basic physiological parameters of these three functional categories. Table 2 provides a description of the performance decrement that can be anticipated with each category.

Table 1. Diver performance category based on thermal state (Weinberger and Thalmann, 1990).

Function Category	Core Temperature 37°C (98.6°F)	Mean Skin Temp	Change in body heat content
Fully	> 36.5°C (97.7°F)	> 29°C (84.2°F)	1.4 Kcal/kg
Adequately	> 36.0°C (96.8°F)	> 25°C (77°F)	2.9 Kcal/kg
Barely	> 35.5°C (95.5°F)	> 20°C (68°F)	4.6 Kcal/kg

Table 2. Diver performance decrement per category.

Fully Functional: Core temperature >36.5°C (97.7°F). Little or no performance decrement caused by thermal stress. Performance equal to 30 min dive conducted in warm water >25°C (77°F).

Adequately Functional: Core temperature >36.0 °C (96.8°F). Loss of mental performance and manual dexterity caused by thermal stress and may experience difficulty accomplishing mission tasks.

Barely Functional: Core temperature >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.

Functional vs. Comfortable

Table 3 shows the typical sensations felt by the diver as their mean skin temperature drops. An examination of the table shows that the diver's comfort deteriorates faster than their functionality. However, if the level of comfort deteriorates rapidly and/or extreme levels of discomfort are reached over time, this distractive effect can take the diver's mind off task performance and/or safety issues.

Table 3. Diver sensations in relation to temperature.

Mean skin temperature (Sensations)	Temperature
Unpleasantly Warm	>35°C (95°F)
Comfortable	34°C (93°F)
Uncomfortably Cold	31°C (88°F)
Shivering Cold	30°C (88°F)
Fully Functional	>29°C (84°F)
Extremely Cold	29°C (84°F)

Hands and Feet

The hands and the feet (*i.e.*, fingers and toes) are the two biggest challenges when designing passive thermal protective systems. The shape of the fingers and toes limits the effectiveness of insulation (van Dills, 1957; Nuckols, 1978; Beckman, 1996). Figure 1 shows that as the diameter of the body region grows smaller, the effectiveness of a given thickness of insulation decreases. The tips of the fingers and toes are small diameter hemispheres and are impacted the most. This is further intensified when combined with reduced blood flow to the fingers and toes as a result of vasoconstriction.

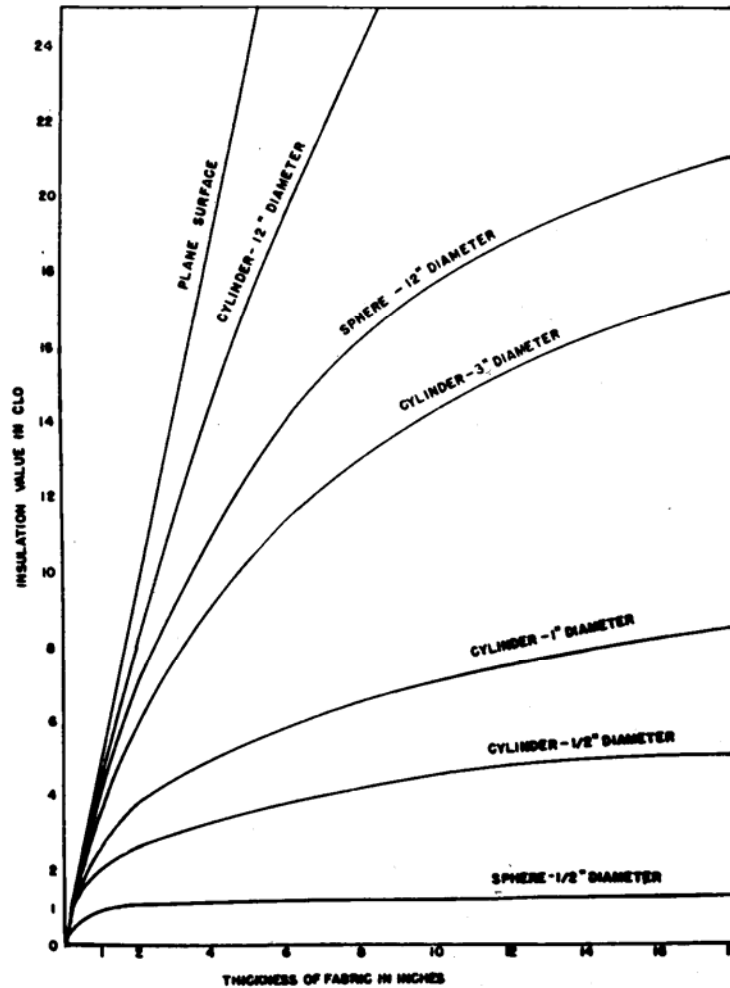


Figure 1. Effectiveness of insulation on body region diameter.

The hands represent the larger of these two challenges as a balance must be struck between thermal protection and dexterity. After all, the hands are the diver’s primary work tools and good dexterity is a primary component for carrying out a safe and effective dive (Table 4).

Table 4. Weinberger and Thalmann (1990) established the following performance milestones, developed after extensive testing.

Finger Temperatures	Impact
20°C (68°F)	Uncomfortably cold
>18°C (64°F)	Loss of full functionality
15°C (68°F)	Loss of usefulness, painful
10°C (50°F)	Numbness

Since the temperature of the fingers is not known during the course of the dive, one is left to rely on the diver’s judgment to terminate the dive when performance limits are reached. The diver must learn that once the hands become uncomfortably cold (20°C/68°F) their performance will start to diminish and an additional 2°C of cooling may only take minutes. If divers do not

terminate the dive at this point, they may enter the realm of Non Freezing Cold Injuries (NFCI) of their extremities.

NFCIs are time- and temperature-dependent and when the water temperature drops below 12°C (53.6°F) the realm for NFCI is entered (Keatinge, 2000). NFCI is most commonly known as “Trench Foot” a malady common in cold-weather military operations. However, it is not limited to cold weather as in Southeast Asia it is known as “Paddy Foot.” NFCI is also not limited to military operations or to the feet. Thalmann (1987) reported divers experienced NFCI of the hands and feet following dives in water temperatures below 7.2°C (45 °F). A single case of NFCI involving the face was reported by Peggy Hamner following a series of dives in Antarctica (Stinton, 1987). NFCI is indicated by fingers and/or toes that are still numb after rewarming with symptoms persisting for more than 3 hours. Depending on the degree of injury of the affected part(s), it could take days, weeks, or months for full recovery and hospitalization may be required.

Table 5 provides guidelines for hand/foot exposure limits by Thalmann (1990), augmented by Keatinge (2000), to avoid diver development of NFCI.

Table 5. Exposure limit guidelines.

<u>NFCI Temperature Limits</u>
Fully Functional >18°C (64.4°F)
12°C (54°F) 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 in temperature and time limits for the hands and feet exist between 12°C (53.6°F) for 3 hours to 8°C (46.4°F) for 30 minutes because the data do not make it clear if one can simply extrapolate safe temperature and time between these two points. Even if one could, there are some predisposing individual variables:

- Personal physiology;
- Previous thermal injuries;
- Acclimatization/Habituation; and,
- Equipment.

Hand Functionality vs. Comfort

From the operational perspective, because the finger and toe temperatures are not easily monitored, the diver should abort the dive when the fingers or toes become uncomfortably cold (20°C/68°F) and before the hands start losing functionality (>18°C/64°F) (Table 6).

Table 6. Hand functionality versus comfort.

Hand Sensations	Temperature
Uncomfortable	20°C (68°F)
Fully functional	>18°C (64°F)
Extremely cold	15°C (59°F)
NFCI exposure limit 3 hrs	12°C (54°F)
Painful and numb	10°C (50°F)
NFCI exposure limit 30 min	8°C (46°F)

Unearned Fatigue

Unearned fatigue is a post-dive consideration. A common non-diving example of unearned fatigue are sun bathers working on their tans for several hours. Following this exposure, they feel tired and need a nap. This same effect has been described by Bowen and Pepler (1967) and DeLaca (1985) following underwater exposures. Bowen described divers as being hungry, thirsty and falling asleep easily after dives. DeLaca described failures to properly complete post-dive tasks resulting in loss of specimens and data. Though cold is not the only stressor in diving creating unearned fatigue, inadequate thermal protection magnifies its effect. Bowen and Pepler (1967) reported that divers, even after active rewarming, were still drowsy and fell asleep easily.

Diver Passive Thermal Protection Strategies

There are two primary passive approaches used in diving: wetsuits and drysuits. Both derive their insulation primarily from trapping and stabilizing gas. The wetsuit, though simple and robust, provides a very limited amount of protection and a rapid decrease in performance when the water temperature drops below 18°C (65°F) or depths are greater than 10 msw (33 fsw).

Wetsuits

The wetsuit, which had been used in polar diving in the past, provides only a marginal level of protection. It is mentioned here only to understand its origin and limitations. 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 wetsuit was put forward and developed by Dr. Hugh Bradner of Scripps Institution of Oceanography in 1951 (Hanauer, 2003). 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 (Underwater Demolition Team) swimmer would be operating at depths of less than 10 msw (30 fsw) and swimming at speeds up to 0.5 knots.

Beckman (1964) conducted a series of tests at the Naval Medical Research Institute (NMRI) to better understand the impact of depth on the effectiveness of the wetsuit (Table 7).

Table 7. Wetsuit insulation effectiveness at 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 the table are units of insulation similar to the more common R value and one clo = 0.155 m² K/W. One clo represents the insulation required to keep a resting person warm in an indoor room at 21.1°C (70°F), 50% RH and air movement of 0.01 m/s. For comparison, 4 clo is considered the requirement for polar dress.

An additional factor not well understood about wetsuits is that the cell structure breaks down with repeated use. As the cells break down, they flood and the insulation value of the foam decreases. Monji (1989) reported this breakdown after studying the impact by simply compressing and decompressing wetsuit materials through multiple cycles. Monji's work, however, did not address broken cell membranes as the result of mechanical impact. The result of cell flooding can be measured over time by simply weighing the suit after each dive. As the cells break down, the suit's weight will increase as water is absorbed by damaged cells. Drysuits made with wetsuit foam neoprene also experience cell breakdown though the impact is somewhat less because only one side of the material is exposed to water.

Drysuits

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 head and isolate the diver from the water. With additional suit accessories it is possible to completely isolate the diver from the environment.

There are two primary construction methods used in fabricating drysuits. The first utilizes the same closed-cell foam neoprene used in the construction of wetsuits. The second is shell drysuits that are constructed using a wide variety of coated, waterproof fabrics. The latter has become the more common style of drysuit. 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. This is a holdover from when most of the drysuits used in the 1950's were called variable-volume suits and did not have inlet and exhaust valves.

Closed-Cell Foam Neoprene Drysuits

The total insulation in the foam-neoprene style drysuit is derived from the combination of the foam's insulation and the garment(s) worn under the suit. Foam-constructed drysuits currently are available in thickness ranging from 1.5 mm to 7 mm. The intrinsic insulation and buoyancy of these suits changes with depth and the magnitude of the changes is dependent on initial thickness. The thicker the material, the more impact increased depth has on performance of the suit.

In addition to the impact of depth on the foam, the closed-cell neoprene foam used in these suits is nominally 1.9 times more conductive than the insulation used in drysuit undergarments. As a comparison, 3.7 mm of Thinsulate (thickness measure under a load) provides the same insulation as a 7 mm foam-neoprene suit (Fig. 2). The additional thickness of 7 mm of neoprene directly adds to increased bulk and displacement, which directly equates to increased weight to trim the diver for neutral buoyancy.

In less than 10 msw, a 1.5 mm foam drysuit would require a 2.9 mm Thinsulate-equivalent undergarment to equal the insulation of a 7 mm foam neoprene drysuit without an undergarment. However, as depth of the dive increases, the 7 mm foam drysuit would start losing insulation and, as the diver approached depths of 40-50 msw (130-140 fsw), most of the intrinsic insulation of the 7 mm suit is lost. Compare this to the 1.5 mm suit/undergarment combination that would have close to the same insulation as it had at 10 msw (30 fsw) (Wattenbarger, 1978). This

variability of insulation of thicker foam suits with depth makes it difficult for a dive planner to plan an exposure.

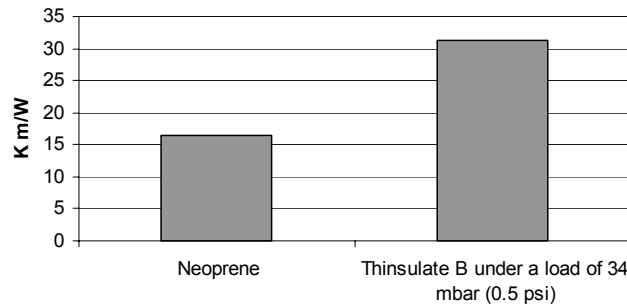


Figure 2. Insulation comparison of neoprene versus Thinsulate.

Shell Drysuits

Shell drysuits (often called membrane drysuits) can be thought of conceptually as rain coats, *i.e.*, they keep the divers dry and the underwear keeps them warm. Therefore, the largest fraction of the total insulation comes from the undergarments worn under the shell drysuit. There are several advantages that come with the shell approach. First, the shell drysuit allows the diver to adjust the amount of insulation worn to meet the anticipated exposure needs and/or adjust for their own comfort needs based on experience. Second, the insulation in this suit/undergarment combination is functionally constant with depth (Wattenbarger, 1989), which is a key benefit to the dive planner. In addition, the diver does not have to deal with the buoyancy changes seen with closed-cell foam neoprene suits. Alternate suit-inflation gases such as Argon can be used to increase the insulation value of the undergarments.

Undergarment Design Consideration

A variety of materials are available that, in theory, would function as insulators under a drysuit. However, the micro-environment that exists between the suit and the diver's skin places a number of demands on these materials.

The common paths for heat transfer between warm and cold objects are conduction, convection, radiation and evaporation. The convection and radiation heat transfer paths all require a gap between the surfaces. In a drysuit undergarment this gap does not exist functionally, *i.e.*, the diver is in contact with the undergarment and the undergarment is in contact with the drysuit (Fig. 3).

The source and impact of this evaporative cooling may not be obvious because one expects the diver to be cold and, therefore, not sweating. However, being cold has no impact on what is called insensible/transdermal water loss. Transdermal water loss involves water diffusing directly across the skin versus sweat originating from sweat glands. The amount of water that diffuses across the skin ranges from 10-25 g/m²hr. Without regard to workload, the heat transported by this water is 2260kJ/kg (979 Btu/lb). Forty percent of transdermal loss takes place on only 18% of the body's surface area (soles of the feet, palms of the hands and head.) The moisture build-up in these areas adds to the already difficult task of protecting them.

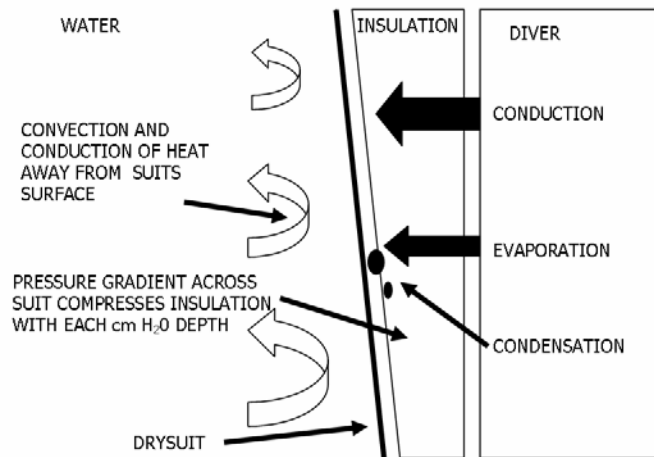


Figure 3. Heat transfer paths

In addition to the evaporative heat loss, transdermal loss degrades the insulation as moisture collects in the undergarments. As water diffuses through the skin, it forms a boundary water-vapor layer next to the surface of the skin. This layer is saturated at 100% relative to the skin temperature. The inner surface of the drysuit is at a lower temperature and the air next to it holds less moisture. The temperature gradient produces a vapor-pressure gradient that moves water vapor across the insulation in the direction of the suit. This water vapor condenses as it moves through the insulation and experiences increasingly lower temperatures. Though condensation can be seen on the inner surface of the drysuit, the condensation in the undergarment is not visible and slowly degrades the insulation.

In the case of long duration dives over several hours, Lippitt (1982) found it beneficial to have a vapor barrier, *i.e.*, a vapor impermeable layer, next to the skin. However, even in short duration cold water dives, a vapor impermeable layer worn next to the skin prevents evaporative cooling and keeps any sweating prior to the dive from degrading the insulation. The vapor barrier in direct contact with the skin feels damp, but a lightweight polypropylene undergarment can be worn next to the skin.

Because of the moisture in the micro-environment inside the suit, hydrophobic materials work best as they absorb little or no water. In the realm of synthetic fibers, polypropylene and polyester are the two most commonly used. Most natural fibers are not hydrophobic and are not suitable with one main exception. Wool is not hydrophobic but its unique construction helps it maintain insulation when wet.

There is no well-defined test procedure to determine a material's insulation values when wet. The following method has been used by some investigators: material samples are immersed in water and kneaded between their fingers for 15 seconds to expunge the air. The samples are then removed, shaken dry with three quick shakes and their conductivity measured using a Holometrics Rabid-K device. This is equivalent to the mountaineer's test: would you want to wear it after it came out of the washing machine spin cycle? Cotton is not appropriate, polyester and polypropylene fleece or pile is fine, and wool is also possible.

Insulation differs whether wet or flooded. If the suit is partially or completely flooded and water is present in and around the insulation, it is not considered “wet” as discussed above. The impact of flooding has not been studied in detail in the diving application. However, several studies have been conducted in the aviation anti-exposure field to help define what the expectable leak rate is when developing a performance specification for an anti-exposure drysuit.

Table 8 shows the result of efforts done by Allan (1985) at the RAF Institute of Aviation Medicine. Allan used a segmented thermal mannikin immersed in water creating hydrostatic pressure effects. Undergarments using a double layer wool and M400 Thinsulate were used in combination with an anti-exposure drysuit. Each ensemble was tested to define its insulation when dry and small measured volumes of water were added. For both materials, the addition of 500 ml of water resulted in approximately 30% insulation loss. In thermal mannikin testing there is a time lag between water injection and the value reading was 90 minutes. Therefore, Allan’s test does not show the immediate impact.

The other factor not known in this test is the surface area affected. For example, 500 ml could wet out 20% of the surface area eliminating 100% of the insulation in one area, *i.e.*, flooded left foot and calf, or, it could wet out 20% of the insulation over 100% of the surface area. Although the end result would be the same the onset of thermal stress would be slower in the second case.

Table 8. Insulation loss due to water introduction.

	Introduced leakage (ml)	Insulation (clo)	% loss
Double layer wool	0	0.79	0
	500	0.55	30.4
	1000	0.46	41.8
	2000	0.37	53.2
	3000	0.34	57.0
M400 Thinsulate	0	0.76	0
	500	0.54	28.9
	1000	0.47	38.2
	2000	0.39	48.7
	3000	0.35	54.0

A second perspective of Allen’s results is shown in Table 8. The first 500 mL produces the largest drop in insulation in both undergarments. In the case of long-duration dives, considering the nominal insensible water loss is 400 ml/day combined with sweat trapped in the suit during pre-dive activity, a large fraction of insulation can be lost over time. A different perspective on flooding comes from testing at the Navy Experiment Diving Unit (NEDU) using Type M Thinsulate undergarments during a long-duration dive. A diver entered the water with the drysuit’s waterproof zipper not fully closed allowing an undefined volume of water to enter the suit. Upon noticing water entering the suit, the diver closed the zipper and completed the test dive. Recorded skin temperature showed an initial drop in the affected area but after a short period of exercise the area rewarmed (Piantadosi, 1979). Allan’s test used the thermal manikin,

a steady-state device that generates heat at a constant rate, whereas the NEDU diver was able to change heat production by increasing his activity level.

From personal experience, Thinsulate type M and B garments are able to reduce the initial impact of minor flooding (500-1000 ml). This is possible because they are able to hold air longer than most materials when immersed because of the size and number of polypropylene fibers per m³. Their tight packing makes inter-fiber space difficult to flood. Holding a piece of type B Thinsulate and fleece under water shows that the air space between the fleece fibers is immediately flooded as air bubbles stream to the surface, whereas it takes several minutes of kneading to work the air out of the Thinsulate sample.

The actual results experienced in a flooding suit are inconsistent because of the variables involved. A liter of water in the arm or liters of water flowing through a large hole have different impacts. Type B Thinsulate may retard the initial impact of a small leak in the drysuit, yet in most cases, the diver must still exit the water. However, in the case of major flooding, the primary means of heat loss is not conduction through the insulation but convection as a result of water moving in and around the diver's body rendering the insulation value of the undergarment a moot point.

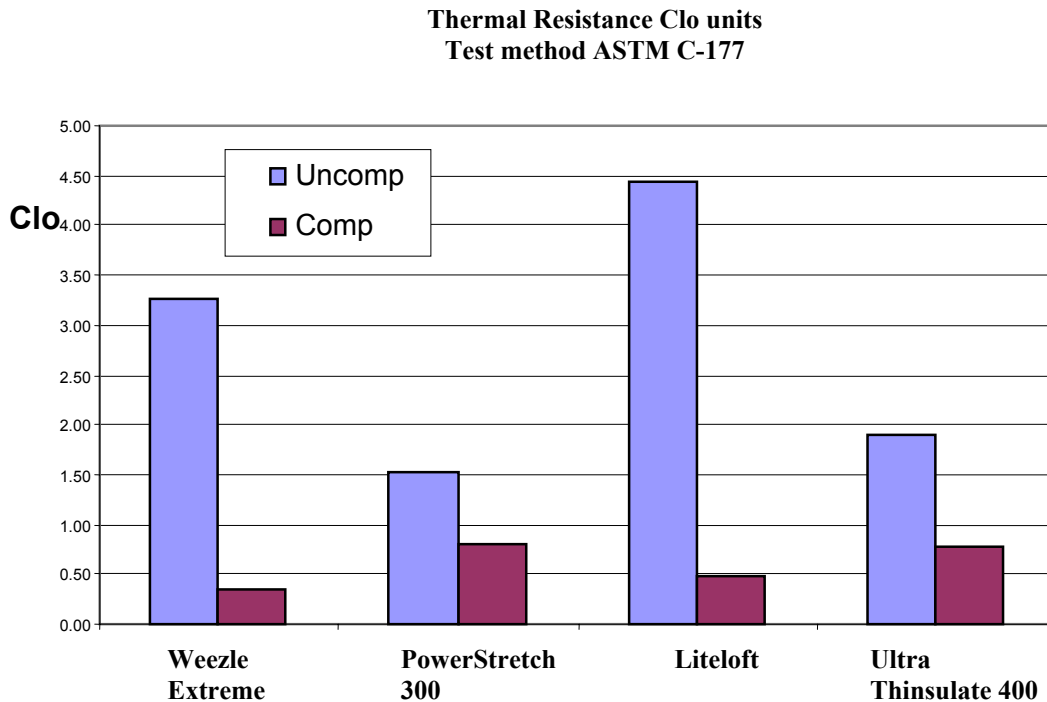


Figure 4. Hydrostatic pressure gradient effect on insulation.

Hydrostatic Pressure

In addition to moisture resistance, the undergarment construction materials must exhibit a level of compression resistance. It is commonly accepted that hydrostatic pressure increases as the diver goes deeper, but it is not obvious that a hydrostatic pressure gradient exists across the drysuit. The magnitude of the hydrostatic pressure gradient varies with the attitude of the diver

in the water column. A diver with a stature of 167cm (56 inches) vertical in the water column will experience a hydrostatic pressure gradient across their body from 0cm H₂O (0 psig) at the highest point to possibly as much as 167cm H₂O (2.4 psig) at the lowest point. When the diver is prone in the water this hydrostatic gradient can range from 0 - 60cm H₂O (0 - .94 psig) and as the diver fins, the gradient fluctuates with each kick. This gradient changes very little as the diver descends, because air is added to the suit to maintain neutral buoyancy.

The impact of this hydrostatic pressure gradient on insulation was investigated by Lippitt (1982), Audit (1987) and Wattenbarger (1987) and its consideration is critical when selecting candidate materials for drysuit undergarments. Currently, candidate materials are screened by testing them in a non-compressed state and then under a load of 35cm H₂O (0.5 psig).

Figure 4 contains two examples of high-loft materials (like down) and both show the highest clo value in the uncompressed state. However, 80-90% of their insulation is lost when a load as small as 35cm H₂O (0.5 psig) is applied. Because of the hydrostatic pressure effect, high-loft insulation is not suited for diving versus topside applications.

Drysuit Inflation Gas

Air has been the traditional drysuit inflation gas. In the past, when electric heating undergarments were used in combination with drysuits, they were inflated with Heliox in saturation diving to not introduce contaminants into the atmosphere of the saturation chamber complex. The presence of Helium has a major impact on suit performance because of its high conductivity (Fig. 5). Wattenbarger (1978), in a series of thermal mannikin tests, demonstrated that Heliox used in a shell drysuit would reduce the effective insulation of the suit ensemble by 71%. Based on these results, if Helium reduces the effectiveness of an undergarment, would switching to a less conductive gas increase its effectiveness?

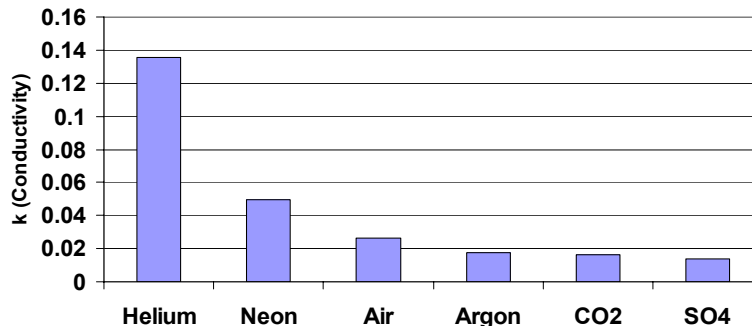


Figure 5. Insulation effectiveness of gases.

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 (2001), who conducted the following test:

- 26 Norwegian Navy Clearance Divers: ages 21-33, mean weight 80.8 kg, 2 dives each with 24 hours surface interval, making a total of 52 dives;
- Water temperature -1°C to 4°C (mean 2°C);
- Scuba with AGA full face mask;
- 6.5 mm foam neoprene drysuit and woolly bear undergarment;
- Dives ~ 9 m for 60 minutes;

- Divers did not know if they were using air or Argon; and,
- Suit pre-purged 3 times with Argon to ensure a high concentration in the suit.

During the dives the skin and core temperatures were monitored and the resulting data did not show any difference between air and Argon, concluding it was not advantageous for this specific ensemble.

However, Weinberger (1989) used U.S. Navy divers and CO₂ as the suit inflation gas, reporting a 19% improvement in suit insulation. CO₂ was used because in the event it enters the breathing loop it could be scrubbed out. Argon and CO₂ have conductivities that are comparatively close relative to air (Fig. 5). The difference in test results can possibly be explained by the style of drysuits used. Risberg's tests utilized a 6-mm foam neoprene drysuit with woolly bears with a large fraction of the total insulation coming from the foam neoprene. The addition of Argon into the drysuit would not change the intrinsic insulation of the foam and at 9 msw (29 fsw) of depth the foam still contributes a major portion of the total suit/system insulation. Shell drysuits were used in Weinberg's tests that had relatively little intrinsic insulation with the majority provided by the undergarments. Argon and/or possibly CO₂ are not a fix for a poor insulation package. They are a means to gain additional performance when there is no more room in the drysuit for additional layers. The effect of CO₂ use at deeper depths is not known.

Exposure Planning

Exposure planning has always been challenging. The insulation values of most diving ensembles are not well known yet are needed for the available planning tools. Thalmann (1990) published a simple algorithm that can easily be set up on a Microsoft Excel spreadsheet that takes into account the following parameters: desired end of exposure functionality, water temperature, size of the diver, and the activity level. Table 9 was generated using the algorithm for a 75 kg (165 lb) diver, fully functional in different water temperatures and doing mild work. Enter the table along the water temperature column then move across horizontally to the time in minutes that best meets the intended dive duration. From that cell, move vertically up to the clo value at the top of the column.

Table 9. Exposure planning table for a 75 kg diver performing mild work.

Full Function Exposure Duration (min)										
		Insulation clo								
°C	°F	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.8	2.0
-2	28	NR			24	35	49	70	156	274
0	32	NR			27	39	57	83	216	493
2	36	NR		20	30	45	67	103	352	720
NR		Not Recommended								

Table 10 shows clo values for 4 different insulation packages. The two Thinsulate garments are base garments and the polypropylene and fleece undergarments can be layered with them to produce different insulation packages. For example, if the minimum insulation needed is 1.4 clo, this could be achieved with the polypropylene underwear and the Thinsulate 400. Table 9 values only address the general thermal state of the diver and not the hands, for which Thalmann

included an additional algorithm. However, even less is known about the clo value of glove and mitten systems.

Table 10. Undergarment clo values.

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

Thalmann provided Tables 11 and 12 for glove ensembles and their Insulation/Surface Area values.

Table 11. Planning table for hand temperature.

Insulation/Surface Area											
°C	°F	6	8	10	12	14	16	18	20	22	24
-2	28	9/15	12/22	22/6	20/39	25/48	31/61	36/75	36/94	50/163	61/*
0	32	9/18	13/25	17/34	22/45	32/74	34/74	41/156	50/130	60/196	72/*
4	39	10/20	15/29	20/41	25/55	38/118	40/103	60/*	60/*	74/*	135/*
18°C		64°F	Fully functioning								
12°C		54°F	Lower limit								

Table 12. Glove insulation/surface areas.

Glove Description	Insulation/Surface Areas
Glove five finger ¼ inch	10.5 (depth 0 msw)
Mitt ¼ inch	12.0 (depth 0 msw)
Glove with M200 Thinsulate	12.0 (Not affected by depth)
Dry Mitt with M200 Thinsulate liner	12.8 (Not affected by depth)
Dry Mitt, M200 Thinsulate liner and ¼” over mitt	24.0 (Affected by depth)

The planning conundrum becomes obvious when trying to select a suit/glove combination for a dive. Using the tables provided, plan a 70 minute dive in -2°C water. Using Table 9 we determine that we need a clo value of 1.4 clo for the diving ensemble. Using Table 10 we can easily combine a 1.3 clo Thinsulate garment with 0.1 clo medium weight polypropylene underwear to get the needed 1.4 clo.

In Table 11, at -2°C, there is no glove combination listed that will maintain the hands at a temperature greater than 18°C (fully functional) for 70 minutes. However, if the hands are allowed to move into the range of “painful” and some loss of some function, then glove choice 5 will do, with some limitations. First, it loses insulation with depth and at 40 msw (132 fsw) it would nominally have the insulation value of glove ensemble 4. Second, the glove/mitt system used an overmitt with very limited dexterity, consisting of a thumb pocket and one large pocket for the remaining four fingers. Dexterity, therefore, is not a design feature for this glove system.

Planning Conclusions

Planning the general thermal state of the diver is possible using information available in Tables 9 and 10. The example demonstrates that the proper selection of equipment to maintain the diver in a fully functional state is not difficult. However, as discussed earlier, a fully functional state is not comfortable and, therefore, the levels of protection provided by such planning tools should be used only as a starting point. Table 11 drives home the limited effectiveness of insulation on the hands. The planner is left relying on experience plus the judgment of the divers to end the dive before the hands become too painful and dysfunctional.

Hand Protection Consideration

The optimum protection of the hands can be achieved with the use of dry gloves attached to the drysuit without a wrist seal (Fig. 6). The elimination of the wrist seal allows the free exchange of gas between the suit and glove. The presence of a wrist seal can impede the circulation of blood flow to the hand, which is very minimal when the hands are vasoconstricted. Work done by Thalmann (1987) and Stinton (1989) demonstrated that glove systems without wrist seals provide the highest levels 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 and, in some cases, divers with mitts were able to draw their fingertips out of the mitt portion and rewarm them on their palms. The hands, feet and head represent 18% of the body's surface area and are responsible for 40% of the insensible water loss though the skin of a resting individual. The insensible water loss never stops and the result is that the insulation gets damp with time. To address this, vapor barrier liners have been found to be helpful on long duration and cold water dives. The ideal vapor barrier consists of a waterproof/vapor impermeable layer being worn next to the skin such as medical examination gloves (Stinton, 1991).

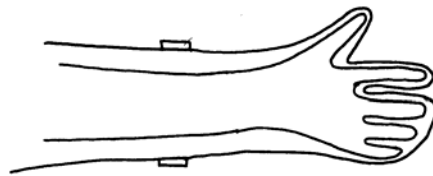


Figure 6. Hand protection without drysuit wrist seal.

Foot Protection Considerations

The feet are easier to protect than the hands because the foot pocket of a drysuit is like a large mitt and dexterity is not an issue. The feet are placed in fin pockets, which if too small, can impair circulation. Similar to the hands, the feet are one of the body areas with a high level of insensible water loss. Again, vapor barrier liners are helpful. A rule of thumb is that the feet require twice the insulation value that is used to protect the diver. This requires the suit to have a larger foot size with corresponding larger foot pockets in the fins, something that is commonly ignored.

Head

The head differs greatly from the body in that a large portion of the head does not experience vasoconstriction as a response to cold. The head accounts for 11% of the surface area of the body and 8% of the heat loss in an individual in a state of thermal comfort (Kerslake, 1964). The ratio of heat lost through the head increases as the body vasoconstricts. However, the head has received little attention because it does not have the constraint that limits the exposure of hands and feet. If increasing levels of insulation to the head are added, the additional buoyancy can stress the neck muscles. Offsetting the buoyancy of the insulation with weights secured to the head compounds the neck problem.

A diving helmet provides the highest level of protection for the head but is not readily available for free-swimming divers. The highest level of head protection is an attached dry hood with an insulative liner used in combination with a full-face mask. The most common form of head protection in use is a wetsuit-style hood (separate or attached to the drysuit) and a standard scuba mask.

Improvements in Insulation

The quest for improved insulation is an ongoing process. Ideally, if the insulative value of a vacuum could be captured, the pinnacle of passive insulation would be achieved. To date, all attempts to produce a vacuum-based insulation resulted in stiff insulative panels and, when encapsulated materials leak, the performance is lost. At some point in the future it may become possible to capture a vacuum in a suit as new materials and processes become available every year.

Figure 7 shows the conductive values of different materials ranging from neoprene to a vacuum. Prior to the advent of Aerogel, insulations that attempted to trap and stabilize air were not as good as stable air because they were more conductive than air. Aerogel represents a major breakthrough to this finding.

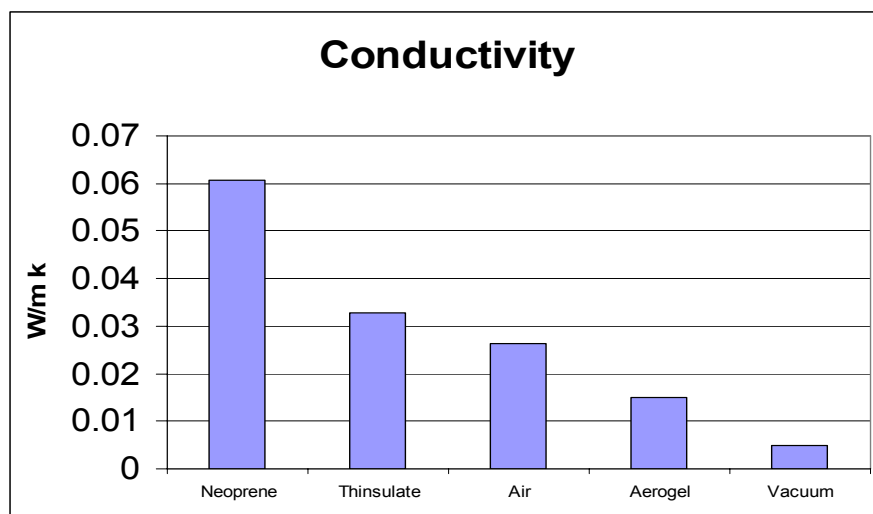


Figure 7. Conductivity values.

Aerogel is currently being tested and evaluated for use in diving applications as part of a U.S. Navy-sponsored effort. The biggest challenge to DUI in fabricating these Aerogel garments has been the materials encapsulation process. Aerogel is 99.8% empty space and cannot be sewn or bonded. It must also be kept off the skin because it is hydrophobic and acts as a desiccant, drying the skin. The Aerogel silica dust has particles as small as 2-3 nm. The solution has been the identification of a membrane that is gas permeable, water impermeable and contains the dust.

In 2006, third-generation Aerogel garments utilizing a new encapsulation process were successfully tested at NEDU on an immersed thermal mannikin. These outperformed the B400 Thinsulate garments used as controls (Fig. 8). Both garments are approximately the same thickness and bulk (Nuckols, 2006). Figure 8 also shows the impact that geometry and water pressure have on insulation. The design of fourth generation pre-production garments is currently underway, along with the development of a five-fingered Aerogel glove.

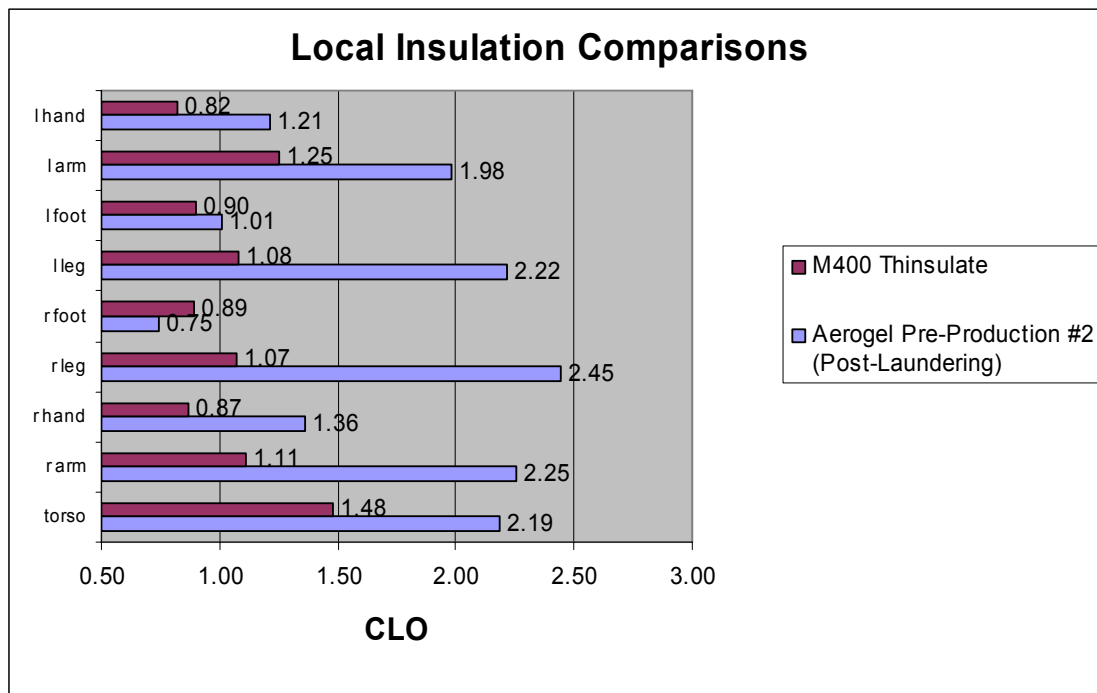


Figure 8. Thinsulate and Aerogel insulation of body parts.

Hybrid Passive Systems

Even with advances in passive insulations like Aerogel, the hands and feet will always present a challenge as designers try to balance thermal protection with performance. Because of the limitations of passive insulation, an approach being investigated at DUI is active heating for the hands and feet to extend the effective range of current and future passive systems. The idea is not new (Stinton, 1989; Weinberg, 1990) and the challenge has been one of available technology. Electric-based systems have been investigated over the years with one of the paramount issues being electrical safety. AODC *Code of Practice for the Safe Use of Electricity Underwater* (1996) is considered the benchmark for underwater electrical safety by many organizations. This document outlines the minimal measures that must be taken for the

prevention of electric shock in different underwater applications, including electrically-heated diving suits. The code specifies that all electrically-heated diving garments with a supply voltage greater than 6 volts must be equipped with GFI (Ground Fault Interrupters) and garments must incorporate screens to channel current leaks to ground. This seemingly conservative standard was set because the current levels that can impact the function of the heart are time-dependent and the levels are lower than expected. Table 13 represents ranges that are considered dangerous current/time combinations.

Table 13. Maximum current exposure time.

Current	Maximum Exposure Time
2000 mA	0.01 sec
500 mA	0.1 sec
70 mA	5 sec

Energy requirements for the hands appear to be in the range of 20-25 watts, values that were independently derived by Stinton (1989) and Weinberger (1990). These numbers represent a balance between how warm the hand needs to be to avoid discomfort while at the same time balancing the needs for dexterity and a minimum energy requirement. The toes also have the same energy requirement and, when combined, results in a total need of 40-50 watts. This level of power can easily be handled by a diver-carried battery pack for the duration of 1-2 hours.

To make such systems economical and practical, human resistance to change must be overcome. Until recently drysuit divers could not envision diving with dry gloves attached to their suits with no wrist seal present. The absence of the wrist seal allows: no interference with blood flow to the hands (Stinton, 1989; Thalmann, 1978), inflation of the gloves during the dive to warm the hands, and a wiring harness to be easily routed to the gloves.

Respiratory Heat Loss

In the normal air environment sensible and insensible respiratory heat loss equals 10% of the metabolic rate. Sensible loss involves the heating of the gas in the inspired breath and insensible is the addition of water vapor to the inspired breath (Berenson, 1973). In a constant environment, as an individual's exercise rate increases, the respiration rate goes up to supply more oxygen and remove more CO₂. However, even with this increased respiration, the heat lost still remains approximately 10% of total heat production. Factors affecting the level of respiratory heat loss are the breathing gas composition, temperature of inspired breath, water vapor content of inspired breath, and ambient pressure. As the ambient pressure increases with depth, the inhaled gas becomes denser and the amount of heat lost increases with each breath. The water content of the inhaled breath of air or nitrox is close to zero.

Figure 9 shows a comparison between Nitrogen and Helium, two common gases that are used as diluents in diving. The key to the sensible portion of respiratory heat loss is thermal capacity, higher for Nitrogen than Helium.

Figure 10 shows that nitrogen-based mixes have higher heat capacity than helium-based mixes. Most regulatory bodies of commercial diving require that breathing gas below 150 msw (500 fsw) be heated, because respiratory heat loss approaches almost 48% at 183 msw (600 fsw). Gas heating is an active process that requires an energy source. Before being pumped to the

diver's suit, hot water is passed through a heat exchanger to heat the gas. There are no active gas heating systems available for free-swimming divers, but one was referenced as in development at Scripps Institution of Oceanography (Stewart, 1992) without further testing details available. This system utilized 1% Hydrogen mixed in the breathing air and a catalytic heater mounted inline between the first and second stage of the scuba regulator, warming and humidifying each breath of air. The actual temperature of the air was not measured during dives though on the surface it was reported to be 49°C (120°F).

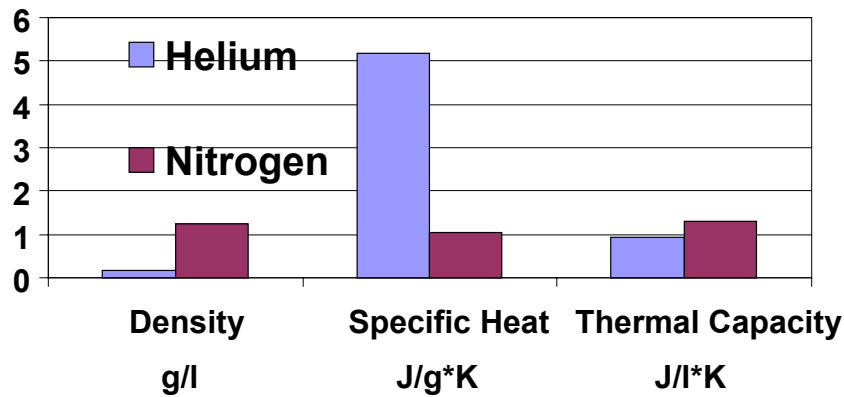


Figure 9. Comparison of physical properties of Helium and Nitrogen.

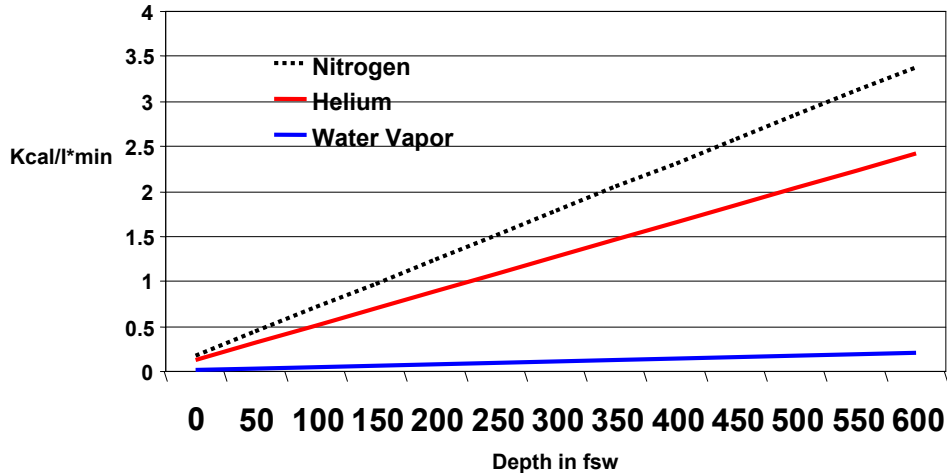


Figure 10. Comparison of Nitrogen- and Helium-based mixes.

The inspired breath in closed-circuit breathing devices was assumed to be at ambient water temperature and in open-circuit scuba it was believed to be lower than ambient water temperature because of adiabatic cooling that takes place as pressure is reduced at the first and second stages of the regulator. Ryan *et al.* (2002, unpubl.) reported inhalation temperatures much lower than previously thought for open-circuit scuba. At a high Respiratory Minute Volume (RMV) and cylinder pressure, the inspired temperature was -27.8°C (18°F). The ambient water temperature was 0°C (32°F), the cylinder pressure 206 bar (3000 psig) and work

rate was at a RMV of 62.5 L/min (the depth was not given.) At this RMV, the diver would be working very hard and would only be able to maintain this level for a short period. As a byproduct of this workload, a large amount of heat would have to be rejected or stored in the body. Ryan *et al.* observations open the door to some very interesting questions, but do not define the impact on the diver's thermal state. To address this problem, Kirby Morgan Dive Systems developed a heat exchanger that is connected between the first and second stage to minimize the impact of adiabatic cooling and provide the diver with breathing gas at a temperature closer to ambient water temperature. The device is referred to as the Intermediate Gas Heat Reclaimer (IGHR; Schultz, 2002.) However, there is no information available as to the efficiency of the heat exchanger and it is not commercially available.

Application of modern passive thermal protection systems results in the hands and feet still being the limiting factors, not respiratory heat loss. Under the theory of constraints (Goldratt, 1990) one should identify and eliminate a constraint before investing limited resources to fix a non-constraint. The process of constraint elimination is continuous, because with the elimination of each constraint, a new constraint is identified. Respiratory heat loss may be one of the last ones to be eliminated, because in a fixed system such as passive insulation, the system does not adapt to the needs of the diver. For example, during high levels of work the insulation does not adapt to cool the diver. However, with high exercise rates and increasing RMVs, some excess heat can be dumped.

Active Heating

Hybrid systems in the near future will extend the performance of passive systems though they will not make the divers truly comfortable. Only when fully active systems become available will comfort come close to being achieved. Active systems such as free-flooding hot water systems are proven technology and are commonly used in the commercial diving industry (Fig. 11). On a daily basis, these systems maintain thousands of divers worldwide in close to thermal equilibrium for four hours in some of the most demanding diving applications.



Figure 11. Free-flooding hot water system.

A large-diameter umbilical is needed to provide a continuous supply of hot water to the diver from the surface. If the umbilical is not an issue and surface support is available, the diver can spend extended periods of time under water, fully functional with good dexterity. The free-flooding hot water suit is an example of what is possible if access to a near-infinite power source is available. The development of active heating systems for untethered, free-swimming divers has been the objective of development efforts over the years. The challenge continues to be the same, *i.e.*, a high-density portable power source that is safe and inexpensive. The power estimated to maintain a diver in thermal equilibrium in a well-insulated drysuit ranges from 250-1000 watts.

Two approaches for meeting this challenge have received continuous exploration over the years: electric-heated garments and closed-circuit, liquid heat-transport garments known as tube suits. Both systems are constrained at this time by available power sources. Battery-power density is limited and portable heaters designed to supply liquid heat-transport garments are not commercially available. Heating systems using hydrogen catalytic combustion (Nuckols, 2001) and zeolite heat storage are currently being investigated, but are far from immediate commercialization. Electrically-heated undergarments will most likely become more dominant because of their relative simplicity, versus the complexity of liquid heat-transport garments and heater-based systems. The complexity of the liquid heat-transport approach is only justifiable where both heating and cooling may be required during the course of the dive. Full coverage electric-heating garments will not be likely be available until more power-dense electrical-storage devices become available.

Conclusion

The one reason to send a diver versus a machine under water is the multitudinous efficiency of human judgment linked to the hands. The diver's primary tools for carrying out underwater tasks underwater, *i.e.*, gathering specimens, manipulating equipment, are the hands, which require the full attention of the dive planner. To date, hand protection has been treated more as an accessory. The goal of the dive planner should be to maintain the diver fully functional during dive by starting with the needs of the hands first, the feet second, and finally the primary insulation package. Once the complete insulation package has been defined, a drysuit should be selected that supports these needs. This suit must include the capability for a dry glove system, large-capacity foot pockets, and should fit over the insulation package without restrictions. In the near future, first-generation hybrid systems will address the constraints of the hands and feet, extending the capability of passive systems. Hybrid systems will eventually evolve into fully active systems as each constraint is eliminated, the need for high-density power sources being the greatest. The gradual evolution from a passive drysuit system to a hybrid system and eventually to a fully active system is more likely than any single quantum leap forward. However, these evolutionary improvements will be of little use to those who have not mastered the basic drysuit.

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SCUBA REGULATORS FOR USE IN COLD WATER: THE U.S. NAVY PERSPECTIVE

John R. Clarke

Navy Experimental Diving Unit
321 Bullfinch Road
Panama City, FLORIDA 32407-7015 U.S.A.

Introduction

There is no such thing as a scuba regulator that will not freeze. In a recent series of 105 coldwater dives in water surrounding the Arctic Research Station at Ny-Ålesund, Svalbard, Norway, (water temperature ranging from -1°C to $+1^{\circ}\text{C}$) there were 3 regulator freezing events, all associated with regulator free-flow. One occurred in air before the dive (AGA Full face Mask), and two occurred during dives in shallow (<20 m) water (Atomic T2 Titanium and Scubapro MK 20).

Ice on the outside of a first stage regulator is usually not problematic. Figures 1 and 2 show regulator first stages tested at NEDU that have become completely enveloped in ice, except for the small pressure sensing port in the center of each first stage. They functioned normally. However, ice accumulation inside a second stage regulator is not well tolerated. Figure 3 shows ice accretion around the second stage lever. That regulator free-flowed as a result of the ice accumulation.

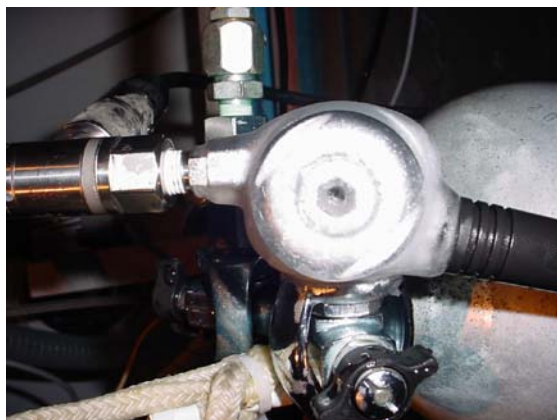


Figure 1. First stage regulator encased in ice functioned normally.



Figure 2. Close-up view of another first stage that functioned normally despite ice accumulation.

Fortunately, some scuba regulators are less likely to freeze than others. This point was made perfectly clear in a paper on Regulator Function in the Antarctic (Bozanic and Mastro, 1992). Shortly after that publication the Navy Experimental Diving Unit was tasked by its parent

Command, the Naval Sea System Command's Director of Ocean Engineering, Supervisor of Salvage and Diving (SUPSALV) based in Washington D.C., with testing candidate cold water regulators to identify those regulators most resistant to freezing under severe operating conditions, such as polar diving.



Figure 3. Second stage regulator that free-flowed because of ice accumulation around critical components.

We define, somewhat arbitrarily, that water above 3°C (~37°F) is unlikely to induce an abnormal flow event (either interruption of gas flow or free flow), whereas water temperatures below that may. Burgess (1982) opined that temperatures inside first stage regulators could drop 5°C or more because of adiabatic expansion during gas flow. Therefore, he reasoned, if moisture were in divers' air it might be expected to freeze whenever water temperature was as warm as 5°C (41°F), thereby leading to regulator malfunction.

Eaton (1990) observed that regulators can certainly free-flow vigorously when the second stage purge valve is repeatedly activated while the first stage is in -1°C to 0°C water. However, his work showed that moisture was unlikely to be the culprit. Perfectly dry air was just as likely to elicit free-flow as moist air, if not more so. His conclusion was that free-flow induced by loss of intermediate pressure control was caused by changes in regulator material characteristics under extremely cold conditions. Eaton's untested hypothesis was given credence by the earlier work of Morson (1987) who found that the material in a first stage diaphragm could affect its ability to control intermediate pressure and, therefore, affect the probability of second stage free-flow.

Mechanisms

"Freeze-up", the generic term for cold-induced flow abnormalities, is a probabilistic event. That is, we cannot predict with certainty under what conditions a particular regulator will free-flow. We can identify risk factors for freeze-up and have, in fact, used an analysis of these risk factors in helping us decide *a priori* (Clarke, 1996) how we would test for susceptibility to freeze-up.

Breathing gas experiences a pressure drop across first and second stage regulators. The resulting adiabatic gas expansion causes a drop in temperature within the regulators. If the water surrounding the regulator is within a few degrees of freezing, the adiabatic cooling of the regulator body will cause any internal moisture to freeze. In turn, this freezing can interfere with the action of the first stage diaphragm spring, or the lever mechanism in second stage regulators. The result can be either a complete blockage of gas flow or, more usually, an unrestrained free-flow. For that reason, divers protect their first stages from freezing in cold water by applying an oil, grease, or dry air filled cap isolating sensitive mechanisms from water.

The likelihood of regulator free-flow (Clarke, 1999) is dependent upon the probability of water gaining entry to the inside of a regulator second stage (P_{we}), and the probability of low temperatures in the second stage (P_{IT}). P_{IT} is in turn governed by a balance between adiabatic processes producing regions of low temperature, and heat flux towards those cold regions. In general terms;

$$P_f = P_{we} \cdot P_{IT} \quad (1)$$

where P_f is the probability of regulator failure caused by freezing. The probability of water entry into the second stage (P_{we}) is a function of exhaust valve design (controlling the ease of exhaust valve leakage) and the magnitude of negative pressures. Negative pressures are, in turn, generated by high ventilatory rates and high gas densities related to depth when a diver works against inspiratory resistance (another feature of regulator design). Therefore, $P_{we} = f(\dot{V}_E, D, \text{ and } C_{1...n})$ where \dot{V}_E is expired ventilation, D is depth, and C is a number of manufacturer determined parameters (*e.g.*, $C_1 =$ exhaust valve leakage pressure, $C_2 =$ inhalation resistance, etc.).

T_f , the temperature of adiabatically expanded gas is given by,

$$T_f = T_i \cdot \left(\frac{V_i}{V_f}\right)^{\gamma-1} \quad (2)$$

where T_i is the pre-expansion temperature in K, V_i and V_f are the respective gas volumes, and γ is the ratio of specific heats for constant pressure and constant volume ($\gamma = 1.4$ for air). However, the balance between adiabatic cooling and the countering heat flow is controlled by \dot{V}_E , and also by certain design features.

Based on the foregoing we can hypothesize an instantaneous risk or hazard function for any particular regulator model:

$$r(t) = (a \cdot D) \cdot (b \cdot \dot{V}_E) \cdot \left(\prod_{i=1}^N c_i \cdot C_i\right) \quad (3)$$

where a , b , and c are various proportionality constants.

The influence of depth and \dot{V}_E can be combined into an expression of mass flow. Mass flow is defined as:

$$\dot{M} = \rho \cdot \dot{V}_E \cdot \frac{P_{amb}}{P_0} \quad (4)$$

where ρ is gas density at 1 atm abs and 0°C, \dot{V}_E is expired ventilation in L·min⁻¹, and P_{amb} is ambient pressure in absolute units. P_0 is the absolute pressure at 1 atm. Mass flow rate reflects the mass of gas flowing through the regulator each minute, with units of grams·min⁻¹.

The total probability of cold induced failure is based on the survivor function:

$$P_f = 1 - e^{-\int_0^T r(t) dt} \quad (5)$$

Figures 4 and 5 show experimentally determined incidences of cold-induced high respiratory pressures in one model of scuba regulator. The probability of encountering high respiratory pressures increased progressively with mass flow and time of exposure to cold water. A mass flow of about 400 g/min is obtained with an expired ventilation of 75 L·min⁻¹ of air at a depth of 30.3 msw (99 fsw), or 62.5 L·min⁻¹ at a depth of 40.4 msw (132 fsw). The least risky dives are those occurring for short periods of time, at shallow depths, and with low respiratory flow rates (Clarke, 1996).

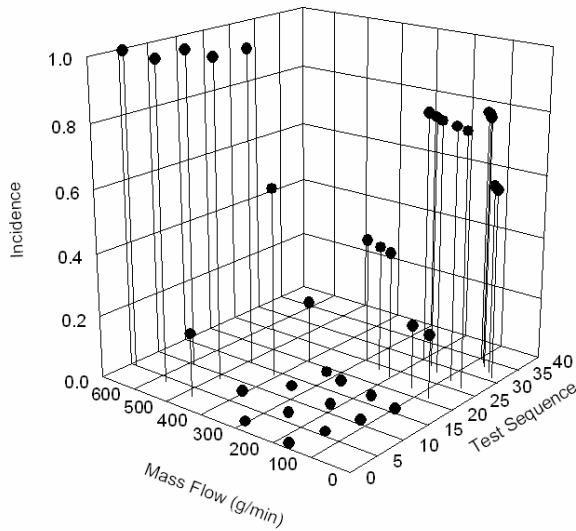


Figure 4. Diagram of freeze-up incidence as a function of time (test sequence) and mass flow rate.

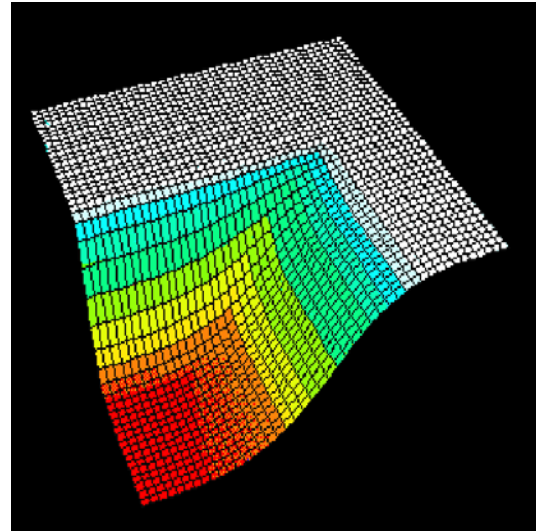


Figure 5. Smoothed surface modelling the test results in Fig. 4. In the lower left of the figure the regulator is relatively warm. As time and mass flow rate increase to the right and top of the figure, respectively, the probability of internal ice formation increases towards unity.

1995 Methods

In NEDU's 1995 testing of cold-water regulators, the probability of a regulator flow event was modified from the theoretical calculations given above. A more empirical method involved the following equation.

$$P_f = \sum_{i=1}^n \left(\frac{n^{-1} \cdot E_i}{t_i^k} \right)$$

where n = the number of regulators tested (typically 5), E is an event code equal to 0 if there is no freeze-up or free-flow, and equal to 1 if there is. The denominator t is the time in minutes to an event if an event occurs, and k is a power factor to give reasonable values for P_f .

In the following example, 2 out of five regulators free-flowed during NEDU's fixed depth "freeze-up" test, one 18 minutes into the 30 min test run, and one 28 min into the test. Using the empirical equation above, we obtain a P_f of 0.158.

$$P_f = 0 + 0 + 0 + (0.2 \cdot 1)/18^3 + (0.2 \cdot 1)/28^3$$

$$P_f = 0.158$$

1995 Results

In our initial testing of five candidate coldwater regulators, the single (fixed) depth profile resulted in the following probabilities of failure.

Table 1. Fixed dive profile.

Regulator Code	Pf
A	--
B	0.179
C	0.274
D	0.446
E	0.463

The bounce dive profile produced a similar ordering of relative freeze-up resistance (Table 2), which tells us that the exact dive profile tested is not a major determinant of the relative rankings of these regulators.

From the above regulator rankings, NEDU recommended three regulators be approved for use in cold water. They were the Poseidon Odin/Jetstream (Clarke and Rainone, 1995a), and two Sherwoods (Clarke and Rainone, 1995b), the Maximus and Blizzard. (At the time of our testing, the Blizzard used a heat sink over the exhaust outlet to carry exhaled heat to the lever support assembly; the Maximus did not.)

Table 2. Bounce dive profile.

Regulator Code	Pf
A	0.074
B	0.194
C	0.314
D	0.459
E	0.625

Perhaps for that reason, we found that the freeze-up susceptibility of the Blizzard was half that of the Maximus. Subsequent to the release of our 1995 report, we learned that the U.S. Antarctic program was successfully using Sherwood Maximus regulators modified with an added heat retention plate within the second stage regulator box, just as had our Blizzard regulators.

Table 3. Pros and cons of empirical probability estimations.

Relative Risk Rating	
<ul style="list-style-type: none"> • Pros – compacts test results into a single number – little human interpretation – good for small numbers of regulators (5) – certifying agency decides acceptable “risk” 	<ul style="list-style-type: none"> • Cons – pushes burden of decision to higher organizational levels – large numbers of regulators crowd the relative risk list

2004 Methods

Testing established for the 2004 survey of cold-water regulators used a category assignment of regulator grades roughly corresponding to freeze-up risk (Layton *et al.* 2004). The method is more subjective than the 1995 procedure, but is more easily interpreted.

Eight regulator manufacturers supplied 5 units each of 20 regulator models for evaluation. Sherwood, whose regulators did well in 1995, did not resubmit its regulators for evaluation. All the regulators were exposed to a test battery outlined in Table 4, with the categorization rules as outlined in Table 5.

Table 4. Test Conditions

<ul style="list-style-type: none"> • 29°F (± 1°F) - 33 ppt salinity • ventilation: <ul style="list-style-type: none"> – freeze-up: 62.5 L/min for 30 min – bounce dives: 50 L/min for 20 min <ul style="list-style-type: none"> • 5 min deco stops at 12.3, 9.2, 6.1, 3.1 msw • 4 dive profiles: <ul style="list-style-type: none"> – freeze-up dives to 132 fsw (40.4 msw) – freeze-up dives to 198 fsw (60.6 msw) – bounce dives to 130 fsw (39.8 msw) – bounce dives to 190 fsw (58.2 msw)
--

Table 5. Categorization Rules.

Category	Number of Freeze-Ups	
	-1.7°C (29°F) ^a	3.3°C (38°F) ^b
A	0	0
B	<=1 ^c	<=1
C	>1	<=1

^a number permitted from each freeze-up dive profile (40.4 and 60.6 msw)
^b number permitted during 3.3°C resistive effort testing
^c freeze-up must occur after 14.5 minutes of immersion

2004 Results

Category A: Acceptable for temperatures $\geq 29^\circ\text{F}$ with minimal free-flow risk.
 - Poseidon Xstream.

Category B: Acceptable for temperatures $\geq 29^\circ\text{F}$ with minor free-flow risk.
 - Apeks TX50
 - IDI Seaira Spirit Airtec
 - Mares Proton Ice Teflon V32 CWD

Caveats

Ice divers should keep in mind the following caveats to NEDU's regulator testing results, quoted from Layton *et al* (2004):

- “Testing the same units with different dive profiles, ventilatory rates, regulator adjustment settings, etc., for needs other than those of the U.S. Navy, can be expected to provide different results.”
- “Even when regulators in the “Not Recommended for U.S. Navy use” category are tested under different conditions to determine their suitability for differing needs, those regulators potentially could exhibit acceptable levels of performance.”

Examples

Examples in Figures 6 through 9 are diagrams of freeze-up incidence as a function of time (test sequence) and mass flow rate.

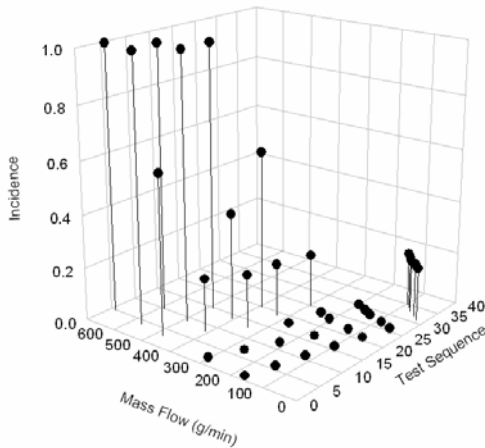


Figure 6. A regulator with good performance across time, but increasingly poor performance at higher mass flow rates.

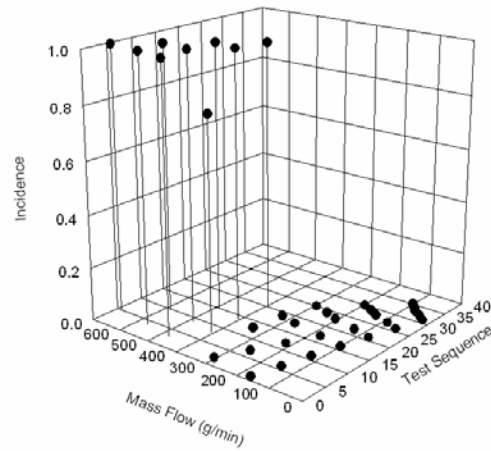


Figure 7. This regulator performed very well at moderate mass flow rates, but froze after exceeding a critical threshold.

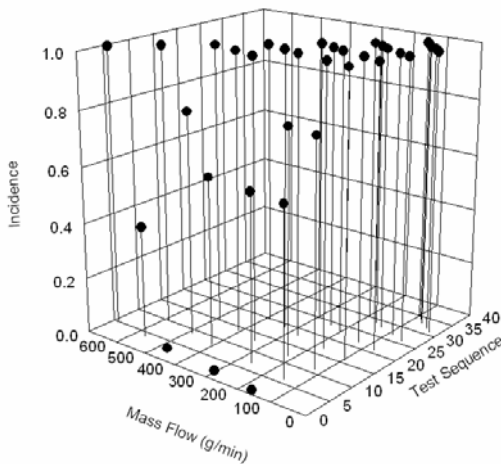


Figure 8. This regulator froze almost immediately.

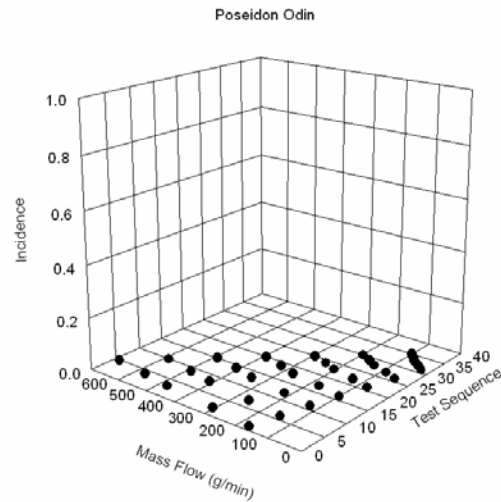


Figure 9. This regulator was essentially freeze-proof.

Discussion

Because of the pressures of the market place, scuba regulator models typically have a short half-life. However, designing a regulator tolerant to freeze-up is a black art for most manufacturers and even “minor” cosmetic changes can affect “freeze-up” risk. Therefore, when regulators that are known performers in cold water are replaced by new models considerable uncertainty is introduced regarding their continued cold water performance.

For instance, in a recent government diving accident, Apeks ATX50 regulators (Apeks Marine Equipment Ltd.) were used, presumably because the Navy approved TX50 was not available. According to the manufacturer, “The ATX50 has all the high performance features and benefits of the highly respected Apeks TX50 regulator with improvements in design and material. Smaller, lighter, lower profile, improved gas flow, finer adjustmentand more.”

From what we know about the potential effect of thermal mass, it is certainly possible that a lower thermal mass - “smaller, lighter” - could yield less heat retention from a diver’s breath. Furthermore, if weight is trimmed by use of plastic as opposed to metal, what effect does that have on thermal conductivity? The simple answer is, we do not know. It is hard to predict what the effect of changes in regulator material or design will have on cold-water performance without testing.

The ability of the industry to arbitrarily make changes to their products varies tremendously depending upon the government regulatory climate they find themselves in and the perceived safety implications of material changes. For example, in the U.S., aircraft manufacturers and owners cannot make arbitrary changes to their aircraft. All components are strictly regulated and any new proposed components have to endure an expensive inspection and testing process.

For the most part, automobile owners and mechanics can apply whichever after-market product to a vehicle that strikes their fancy. Of course, a failure of an automobile component is unlikely to result in fatalities unless it deals with brake or fuel system components. Not so for aircraft components – virtually any change can result in catastrophe.

Knowing that, when you are diving under Arctic or Antarctic ice, far from a safety hole, do you consider your regulator to be more like an automobile or an airplane? Would you find comfort in a laissez-faire attitude towards regulator design changes or would you prefer that new models be thoroughly tested to confirm equality with old models in the under-ice environment?

Conclusion

Over the last thirteen years NEDU has seen the number of regulator manufacturers with successful cold-water regulators double from two to four. It has also been our experience that fewer than half the manufacturers who submit cold-water regulators for evaluation succeed in meeting the stringent standards adopted by the U.S. Navy.

Unfortunately, those manufacturers with successful products tend to change their products in ways that could have unpredictable effects on cold-water performance. Certainly, it is unlikely

that ice divers will be able to convince regulator manufacturers of our needs for performance verification. Cold-water testing is both expensive and time-consuming (NEDU's 2004 test series took one year to complete) and ice divers represent a tiny portion of the regulator market. For our own self-preservation then we, and the organizations supporting us, should ensure that regulators used for polar science diving are tested either by an independent laboratory such as the U.S. Navy's Experimental Diving Unit or equivalent, or field-tested by highly experienced test-divers, such as those associated with the Smithsonian Institution and the National Science Foundation's Antarctic Program.

Acknowledgements

I would like to thank Drs. Phillip Layton and Dan Warkander, and Mr. Mike Brier and Dave Cowgill of NEDU for their efforts in revising NEDU's regulator testing procedures prior to the tests of 2004. I would also like to thank Mr. Dave Eaton from DCIEM, Toronto, CA for his historical perspective on scuba regulator cold-water performance.

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2. Equipment Discussion Session.

- P. Mueller: In the study on the use of Argon the divers were questioned at the end of the dive about their level of comfort and they did not know which gas was in their suits. It was surprising that the ones with Argon in their suits stated they were less comfortable.
- B. Stinton: Right, one has to look at Argon's contribution to the total insulation.
- P. Mueller: That's a very good point; the study was not designed to fully evaluate Argon's contribution with respect to the total insulation.
- B. Stinton: The study was designed for the Norwegian mine-countermeasure divers who dive deep and long and spend much time decompressing. Hope's conclusion was that Argon made no difference with that dive ensemble. If you're diving heliox or trimix Argon might make a fractional difference. Argon is not twice as warm as air.
- L. Quetin: Are you aware of any acclimatization studies of cold water diving?
- B. Stinton: Studies of acclimatization are related to cold weather and not particularly to diving; it takes time and can be lost very quickly. In a Norwegian study of inadequately clothed individuals they were able to sleep all night within a week as they had become acclimatized to the cold. This probably goes on in diving as well. In another Norwegian study of 6 mm 5-finger gloves versus 6 mm mittens the end result was the same: the hands got cold just as fast. However, they looked at completion of underwater tasks. The gloved divers completed the task quickly and then sat there while their hands got cold. The mittened divers took longer to complete the task because they had no dexterity. The conclusion was that it's better to complete the task quickly but the end result remained the same.
- M. Lang: Why do manufacturers not incorporate vapor barriers into undergarments?
- B. Stinton: They were removed by popular demand. In the terrestrial world water-wicking, vapor-permeable clothing is the norm. In an encapsulated drysuit environment divers didn't like vapor barriers. As a manufacturer we have to respond to what the customers demand.
- D. Long: U.S. Navy regular Mark VII boat drivers reported a higher degree of function and comfort because they were used to having that level of discomfort on the skin. New incoming SEAL combat divers were even more uncomfortable. The boat drivers were only acclimatized insofar as being accustomed to the sensation of misery of the cold skin.
- M. Lang: Operationally we know that expiratory moisture is a factor in regulator freeze-up especially if you breathe from it prior to submerging before water entry is possible. That was not included in your freeze-up probability remarks. Pre- and post-dive care is also important and we know that NEDU protocols include not only objective data, but also subjective findings in their regulator testing protocols. Can expiratory moisture be accounted for?
- D. Clarke: There's nothing we can do about expiratory moisture. The breath coming from the lungs is 100% humidified in the lungs, is exhaled fully saturated with moisture and is going to condense against any cold object it finds. Any regulators used in the cold must be able to handle that situation because we cannot get rid of it. All one can do is offset the possibility of that moisture freezing by keeping the moisture in the gas it's contained in above 0°C. In terms of procedure and maintenance the U.S. Navy manual states to not breathe off the regulator in the air because it is much colder than the water temperature.

- M. Lang: Removing water from the second stage after rinses and keeping the regulator warm we have found to be effective. In the 1992 Polar Diving Proceedings a paper by Bozanic and Mastro was published who as dive locker technicians had been tracking regulator performance through the USAP dive program. Since Robbins took over as Diving Supervisor in 1995, we have accumulated another 12 years of regulator performance data under ice, now totaling 10,800 dives. Our standardized equipment program now includes issuance of regulators to ice divers at McMurdo. This is sledgehammer data collection (problem/no problem) but it constitutes our ice diving experience at McMurdo.
- R. Robbins: What that means is we have good regulator performance data for the regulators we issue because we don't allow any other regulators to be used. It does not, however, increase our knowledge of ice diving regulators in general.
- M. Lang: Right, it's not a regulator test data collection but a monitoring of the performance (freeze-up or not) of regulators we have stocked in the dive locker (modified Sherwood Maximus 3600, the 1991 model, 3 generations ago).
- D. Clarke: Nothing is better than real world experience and USAP is getting more ice diving experience than the U.S. Navy is.
- M. Lang: Sherwood Maximus may go the way of the double-hose regulators as they become tired and we just run out of parts for their annual rebuild.
- M. Lang: There seems to be a world of difference in regulator performance between 0°C and minus 1.86°C.
- D. Clarke: In our NEDU reports we draw the line at 37°F below which you have to worry about cold water regulator standards. That limit was taken from some old Canadian data but I agree with you that once you have external temperatures low enough with internal temperatures even lower that is when you can tell the difference in regulator performance.
- O. Oftedal: Regulator free-flow is a discrete event (the end result of ice accumulation). Were you able to monitor ice accumulation?
- D. Clarke: We were not able to. Every 10 minutes we stopped the breathing machine to check for free-flow since we did not have a camera to look inside the second stage. We didn't wait until the end of the test either. Whenever we had massive free-flow we would open up the second stage and see ice accumulation. But the camera is a good suggestion.
- P. Mueller: In intensive care units we use readily available devices on spontaneously breathing patients to keep the breathing tract warm and moist.
- D. Clarke: We have not tested breath warming/moisturizing devices but we have tested Diving Systems' heat exchanger. The concern with the other devices in the airways is the potential increase in breathing resistance. Low ventilation rates or a patient on a ventilator are not as worrisome as a diver working hard.
- M. Lang: Has it also been your experience in the testing environment that for an average ice dive profile of 45 minutes most regulator problems occur in the second stage and not the first stage regardless of the amount of its ice accumulation?
- D. Clarke: We have only seen first-stage failure once and that happened early on. Modern regulators almost invariably experience a gradual buildup of moisture followed by a gradual build-up of ice until the critical point is reached when the regulator free-flows.

Session 2: *Equipment Discussion*

- R. Robbins: Can you make a projection on when battery-operated fingertip and toe heating will be come commercially available?
- B. Stinton: This is probably a year away. The heating elements exist; it is a matter of getting the temperature controls built in.
- J. Clarke: We're also working on related technology, *i.e.*, electrically conductive fibers in soft materials.
- B. Stinton: Divers are beggars, and there's not much money for R&D. We try to develop products with slight modifications to meet multiple applications in different communities (diving, boating, etc.) to get scale of economy.
- D. Long: The products have to be thoroughly tested, reliable and not put the mission at risk because of failure from a performance standpoint.
- L. Quetin: Is there a cost estimate?
- B. Stinton: The cost of an Aerogel garment is currently \$5,000 but the first Thinsulate garments were also expensive due to the manual labor. It is a matter of tooling and volume. Other communities (*e.g.*, Navy, NASA, Air Force) also need insulative garments so we try to have them embrace this concept. If we only make 20 units per year and there are 12 panels within each garment each with an RF welding and dye-cutting tool and a dust-containment environment it gets expensive. These are not your standard sewing machines.
- D. Long: We consider the cost of the glove itself and the penetrators and encapsulated battery packs. Our glove target cost would be \$100 or less.
- B. Stinton: What are the risks of charging this battery? What is the yield of a Lithium-ion battery? The complications and costs of a central control, wires, connectors and penetrators require that we get the system down to a minimum so that the battery can be worn internally with GFI protection. The battery inside the suit, however, carries some risk. Data on potential risks needs to be experimentally derived.
- J. Clarke: We've had an explosion and fire with a Lithium-ion battery being charged. It started shorting out and electrocuting the diver. You do not want to have that embedded against your skin in an electrically powered vest.
- B. Stinton: Regarding battery sizes how long would you expect to be in the water on an under-ice dive?
- R. Robbins: The average scientific ice dive is approximately 33 minutes and no more than two per day are done with cold being the main limiting factor. A one-hour dive duration would be desirable with heated gloves.
- M. Sayer: The diver's workload also needs to be considered since the diver usually doesn't move very far or fast under ice.
- H. Hop: How about a battery pack on the diver's wrist similar to a dive computer? Would it be safer?
- B. Stinton: It comes down to money: all penetrators and connectors through the suit are expensive. My goal is to not put the batteries inside the suit. NASA is experimenting with Peltier devices that are solid state units through which a current is run. They get cold on one side and warm on the other. Instead of using a liquid cooling garment a Peltier film setup would charge the battery (cooling effect while suiting up) and when in a cold environment it is discharging the battery (warming effect).

- E. Ochoa: Glove size and thickness would be important.
- B. Stinton: The goal of dissipating energy to the hand and fingers is to provide warmth and dexterity. We would like to make the gloves light (*e.g.*, Army field wool glove). The objective is not to make the hands toasty but to make them functional so they don't become the limiting factor.
- A. Brubakk: The hand is a regulated system in the body. The reason the arms get so cold is because they lose heat in the sense that the body is trying to protect itself by cooling down the extremities. If you are able to heat the central core sufficiently the hands would not experience the severe temperature problems.
- B. Stinton: DCIEM has published studies on the efficiency of a light electrical vest. A sentry can stand guard in the cold with very light gloves on and have warm hands. The data they do not show you are that as soon as he picks up his weapon (a conductive environment) his hands immediately cool to the temperature of the weapon and he has to put his big mitts back on.
- A. Brubakk: Sure, water is a conductive environment and would have a significant effect. Has anyone tried to test warming the core in diving?
- J. Clarke: We did experiments last year and it did not work. The results should be published soon.
- L. Quetin: Gloves collapse when we grasp scientific equipment and cameras under water which is when the hands get cold quickly.
- B. Stinton: We put insulation on the body before we get in the water where the body vasoconstricts. As soon as the body heats back up to where it is not vasoconstricting the energy dissipation increases. Weinberg and Thalmann were concerned about tricking the body into vasodilation and therefore kept the finger and toe temperatures above the non-freezing cold injury level into the fully functional level but not toasty warm. Whistler had examined electrical heating of air crewmen in WWII. The waste gunners on bombers had full electrical suits and were toasty warm to their target and back. Bomber command decided the suits were taking horsepower from the engines and took away the electrical flying suits and some bullets so more bombs could be carried. Always in the breeze the gunners' hands got very cold and they froze their hands to the weapons when they discharged them. Bomber command gave them electric gloves back so they could operate their weapon. Now the hands were toasty warm but the body was tricked into thinking it was not cold and vasodilated. This created hypothermia victims who could not shoot once they were across the English Channel due to decreased upper-level mental function. Bomber command gave the crews their electrical flying suits back.
- J. Clarke: From a decompression standpoint it is advantageous to be uncomfortably cold under water and warm coming up at the end of the dive.
- R. Palozzi: Have chemical heating packs been routinely used under water?
- D. Andersen: I use them routinely while diving and they work well. They are nice to have when you get out of the water too.
- B. Stinton: The chemical heat packs are essentially Magnesium and Iron and functionally a sea water battery. The diver supplies moisture and the corrosion reaction provides the heat. Be cautious with the larger heat packs (such as inner soles) as they can provide enough heat to cause burns.

Session 2: Equipment Discussion

- L. Quetin: They are alright if worn on the outside of thinsulate booties or outside the glove liner but only last about 20 minutes.
- M. Lang: Have rebreathers been tested under very cold conditions for the various operational considerations?
- J. Clarke: We certainly do test under cold conditions. Draeger has a temperature limit of 2°C and the manufacturer did not allow us to freeze that rig but the MK16 was tested to -2°C and for the most part it worked well. We have also tested certain scenarios of swimming under ice, surfacing, stowing the rig where it freezes and then donning the gear again. At that point it does not work too well until things start thawing out.
- S. Mercer: Our rebreather diving with Draeger Dolphin and Halcyon units was at 4°C under ice in Antarctica. We were a bit anxious about that because 4°C was the cutoff point for the scrubbing material we were using. The benefit is the warm gas produced from the scrubber which you don't notice under those conditions but there must be some effect. For canister insulation we made a little wetsuit cover.
- J. Clarke: Low temperature has a dramatic effect on canister duration which drops off like a ski slope even before you reach freezing temperatures.
- J. Flinkman: I have used the Draeger Atlantis semi-closed rebreather in under ice work. The topside temperature ranged from 0°C to -15°C and water temperature from just below 0°C to 2°C. We access the sites by helicopter and pack the rebreather in a crate with hot water bottles and blankets around the canister to keep it warm. I start breathing from it immediately and never had any problems in about 50 dives. Once the exothermic reaction starts it keeps going and produces a lot of heat for itself. Scrubber times were about the same as for summertime diving. The breathing air is significantly warmer and I never felt cold during under-ice dives up to one hour in a drysuit with argon inflation.
- S. Mercer: We also transported the rebreathers in insulated boxes and used teabag heaters on the canisters. We sat the divers on the side of the hole using the units for about 5 minutes to get the reaction going before they jumped in.
- J. Clarke: I can give an example of how that impedes the diver. We had some cold-water operators complain that they were having massive problems with Sofnolime. They had started off with the Sofnolime cold versus keeping it warm which is critical. The cold absorbent would in fact heat up once the breathing started but then it would quit. My computer model indicated this phenomenon as well and the data from lab testing confirmed it. There is no way for the diver to know that when he starts breathing cold it warms up and then a few minutes later it stops; the probability for a severe CO₂ hit exists.
- H. Hop: Divers are using rebreathers under ice in Svalbard and the Bering Sea. The advantage for science (*e.g.*, ice algae sampling or under-ice structure documentation) is that diving rebreathers under the ice has less of an impact on the sampling environment than open-circuit exhalation bubbles.
- J. Flinkman: The Draeger Atlantis used in a semi-closed nitrox mode does burp out some gas every minute or so. You can however plug the bleed valve and use the unit as an oxygen rebreather. For shallow-water work under the ice there will be no bubbles in this mode.
- S. Mercer: Divers are often on their back while sampling under ice and an uncomfortable increased pressure can result in this orientation. These units are designed to work face down under water.

- H. Hop: True, but much work is accomplished in a vertical position with a slight backward lean, such as for suction sampling under ice.
- J. Clarke: The LAR-V is chest-mounted and would solve the positioning problem for shallow diving.
- D. Andersen: We have a group using that set-up for high altitude diving.
- L. Quetin: There should be a more standardized means of gathering information on the performance and acquisition/replacement of effective cold-water regulators other than word of mouth especially due to the models changing on an annual basis.
- M. Lang: The scientific ice diving community is rather small and the scientists are known to us. Other than getting information from an organized scientific diving program that tracks regulator performance under ice another way might be through an ice-diving listserver for exchange of information.
- R. Robbins: The last time we did a relatively extensive study of various models of regulators for under-ice use was in 1991.
- M. Lang: I agree that this is an evaluation project that urgently needs to be re-visited. The limitation is that we have certain models currently in stock and have not pro-actively rotated other regulator models to certain scientific divers through the USAP diving program to evaluate their effectiveness as replacements. There exists the problem of manufacturers' claims regarding performance of a product without any third-party independent testing to validate the performance. I suggest that we can target regulators with design and performance features (such as those in the second stage of the 1991 version of the Sherwood Maximus) that have a high probability of working in our under-ice environment.
- O. Oftedal: What are the regulator engineering or design constraints and variables that would be examined to evaluate probabilities of performance?
- M. Lang: A matrix of design features could be constructed of commercially available "cold-water regulators" as designated by manufacturers. This would allow for a selection process to narrow down the current crop of 2007 regulators models with desirable features for under ice.
- M. Sayer: We should continue to track international manufacturers' regulator model use under ice by scientific divers since the models differ and compile this data to evaluate in the future.
- H. Hop: The specific use (*e.g.*, shallow under-ice diving) might be different than other types of ice diving, but certain brands we know from experience do not work.
- J. Flinkman: The Poseidon Odin has basically been the same regulator for 25 years. At one point Poseidon changed the outward appearance of the first stage a bit with a pressure relief valve. The Apeks TX50 and TX100 have also remained fairly unchanged for a number of years.
- B. Stinton: What would the community recommend as switch-over procedure for full-face masks in case of malfunction under ice? I have seen various options: rip the mask off, two disconnects, switch-over block, and wreck divers who use two Odins on their full-face mask.
- H. Brown: Our AGAs have a bail-out (a free-flow mode) going into the mask.
- J. Flinkman: An AGA free-flow at 50m will deplete the air supply very quickly because of its high flow rate; a switch-off option is needed. We carry a mask in our buoyancy compensator pocket and a spare second stage but this is a switch-out skill that requires proficiency and routine practice.

Session 2: *Equipment Discussion*

- M. Lang: I do not recall having experienced a full-face mask that has not free-flowed under ice.
- R. Robbins: Our presentation on regulator performance data will point out that full-face masks have not functioned well.
- M. Lang: Data from our dive computer downloads used here show that the current Kongsfjorden water temperature ranges from 0 to 0.5°C, similar to Palmer Station diving. The 2 degree lower temperature difference we experience at McMurdo makes a world of difference in regulator performance in supercooled sea water.
- J. Flinkman: Poseidon now manufactures a full-face mask that is very similar to the AGA system with a Jetstream second and first stage. This seems to be a good solution because we know the AGAs have to be absolutely dry prior to diving in freezing conditions and are still prone to free-flow.
- R. Robbins: Diving Systems International (DSI) has manufactured a full-face mask where the regulator pod can be unsnapped and removed and the mask stays in place. We don't know yet how they would perform in ice water but there are options as to which regulator second stage you mount on the spare pod.
- B. Stinton: The only complaint I have heard is primarily from photographers who claim the unit sticks out too far and interferes with their camera's viewfinder.
- M. Lang: We would tend to opt for a solution where the diver would not have to take a mask off under ice because opening eyes in freezing sea water does not appear to be a physiologically preferred option. Switch-outs increase the level of skill complexity by orders of magnitude but the DSI unit advantage is to not have to take the mask off.
- L. Quetin: Our Antarctic project uses many students for whom we try to maintain the same type of equipment they use in temperate waters during training.
- H. Hop: With face masks the diver has the regulator in his mouth and taking the mask off is not an option. The diver gets only one attempt at fixing the problem and should not fail. We never dive with more than one regulator. We have a maximum depth limit of 30m and no-decompression profiles. It would appear to be easier to have voice communications and swim to the exit hole with the free-flowing regulator and get out.
- M. Lang: I would make the observation that some divers on the KingsBay dock earlier today had trouble adjusting all their equipment even with warm hands prior to diving. This tells me that 20 minutes into a dive a free-flowing regulator switch-over procedure has just become that much more complicated with hands that are nowhere near fully functional. It can be done but the complexity level is increased.
- D. Long: With the protrusion of DSI full-face masks the diver can't see very far down. On the thermal protection front not protecting the face gives us many problems and a full-face mask is but one option to resolve this issue. Protecting the entire body except the face from freezing sea water does not make sense. Never go to a higher technology than you need to get the work done. If a wetsuit works for the environment you are diving in there is no need for a drysuit. If a mask works then there is no need for a full-face mask. But face protection is a priority for us and although full-face masks may not do the job under ice right now we are not ruling them out vis-à-vis face protection.
- M. Lang: It is good to know that full-face masks are a high priority because there is a huge market of polar divers out there just waiting to plunk down their cash!
- K. Richardson: Have balaclavas developed further as a way of extending the wetsuit hood to cover the face?

- D. Long: We have made no-nose hoods, nosed-hoods, arctic face protectors and some neoprene masks attached to the hoods. As of now there are very few divers who use them religiously.
- R. Robbins: I estimate that $\frac{3}{4}$ of McMurdo divers use the Henderson thin, 1/8" full-face wetsuit hood (ice cap).
- D. Long: That is an example where adaptation and modification makes a piece of equipment work so is it a mechanical or training problem? Diving is so conservative because if something goes wrong the diver can die. Anything new that is introduced into the environment must have a safety margin at least as good as what we currently have.
- H. Hop: We always use a line while diving under ice and a communication line for which the diver must use a full-face mask to communicate with the tender.
- M. Lang: Some of our colleagues who wished to participate here but could not specifically requested that we share our experiences with line-tending and communications. In this regard we need to specifically refer to the underwater conditions (e.g., crystal clear 100 m visibility with no current under fast ice where line-diving is an encumbrance to the scientific objective or low-visibility plankton bloom under oscillating pack ice).
- H. Hop: NPI treats all under-ice dives regardless of visibility as line-tended dives.
- M. Sayer: Same for the U.K.: all under-ice dives must be tethered. Buddy line between divers is acceptable as long as one diver is tethered to the surface.
- D. Andersen: Diving under ice in the dry valley lakes has always required a line. For safety reasons, it ensures that the line is still attached from the diver to the hole and for work reasons it allows the diver to ferry samples back to the hole with ease. Multiple exit holes are thus not needed.
- R. Robbins: In McMurdo Sound, in general, we do not use lines. If we have the need for communications we would use surface-supplied diving with a Superlite 17 helmet and unlimited amounts of air from the surface in lieu of full-face masks that tend to free-flow. For required line-tended diving operations is there a reason you are not using reel-technology as in cave diving (overhead environment and single exit point).
- M. Lang: Line pulls are medieval communication methods that make it difficult for the tender to distinguish anywhere between 1 to 4 pulls on lines perhaps wrapped around ice floes. This is an unreliable form of communication for ice diving operations. If you need communications it would appear that surface-supplied helmets would be the first choice.
- J. Flinkman: In Finland all ice diving is line-tended. Frequent use of line tending actually improves the communication from the tender's point of view. Our diffuse light and poor visibility under the ice makes seeing the hole after 25 m difficult. The best situation would be to have comms. When the under-ice surface is flat we use floating line, for pack ice we use sinking line to avoid tangling in the ice floes. For diving on wrecks in northern Norway we have used continuous cave diving lines to the point of exit. If there were the possibility of currents we would have used surface line-tending.
- M. Lang: What was the evolution of line-tending, *i.e.*, what was the reason for implementing the line requirement? Were divers lost and never found again under ice?
- M. Sayer: Risk assessment of the diver not getting back to the hole. If divers use the line 100% of the time they are used to it and it is not a problem.
- H. Hop: Our primary reason for line use is if there is a need to get out in a hurry you can signal and get the diver out of the water.

Session 2: *Equipment Discussion*

- D. Andersen: Looking for the hole under lake ice is more difficult than from under sea ice. The ice is smooth and featureless and we have shallow viewing angles. In a lake with a single exit hole it is paramount that the diver has a line to the surface.
- S. Mercer: All Antarctica New Zealand diving is on a line including at McMurdo Sound. We are infrequent divers and there for a short period of time versus season-long as in USAP. ANZ divers are happy to dive on a line and are quite uncomfortable in not using a line even toward the end of their stay.
- L. Quetin: We use a modified blue-water diving procedure for pack ice diving and have but one signal: a slow pull back towards the zodiac. This works around icebergs as well. Slow in order to not disrupt your ability to swim back to the hole by having someone pulling on your line. We do not waste the whole dive trying to figure out what different line pulls might mean.
- H. Hop: In Norway they are now trying to apply a rule that if you dive in open water you need either communication between the divers or a line to the surface. Voice communication devices between divers are apparently not very good.
- J. Flinkman: Finnish sport divers must have a 3-m buddy line between the wrists of the two divers and a float in the middle so it stays off the bottom. Diving in Norway most of the Finnish divers spend their time untangling the buddy line from the kelp. In Finnish waters under training conditions it might make sense but generally you cannot have a rule for everything.
- D. Andersen: With multiple divers or buddy teams in the water simultaneously how many lines are you allowed to have down? Many divers cannot exit the same hole either.
- M. Sayer: We limit the number of divers in the water at once.
- M. Lang: Risk levels must be calibrated against data. With over 10,800 ice diving exposures in our database with zero lost diver incidents a correlation with the requirement for a line-tending regulation is not evident. We support the science to conduct it as effectively as possible without further encumbrance but apparently some scientists are not objecting to the use of a line.
- M. Sayer: Our UK diving at work regulations contain a specific paragraph on communications between the surface and the diver not necessarily diver to diver. That paragraph can be interpreted through the use of a line or hardwire communications is another way. It is something people grumbled about at first but with some experience found it not to be a problem. For the British Antarctic Survey dives are done on full-face mask with through-water communications. Having two divers down with two ropes creates a problem so we use the L-shaped tether.
- D. Andersen: In the Dry Valley lakes we rarely dive with more than one person at a time.
- L. Quetin: Pack ice diving conditions can change rapidly so two divers in the water is our maximum.
- K. Richardson: Where and how do you attach the rope to the diver? In a situation where the diver is dragged backwards towards the hole is the diver still able to change out a regulator or full-face mask or is he restricted physically?
- M. Sayer: We use screw carabiners attached to a d-ring.
- M. Lang: It does not sound like a quick-release system which I accept it is not supposed to be. In blue-water applications we use snap-schackles to enable the diver to release the tether should he need to.

- D. Long: To develop a set of tools that your Diving Officer has to choose from to address the task at hand is a wise thing to do. To put rules in place that you think will cover everything yet cannot is not. It is as important to understand what your rules exclude as well as what they include (the fencing in/out phenomenon). Because a rule was set and that precedent exists you may be ruling options out that you might otherwise have available at a future time. In the commercial diving world we learned to be careful of the safety hazards or safety devices (*e.g.*, the drop weights attached to diving bells killed more divers by being dropped at the wrong place and time than they ever saved.) Keep things as simple as you can and never go to a higher technology than you have to in order to get the task accomplished.
- M. Lang: Regarding the evolution of the line-tending requirement, I asked about the quick-release mechanism for the tether line because of a scientific blue-water diving fatality in 1984. Two divers were attached, each by individual tether, to a down-line with a 50-lb weight tied to a zodiac above deep water. Either the line came undone or the shackle broke, but events quickly unfolded where the line and its 50-lb weight were heading south towards 300 m. One diver was able to ditch the weightbelt (and thus the attachment to the downline) that added another 25 lbs of negative ballast to the tether system. The other diver was never retrieved. The community's mandate for a tether-diving quick-release mechanism stems from this mishap. The diver must have the ability to release himself from a system dragging him in a direction he does not wish to go.
- H. Hop: We started line-tended diving under ice by tying a knot around our waist and have progressed to the use of a locking carabiner to prevent accidental release.
- J. Flinkman: Our line is tied around the waist. In ice diving the probability that the rope gets snagged and you have to release it is negligible and the diver also has a knife to cut the rope if needed. We also put a loop in the line at the arm's maximum reach to insert the wrist. This does not affect mobility, but it's always there so you can feel any signal.
- B. Forbes: We use two quick-release clips in line instead of carabiners.
- K. Richardson: From a climbing perspective you want something that releases quickly and is reasonably safe by taking two spring-clip carabiners and reverse their direction
- L. Quetin: Our system uses a spinnaker shackle that can be released with either hand.
- B. Stinton: Carabiners cannot be unclipped under load so if the diver is being dragged under water the line must be pulled in (unloaded) and the carabiner removed.
- D. Long: Accidents provide valuable information. In the commercial world we used snapshackles effectively but on the umbilicals with surface-supplied gas we did not. If the snapshackle comes undone and the tender pulls on the line, there goes the diver's mask and breathing supply.

ACCOUNTING FOR COLD WATER EFFECTS IN A DECOMPRESSION ALGORITHM

Sergio Angelini
UWATEC AG
Riedstrasse
5705 Halwill, SWITZERLAND

A decompression model that accounts for diminished blood flow in the presence of extreme cold water is presented. This is accomplished by using continuous modification of compartment half times that, in essence, describe an alteration in gas exchange rates between the blood and tissue compartments. An example describes and quantifies the effect for a dive with and without strong thermoclines.

Introduction

Diving in extreme cold waters, such as under the arctic ice, carries with it a series of complexities that makes this activity vastly different from leisure dives in warmer waters of the world. Complexities include using equipment that has to function in temperatures of -2°C under water and below -40°C on the surface. These thermal challenges extend also to the diver and to the response of human physiology to such an environment. In the presence of excessive heat loss, overall blood flow is redistributed to protect the core parts of the anatomy (head and torso) at the expense of the arms and legs. This strategy is based on two principles: for one, arms and legs are expendable when it comes to sustaining life and, secondly, they present the highest degree of heat exchange to the ambient environment. Hence by confining blood flow to the head and the torso, the body minimizes heat loss and increases its chances of survival.

Divers, however, do not plan on losing limbs during or after a dive under the ice. Thermal protection is available so that anybody can endure a swim for a certain amount of time in these conditions. Still, arms and legs will experience a higher degree of cooling than the rest of the body and, hence, the brain will counteract with vasoconstriction, a reduction of the cross section in the capillaries that limits the amount of blood flowing to the periphery of the limbs.

The reduced blood flow at the extremities will, in general, take place after a certain exposure to the cold water since divers will normally have been thermally comfortable just prior to the dive. Hence, the blood flow during the initial part of the dive will be normal and vasoconstriction will take place only after a certain amount of time.

This non-uniform distribution of blood flow over time carries with it an implication regarding decompression. Dives are usually carried out with the deeper portion first and, when decompressing using staged and/or variable depths, the final part of the dive is the shallowest.

Hence, during the initial part of the dive the diver is deep but also warm and the normal blood flow distribution means that the limbs are loading up with nitrogen at the regular rate for the given depth. However, towards the latter part of the dive, when the diver is shallower, he or she is also cold. The ensuing redistribution of blood flow implies that the offgassing of nitrogen from the limbs is diminished with respect to what it would normally be. Utilizing gas exchange rates that do not account for water temperature carries the risk that not enough time is given for nitrogen to actually leave the limbs, increasing the probability of decompression sickness upon surfacing.

The ZH-L8 ADT model

The ZH-L8 ADT model comprises 8 compartments with half times of 5, 10, 20, 40, 80, 160, 320 and 640 minutes. The ADT in the name stands for adaptive, signifying that the model can react to certain situations. In particular, it can react to increased workload, diver behavior, and cold water. The adaptation is carried out by modifying, on a temporal basis, the half times of the compartments. This is a mathematical equivalent to a change in perfusion. A change in perfusion is what actually takes place during increased workload, vasoconstriction and when microbubbles that have formed because of excessive ascent rates obstruct the otherwise unimpeded flow of blood.

For the temperature adaptation, compartments with half times of 40, 80 and 160 minutes (representative of skin and to some extent muscles) are affected by perfusion reduction. The half times of the compartments are changed only if the diver is offgassing, *i.e.*, regardless of cold the uptake of nitrogen is not reduced, which maximizes the amount of gas that must be released later and, therefore, is on the conservative side of the calculation.

The nominal values of perfusion for the 40, 80 and 160-minute compartments are, respectively, 0.41, 0.96 and 2.47 l/min. The maximum reductions in perfusion caused by cold are, respectively, 0.21, 0.29 and 0.17 l/min. This leads to a change in half times from 40 to 59.6 min, from 80 to 97.6 min and from 160 to 166.4 min.

An interesting aspect of the model is that it “remembers,” during the initial descent, what the temperature in the 7-9 m range was. This is important so that a diver is not unnecessarily penalized by very strong thermoclines. As an example, Swiss lakes at depths deeper than 10 m have a very constant temperature between 4 and 6°C throughout the year, but at depths shallower than 10 m in the summer it can be 25°C or even higher. Hence, during decompression the diver is able to recuperate heat, blood flow increases again and nitrogen elimination can again take place at the nominal rate. For this to function, of course, the temperature measurement in the dive computer must quickly adapt to the surrounding conditions so that during the initial descent the correct value is captured.

One obvious limitation of the model is that it bases its perfusion changes on an interpretation of body cooling based on water temperature. Divers may comment that they have enough thermal protection to be comfortable in most conditions. Although, in reality, many divers come out of the water shivering. Since the model pushes the calculation of nitrogen elimination towards the conservative side of the spectrum, very well thermally protected divers will be

spending more time decompressing than they theoretically should, while cold divers could be presented with more serious issues.

Quantification of the adaptation with a dive in a Swiss lake

The following describes the results from the decompression calculation on an actual dive carried out in the Lake of Zug. Real water temperatures were 5°C below 20 m, 18°C above 6 m, and a somewhat linear gradient in between. The diver carried 4 dive computers: computers 1 and 2 were forced to read a constant temperature (respectively 2°C and 25°C), computers 3 and 4 measured and utilized the actual water temperature. But whereas computer 3 applied the value measured at 7.5 m during the descent for decompression prognosis (for any portion to be spent above 7.5 m), computer 4 always applied the instantaneous temperature value for all decompression calculations. Figure 1 shows the depth and temperature profiles as downloaded from computer 3.

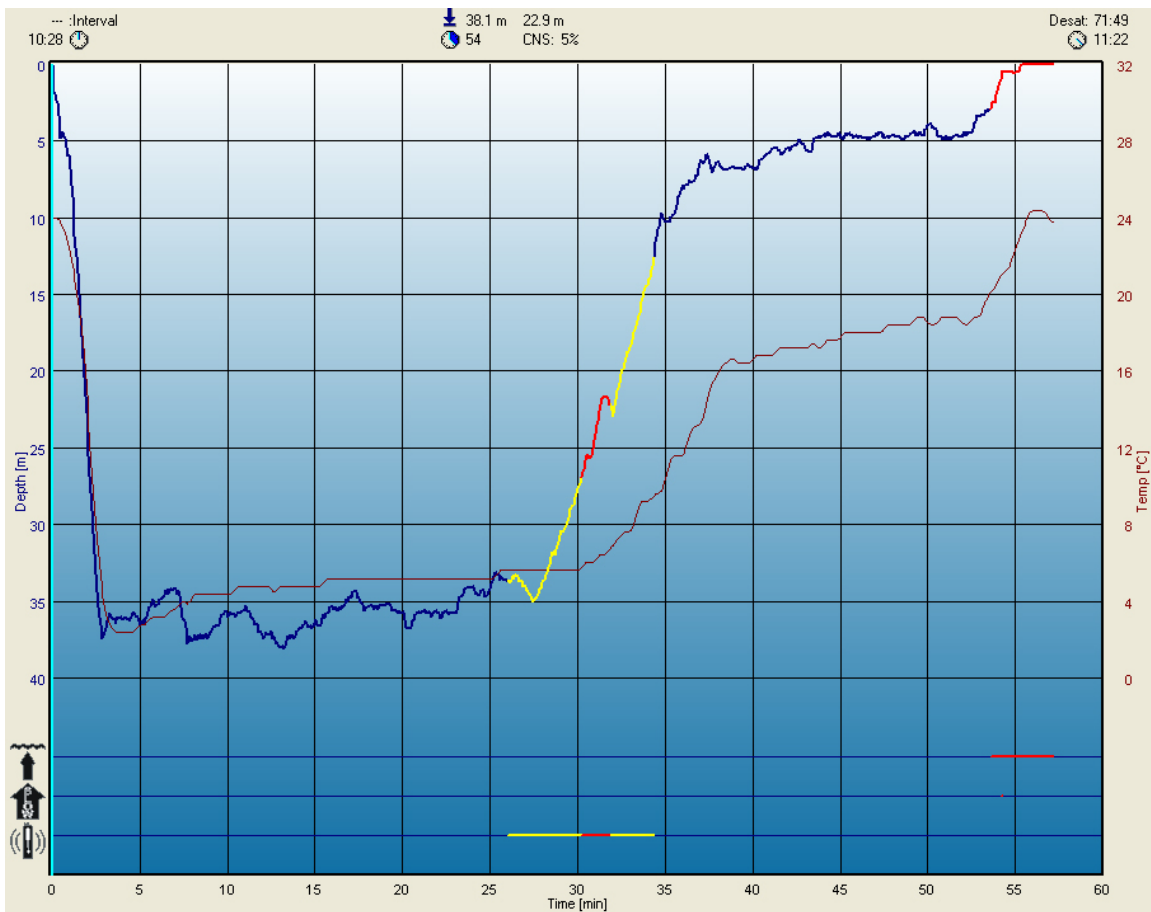


Figure 1. Depth and temperature profile.

The results are discussed with help of the SmartTRAK software, which reproduces the dive on a PC after each dive computer is downloaded. As depicted in Figure 2, SmartTRAK shows the complete dive profile to the left, with a moving cursor that can be positioned at one specific point of the dive. To the right of the dive profile, SmartTRAK then reproduces the display of the

dive computer with the information just as it would show it during the actual dive. Underneath the display, a sequence of 8 colored bars represents the instantaneous situation for each of the 8 compartments in the ZH-L8 ADT model. Green is used to describe a compartment that is offgassing, while red is used for a compartment that is ongassing. Below this graph there are three smaller bars, which quantitatively describe the adaptation parameters. The one in the middle is for the temperature.



Figure 2. SmartTRAK display.

Since two types of computer are utilized here, the look of the display changes a bit between that of computers 1, 2 and 4 (UWATEC Aladin PRIME, Fig. 3) and computer 3 (Uwatec Smart Z, Fig. 4). For all of them, the top row shows instantaneous depth on the left and total bottom time to the right. Computers 1, 2 and 4 show, on the middle row, from left to right, duration of deepest deco stop, depth of deepest deco stop and total ascent time (sum of all deco stops and time needed to go from current depth to the surface at the ideal ascent rate). Computer 3 has a slightly different layout of the decompression information, with the information positioned in a triangle in the bottom right corner: total time to ascend is positioned underneath the total bottom time and directly underneath it the depth of the deepest stop and the duration at that stop.

In the following, the results are interpreted in terms of the total ascent time and the extent of the quantitative temperature adaptation bar.

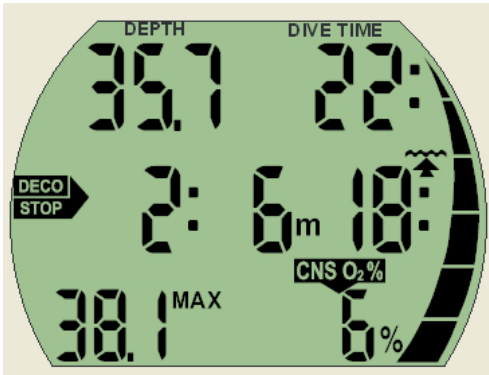


Figure 3. Display in computers 1, 2 and 4.

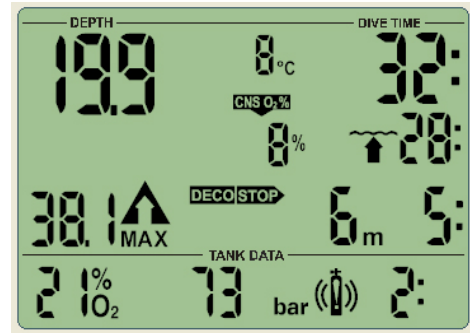


Figure 4. Display in computer 3.

1. No stop

Figure 5 shows the results 10 minutes into the dive, for computers 1 through 4, left to right. It shows that regardless of water temperature, the no-stop time is not affected (3 minutes for this example), though for the computer set to 2°C the temperature adaptation parameter is starting to grow.

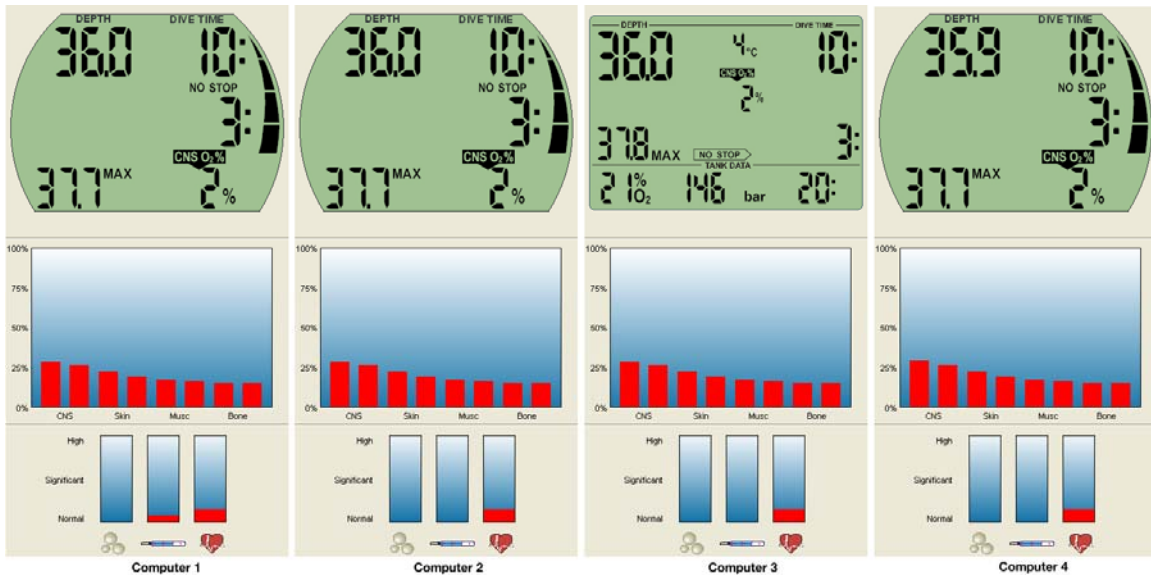


Figure 5. Situation at minute 10.

This makes perfect sense within the context of the model, since the adaptation affects only the offgassing. When the computer is within no-stop time, a direct ascent to the surface is considered possible, implying that there is not a surplus of nitrogen that needs to be eliminated with a stop at 3 or 6 m. Hence the perfusion during offgassing does not play a role.

2. At the beginning of the ascent, after more than 25 minutes below 30 m.

Figure 6 shows the results at minute 30. The temperature adaptation parameter (middle bar graph) for computers 1, 3 and 4 is 2/3 of maximum, indicating that the effect of temperature is

very pronounced. Indeed, the direct comparison between computers 1 and 2 (2°C and 25°C respectively) shows a difference in total ascent time of 13 minutes, from 24 to 37. In other words, the quantitative effect of cold is an extension of the decompression time by 50% with respect to the same dive in warm water.

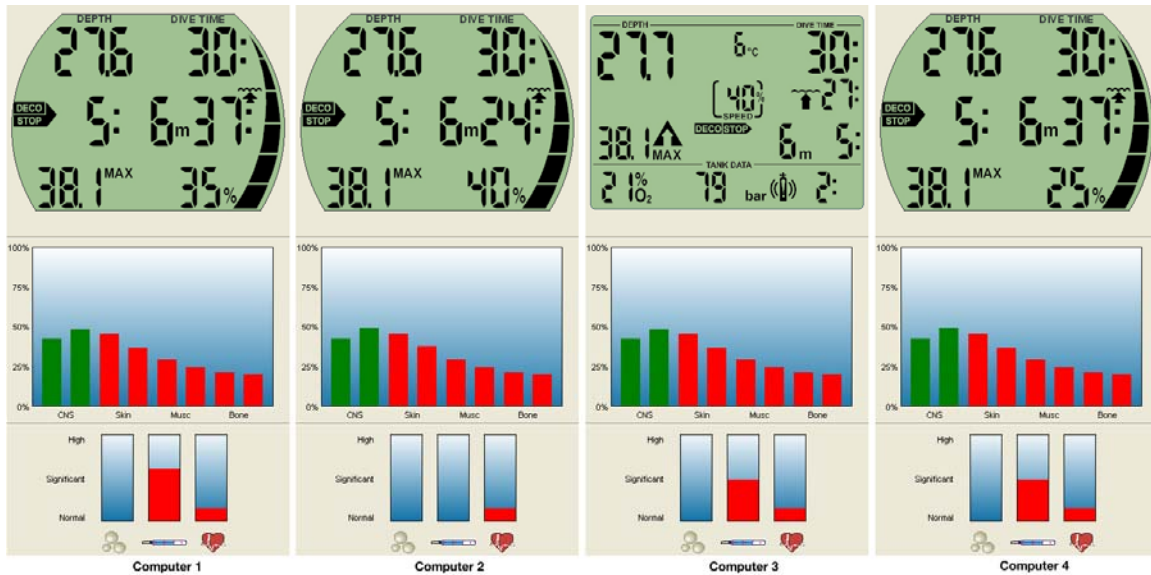


Figure 6. Situation at minute 30.

Interestingly, the computer with memory at 7.5 m (computer 3) shows only a very small difference with respect to the computer at 25°C (computer 2). The temperature adaptation parameter is 2/3 here also, but the computer predicts that the decompression will take place in warmer water, though lower than 25°C, hence the penalty is minimal.

Computer 4, however, shows as much penalty caused by cold as computer 1. This is expected since this computer applies the instantaneous temperature only and thus sees the full effect of the low temperature.

3. Towards the end of the ascent, at minute 35.

Figure 7 shows the results at minute 35. The temperature adaptation parameter has grown further in computer 1, whereas it is stable in computers 3 and 4. In other words, an additional 5 minutes spent at 2°C are adding to the perfusion reduction, whereas computers 3 and 4 are starting to feel the warmer temperatures found during the ascent. But whereas computer 3 has already accounted for these warmer temperatures, and hence its total ascent time grows by one minute because of the continued exposure to elevated ambient pressure, computer 4 compensates the same exposure to ambient pressure with an increase in perfusion because of the increase in instantaneous temperature.

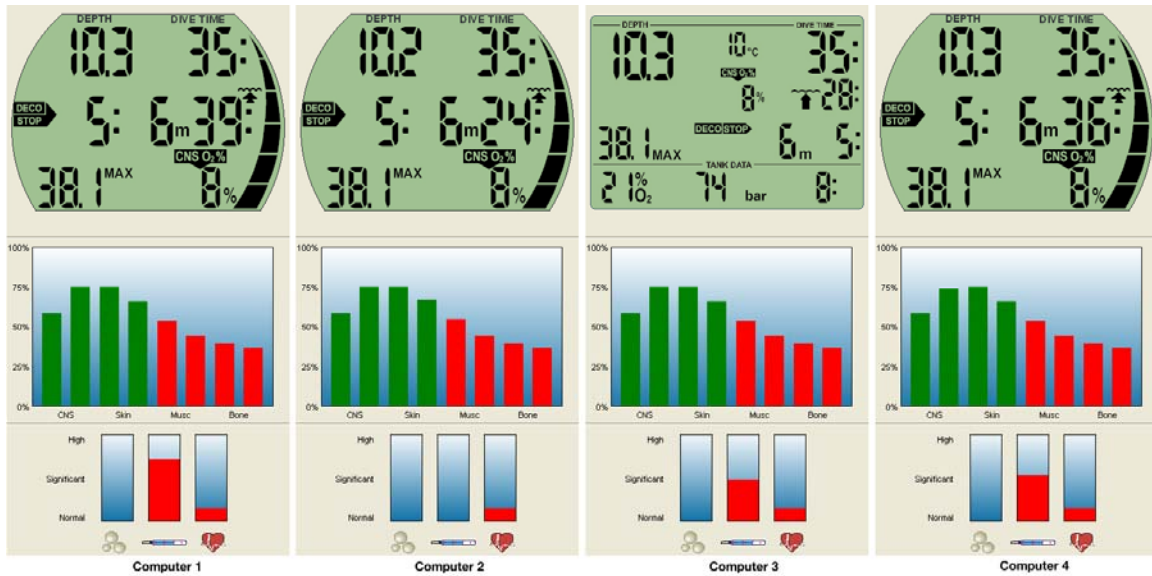


Figure 7. Situation at minute 35.

4. At minute 40.

Figure 8 shows the results at minute 40. After 5 minutes between 6 and 7 m, at temperatures above 16°C, computer 3 has “clocked” off 5 minutes of total ascent time, the same as computers 1 and 2. This is expected, since the required decompression stop is now at 6 m. Computer 4, however, sees the total ascent time reduced by 11 minutes. This is caused by the computer recognizing warmer temperatures and adapting the decompression calculation to the higher than expected perfusion. Hence the total ascent time is reduced by more than anticipated (11 minutes instead of 5 minutes).

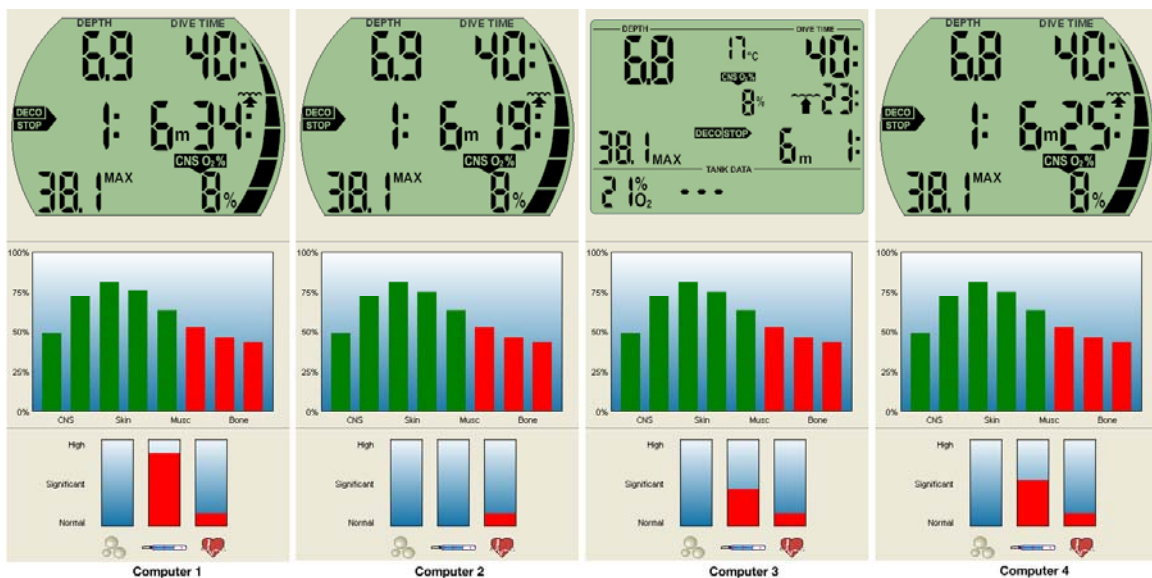


Figure 8. Situation at minute 40.

5. At minute 45.

Figure 9 shows the results at minute 45. From this picture we see that computer 4 has recovered as much as it could from the warmer temperatures, since 5 minutes have elapsed and the total ascent time is about 5 minutes shorter, as it is for computers 1, 2 and 3.

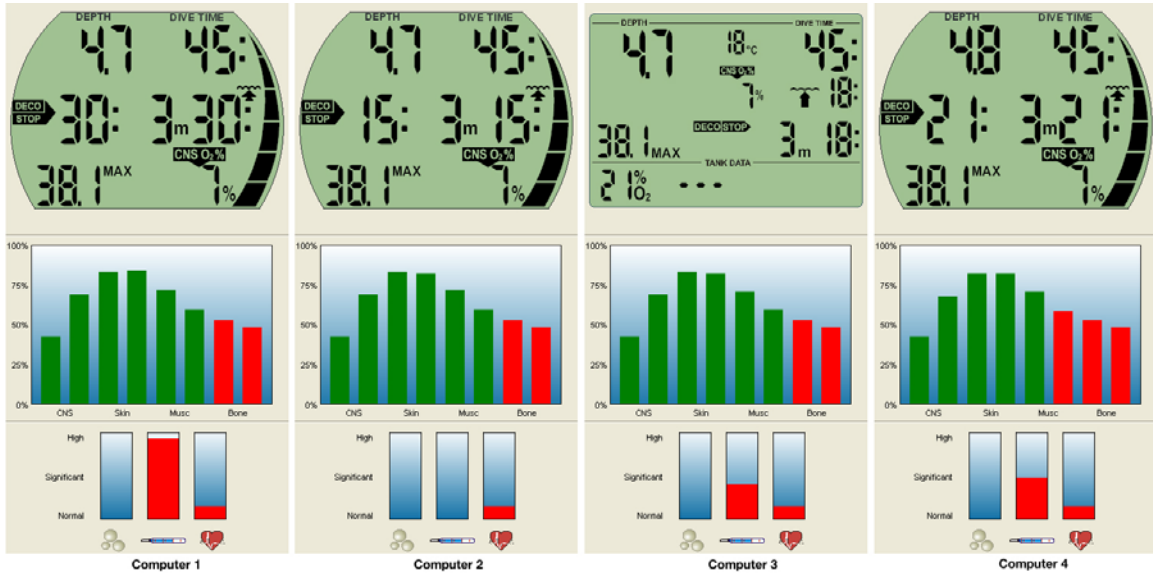


Figure 9. Situation at minute 45.

Discussion

The results presented above show the following important facts:

- decompression times in very cold waters can increase by as much as 50% with respect to the same dive carried out in warm waters; and,
- strong thermoclines need to be accounted for, as a diver would otherwise be unnecessarily penalized; however, this requires a fast acting thermocouple. The alternative is to adapt the decompression calculation to the instantaneous temperature. This imposes a much reduced penalty in overall decompression though it is less effective for managing bottom time during the dive itself.

COLD STRESS AND DECOMPRESSION SICKNESS

Peter H.J. Mueller

German Society of Diving and Hyperbaric Medicine
PO Box 1225
D-76756 Bellheim, GERMANY

Introduction

It has long been established that both hypo- and hyperthermia affect mental acuity, reasoning and cognitive function (Stang and Wiener, 1970; Vaughan and Mavor, 1972; Millar, 1990). As a consequence, subjects suffering from hypothermia have an increased risk of errors during activities such as diving, which leaves the divers prone to accidents (Bowen, 1968; Baddeley *et al.*, 1975; Biersner, 1976; Vaughan, 1977). In scientific diving this is of particular interest as the diving scientist who suffers from hypothermia may also cause errors during the course of scientific work (Vaughan, 1975; Hanson, 1978; Knight, 1981; UHMS, 1985).

Thermoregulation is a well-tuned balance between production and loss of heat in the human body (Rochelle and Horvath, 1978; Tetzlaff *et al.*, 2001) and is fully automatic. Physiological factors affecting heat loss include distribution of blood flow, gender, body composition and age (Paik *et al.*, 1972; Russell *et al.*, 1972; Hong, 1973; Takano *et al.*, 1983; Curley *et al.*, 1989; Shake *et al.*, 1990; Tetzlaff *et al.*, 2001). Environmental factors such as temperature, wind-chill, acclimatization, adaptation and thermal insulation used play an important role in the determination of the amount of heat loss (Skreslet and Aarefjord, 1968; Park *et al.*, 1983; Lippitt and Nuckols, 1983; Cattermole, 1999; Beckett *et al.*, 1993). On the other hand, physiological heat production is determined solely by muscle activity, with shivering being the typical example during hypothermia.

The primary effect of the exposure to cold is a vasoconstriction in the human peripheral vasculature leading to a perfusion of the core (heart, lungs, CNS) only. The purpose of this severe peripheral vasoconstriction is to preserve heat in the core, which is particularly vulnerable to hypothermia. The human heart in particular suffers from potentially fatal arrhythmias when the core temperature drops below 32°C.

Physics and physiology are intrinsically linked in the following ways:

- The density of gases increases with pressure;
 - Inert gases have different heat transport capacities;
 - Breathing gas is warmed to 37°C within the human respiratory system;
 - The solubility of gases in liquids decreases with the absolute temperature of the liquid;
 - Uptake of any gas into a liquid solution occurs passively through absorption;
 - The movement of gases between different liquid compartments is passive (diffusion);
- and,

- The movement of liquid compartments within the human body is actively accomplished through blood flow (perfusion).

These effects become very important if Helium is used in the breathing gas, as the heat loss through the respiratory system increases significantly (Hall and Galvin, 1969; Brubakk *et al.*, 1982; Jammes *et al.*, 1988; Burnet *et al.*, 1990; Naraki and Mohri, 1988).

Present modeling of decompression, in the development of decompression tables or dive computers, is largely based on the absorption and diffusion of gases only and does not take into account changes in perfusion during the dive or decompression (Hills, 1967a; 1967b). The development of valid models of perfusion changes induced by diving has yet to be completed since these changes are extremely complex and probably affected by intra- and inter-individual factors (Rattner *et al.*, 1979). However, from a physiological perspective, the perfusion changes, namely the vasoconstriction induced by diving and/or cold should be taken into account to enable a more precise determination of the actual process of inert gas elimination during decompression.

Furthermore, temperature changes and inert gas distribution are linked by a causal relationship between the temperature of different biological fluids and tissues, and the solubility of inert gases (Bove *et al.*, 1978; Leitch and Pearson, 1978; Simmons *et al.*, 1982). Tissue temperature may influence the formation of venous emboli and the rate of inert gas exchange. However, the actual incidence of decompression sickness (DCS) is more likely related to the temperature-induced changes in the distribution of peripheral blood flow than the temperature of the tissues *per se* (Mekjavic, 2003).

Methods

A literature search was performed for additional data to those mentioned in the introduction. The Medline database was searched as was an additional database (GTÜMLIT) that the author has access to, which is administered by the German Society of Diving and Hyperbaric Medicine (GTÜM e.V.) This database contains largely the so-called “grey literature” such as proceedings, unindexed journals, etc., and returned over 18,000 results for the key-words “cold and decompression.” The relevant results related to cold stress and decompression are presented.

Results

Temperature and inert gas distribution.

Hesser (1962) showed early on that reduced blood flow caused by vasoconstriction and the consequent reduced inert gas washout from tissues causes symptoms of DCS. This was supported by the findings that the inert gas transport-limiting process (diffusion or perfusion) through tissues of the decompressed eel is influenced by cold (Belaud and Barthelemy, 1979) and Hempleman *et al* (1984) demonstrated that local occlusion of blood flow causes skin mottling post decompression. The conclusion was that cold is not favorable to tissues during, or following, decompression.

Dunford and Hayward (1980; 1981) detected a greater number of Doppler bubbles in drysuit divers than wetsuit divers during underwater exercise in cold water. Their conclusion was that

vasoconstriction hindered the uptake of inert gas during the cold dive, which was present in the wetsuit divers only. Mack and Lin (1986) showed that nitrogen elimination is reduced when cardiac output is reduced during hypothermia and that hyperthermia has no advantage over normothermia in terms of nitrogen elimination. These two results also lead to the assumption that it may actually be beneficial for the diver to be hypothermic during the bottom phase of a dive.

Perfusion changes and DCS.

When cold post-decompression exposure was followed by a hot shower, symptoms of DCS were recognized (Mekjavic and Kakitsuba, 1989). The rapid change in peripheral tissue temperature from the hot shower initiates an increased peripheral tissue perfusion, resulting in their greater elimination of inert gas. This sudden increase in local elimination of inert gas from superficial tissues is, however, not matched by an appropriate corresponding increase in perfusion, therefore causing symptoms of DCS.

Koteng *et al.* (1996) simulated a reduction in blood flow to peripheral tissues similar to vasoconstriction. During decompression this reduced perfusion caused an increased amount of bubbles to be present, both locally and in the pulmonary artery. This can only be interpreted as the muscles contributing significantly to the quantity of bubbles. The effect of a 50% blood-flow reduction on inert gas movement yielded a 90% reduction in perfusion.

The U.S. Navy (Ruterbusch *et al.*, 2004) conducted a study to test whether diver thermal status is a risk factor for DCS. U.S. Navy divers completed 357 water-immersed, working air decompression dives to 120 fsw in the NEDU Ocean Simulation Facility. All dives were identical except for bottom time (BT) and diver thermal status during certain phases of the dives. Divers completed either the compression and working bottom phase, or the resting decompression, semi-nude in water that was either "warm" (W) at 97°F or "cold" (C) at 80°F. (CW represents cold compression and time at bottom followed by warm decompression; WC represents the reverse case.) All decompressions were 120 fsw/70 min U.S. Navy Standard Air Tables (91 min decompression) and were followed by a 4-hr resting observation period at 78°F. 11 DCS cases occurred in 112 WC dives and 2 DCS cases occurred in 245 CW dives. At the extremes of thermal status and BT examined, DCS incidence (95% confidence limits) was 1.3% (0.15 - 4.5) for 120 fsw/70 min CW dives compared with 21.9% (9.3 - 40.0) for 120 fsw/30 min WC dives. It was concluded that diver thermal status has a large effect on DCS risk under the conditions tested, with warm decompression favoring lower DCS risk. Appropriate manipulation of diver thermal status during different phases of a dive might significantly decrease diver DCS susceptibility.

In a follow-up study (Ruterbusch *et al.*, 2005) the U.S. Navy transitioned these experimental findings to "operational" dives in this series by applying the use of hot water suits to warm the divers. Divers were immersed in $55 \pm 2^\circ\text{F}$ water while wearing MK 21 helmets and U.S. Navy standard-issue hot water suits. Thermal status of the divers was manipulated during different phases of the dive. During bottom phase, all divers performed cycle-ergometer exercise and diver thermal status was controlled by circulating cold ($80 \pm 2^\circ\text{F}$) water through the hot water suits via a Mare Island Naval Shipyard custom hot water system (currently unavailable to fleet divers). Warm water ($97 \pm 2^\circ\text{F}$) was circulated through the suits while divers were at rest during

the ensuing decompression. Divers were fitted with Depth, Time and Temperature Recorders (DTTR) to log data from 4 skin temperature sensors placed on the chest, back, and left calf and forearm to monitor regional skin temperatures (Tsk) induced by the circulating water system. The results of 128 man-dives completed under these more operationally relevant conditions were in full accord with those obtained with semi-nude divers. One DCS case occurred in 100 120':70 man-dives decompressed on the 120':70 Standard Air schedule. Moreover, it was also shown that decompression from this dive could be shortened under these thermal conditions (C/W). One DCS case occurred in 28 120':70 man-dives decompressed on the 120':60 Standard Air schedule. This work established the efficacy of warm decompression.

Environmental and operational factors.

Broome (1993) hypothesized that the weather and tidal factors could contribute to the risk of DCS in otherwise "safe" dives. 177 cases of DCS were identified from the Institute of Naval Medicine's diving accident records and allocated to a 'safe' group or 'risky' control group, depending on the dive profiles. Comparison of the prevailing environmental conditions between groups revealed significant differences in air temperature and wind-chill ($p = < 0.001$ for all dives) and for air minus water temperature ($p = < 0.01$ for all dives). The results imply that exposure to a cold thermal environment following diving, particularly when the air temperature is colder than the water temperature, may be a previously unrecognized risk factor for DCS.

Taya *et al.* (1985) discussed the combined effects of aging and environmental temperature on decompression sickness incidence. Following a 40 min stop at 11 bar, the subjects (rats) were decompressed in stages, and observed to determine fatality ratio. The results demonstrate two consistent findings; (1) there is a significant relationship ($P < 0.01$) between age and fatality ratio; and, (2) the fatality ratio is increased under low environmental temperature compared with a higher environmental temperature. There were scarce gender effects on fatality.

Knudsen *et al.* (1991) showed that a symptom-free cooling occurs during cold gas (Heliox) breathing at 46 bar. The heat was lost both over the skin and the respiratory system at a rate that cooled the divers without their awareness of it. The findings therefore confirm earlier hypotheses and conclusions that a symptom-free cooling situation may occur when exposing divers to such a thermal situation during deep diving.

Diving in cold waters has been attributed to the cause of pulmonary edema in scuba divers (Hampson and Dunford, 1997). However, Hampson and Dunford (1996) showed that the pulmonary edema of scuba divers may occur both in "cold" or "warm" water. The pulmonary edema can be self-limiting (Roeggla *et al.*, 1996), but usually is a life-threatening situation for the diver.

A two-phased study (Thomson *et al.*, 2004) investigated the extent of post-dive bubble formation, and possible contributory factors, to improve safety in scientific scuba divers in the Antarctic. Subjects were monitored using pre-cordial and subclavian Doppler ultrasound (using the Kisman-Masurel system) following routine dives at scientific sites. Doppler audio signals were recorded and scored by an observer, and sent to DRDC Toronto for independent scoring. In Phase 1, all subjects followed U.S. Navy (USN) Decompression Tables (1995) with added safety increments. In Phase 2, all subjects followed the DCIEM Air Diving Tables (1992).

Contributory factors to bubble formation including cold, exercise level, sea and air temperature, and barometric pressure, were also investigated. In phase 1, 10 subjects undertook 84 monitored dives, mean depth of 28.8 (\pm 5.7) m. Bubbles were detected following 34 dives (40.5%). Bubble detection was related to increased maximum depth of the dive ($p=0.0038$) with the maximum bubble score increasing with depth ($p=0.008$). Of those dives calculated to be outside DCIEM no-stop times, 66.7% formed bubbles, and were related to a high maximum bubble score ($p<0.001$). In phase 2, 8 subjects undertook 116 monitored dives, mean depth 26.3 (\pm 6.7) m (not significantly different to Phase 1). Bubble formation fell to 24.1% of monitored dives ($p=0.014$) and was reduced at all scientific sites ($p=0.021$). There was no correlation between bubble formation and depth. Maximum bubble scores were lower using DCIEM tables ($p<0.001$) with grades associated with a low risk of DCS. There was significantly less bubble formation and of a lower grade using DCIEM tables compared with USN tables. Significantly more dives with bubbles occurred (many dives well within table limits) than during the original testing of the DCIEM tables. Bubble formation was evenly distributed throughout the depth range using DCIEM tables, indicating some variable(s) other than depth are of importance.

Exercise during decompression and right-to-left shunting.

The exercise effects during diving and decompression on post-dive venous gas emboli were studied by Jankowski *et al.* (2004). Their results demonstrated that post-dive exercise may reduce the number of venous gas emboli, indicating a lower risk for DCS with this routine. However, the effect of exercise before, during, and after dive on bubble formation remains controversial within the diving community. The current practice of divers and aviators is to still avoid strenuous exercise after diving.

A field study by Dujic *et al.* (2005) evaluated the impact of mild, continuous exercise during decompression. Ten healthy, male, military divers performed an open-sea dive to 30 m depth breathing air, remaining at pressure for 30 min. During the bottom and decompression phase, the subjects performed underwater fin swimming at about 30% of maximal oxygen uptake. Each diver underwent two randomly assigned dives, one with and one without exercise during the 3-min decompression period. Monitoring of venous gas emboli was performed in the right heart with ultrasonic scanner every 20 min for 60 min after reaching surface pressure in supine rest and during a forced two-cough procedure. The study demonstrates that mild, continuous exercise during decompression significantly reduced the average number of bubbles in the pulmonary artery from 0.9 \pm 0.8 to 0.3 \pm 0.5 bubbles/cm² in supine rest, as well as during the two-cough procedure, which decreased from 4.6 \pm 4.5 to 0.9 \pm 0.9 bubbles/cm². No symptoms of decompression sickness were observed in any subject. These results, obtained under field conditions, indicate that mild, underwater swimming during a 3-min decompression period reduces post-dive gas bubble formation.

The objective of a further study (Dujic *et al.*, 2006) was to determine whether a short period of strenuous post-dive exercise promotes venous bubble formation. Seven male military divers performed an open-sea dive to a maximum depth of 30 m for 30 min. At maximum depth, subjects performed mild underwater fin swimming, followed by standard decompression. Diving was followed by a post-dive exercise session consisting of short, strenuous, incremental, upright cycle ergometry, up to 85% of maximal oxygen uptake, for about 10 min. Subjects were monitored for venous gas bubbles in the right heart with an echo-imaging system starting 20 min

post-dive while in the supine position, during cycle ergometry in the seated upright position, and immediately after exercise in a supine position. The average number of bubbles was 1.5 +/- 1.4 bubbles/cm² 20 min after diving. Changes in posture from supine to seated upright resulted in significant reduction of bubbles to 0.6 +/- 1.3 bubbles/cm² (p = 0.043), with further reduction to 0.2 +/- 0.3 bubbles/cm² at the end of exercise (p = 0.02). No cases of DCS or intra-pulmonary shunt were observed during or following post-dive exercise. These results suggest that strenuous post-dive exercise after a single open water dive reduces post-dive gas bubble formation in well-trained military divers.

These findings coincide with the fact that most “undeserved” DCS cases have been attributed to the presence of a right-to-left shunt in the individual – usually through a patent foramen ovale (PFO), and the knowledge that physical exercise such as lifting of weights during decompression initiates the transition of venous gas bubbles into the arterial circulation, particularly after cold water diving (Gerriets *et al.*, 2000). Unpublished reports by scientific divers who felt cold after a dive and tried to warm themselves up through a more generalized muscle activity such as walking on the ice, indicate no increased incidence of DCS as a consequence.

Discussion

From the results presented it seems most likely that the inert gas uptake into the blood is not affected by the ambient temperature to a relevant degree since the distribution of inert gas is mainly determined by perfusion, while diffusion only plays a limited role. This effect of cold on inert gas uptake in diving is obviously complicated by the diver’s activity level and the duration of the dive.

The findings also indicate that it may actually be beneficial for the diver to be cold during the dive, but not during the decompression, which continues at the surface. For scientific diving it may, however, not be beneficial for the diving scientist to be cold during the dive, as this will impair mental acuity and dexterity which are absolute requirements for the diver.

No mathematical model for the elimination of inert gases has yet considered the redistribution of inert gas between the different compartments during and after decompression. This redistribution is also determined largely by local perfusion, which still has to be satisfactorily implemented into physiological models of decompression, in particular for diving in cold environments.

The relatively slow tissue compartments with less perfusion (bone, skin) are most likely to develop symptoms of DCS after diving in cold waters, compared with the well-perfused slow tissues such as muscle, where local perfusion matches the inert gas liberation.

Nevertheless, physical exercise such as lifting of heavy weights after diving, must be avoided. However, general physical activities such as swimming during decompression or walking after the dive may play an important role for a reduced incidence of DCS, particularly in cold water diving. This should be further investigated.

Conclusions

The relative contributions of tissue N₂ solubility and tissue perfusion to the etiology of DCS are not resolved completely.

Over-warming of divers, especially active warming of cold divers following a dive, may induce DCS. Divers in cold environments should, therefore, avoid getting cold during decompression and/or after the dive and should wait with hot showers/baths after the dive if they feel hypothermic until they have re-warmed themselves, for example by walking. Being only slightly cold may have the same effect on bubble grades as being severely hypothermic.

Long-term health effects for divers with a high proportion of cold water dives should be considered in the future.

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3. Decompression Session Discussion.

M. Lang: I wish to cover briefly the recommendations pertaining to diving physiology and decompression from our past diving safety workshop efforts in which several of you have participated. The following regulations have been adopted by the Smithsonian Scientific Diving Program and are referenced in the AAUS diving safety standards:

Diving Safety Regulations

It has long been the position of the American Academy of Underwater Sciences that the ultimate responsibility for safety rests with the individual diver. Buoyancy compensation is critical in slowing ascent rates and fundamental to safe diving practices.

A. Dive Computers

1. Only those makes and models of dive computers specifically approved by the SDCB may be used.
2. Each diver relying on a dive computer to plan dives and indicate or determine decompression status must have his/her own unit and be proficient in its use. It is strongly recommended that each diver also dive with a back-up dive computer.
3. A diver should not dive for 18 hours before activating a dive computer to use it to control his/her diving. Once the dive computer is in use, it must not be switched off until it indicates complete off-gassing has occurred or 18 hours have elapsed, whichever comes first. Only 1 dive on the dive computer in which the NDL of the dive computer has been exceeded may be made in any 18 hour period.
4. On any given dive, both divers in the buddy pair must follow the most conservative dive computer.
5. If the dive computer fails at any time during the dive, the dive must be terminated and appropriate surfacing procedures should be initiated immediately.
6. Breathing 100% oxygen above water is preferred to in-water air procedures for omitted decompression.

B. Ascent Rates

7. Ascent rates shall be controlled at 30fsw/min from 60fsw and not exceed 60fsw/min from depth.
8. A stop in the 10-30fsw zone for 3-5 min is required on every dive.
9. Drysuits shall have a hands-free exhaust valve.
10. A buoyancy compensator is required with drysuit use for ascent control and emergency flotation. BCs shall have a reliable rapid exhaust valve which can be operated in a horizontal swimming position.

C. Dive Profiles

11. Multi-day repetitive diving requires that a non-diving day be scheduled after 6 consecutive diving days.
12. Reverse dive profiles are not prohibited for no-decompression dives less than 40msw (130fsw) with depth differentials less than 12msw (40fsw).

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L. Quetin: What about exercise after a cold dive?

P. Mueller: Exercise immediately after any dive is not a good idea.

A. Brubakk: More work needs to be done on the “no exercise after diving” issue. Our experiments with divers (albeit not at low temperatures) showed that there was much less bubble formation from exercise during the dive and after the dive.

H. Hop: After our ice dives we run around on the ice just to warm up.

P. Mueller: Yes, exercise and muscle activity produces heat. If there is no vasoconstriction in the muscles the perfusion matches the washout of the inert gas but inactivity does not. If there is a mismatch between perfusion and elimination bubbles will show up.

J. Flinkman: There were two recent incidences in Finland where commercial divers trained in a limestone quarry. After a couple of hours they went to the gym to lift weights and got a hit. Our science divers are trained to not do heavy work after a dive but some exercise to warm up is fine.

A. Brubakk: That is probably true. We did high-intensity exercise on a treadmill but did not test the effects of heavy lifting. Bubbles will grow because there is a supersaturation of gas but they also grow because they are producing gas bubbles from the bubble nuclei. In a situation where there is high supersaturation without bubble nuclei bubbles will not form. We have demonstrated in experiments with animals and man that with heavy exercise at some time before the dive gas bubbles disappear and even with high supersaturation do not form afterwards. This is a complicated story without a simple application. But with the right amount of exercise at the right time before a dive one can probably prevent decompression sickness effectively. Some of these decompression models do not describe physiology at all. That is the next step in decompression modeling: incorporation of observations of physiological effects on the diver and what is actually happening.

P. Mueller: The French Navy has already applied this concept. All of their divers go for heavy physical exercise before every dive. This is not a physiological approach but their daily routine consists of running for four hours then going for a dive. There was a very low DCS incidence rate in that group compared to another group that could not exercise due to operational factors.

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- P. Mueller: Inert gas uptake from the lungs into the blood is not affected by ambient tissue pressures. Blood is the fastest tissue in the body and inert gas will move into it at the same speed regardless of the temperature. The distribution is determined by the perfusion and diffusion plays a very limited role here. Diffusion may have an effect when there is limited perfusion such as through severe vasoconstriction but we do not know exactly what occurs at the compartment level in this situation. This is also heavily affected by the timing of the activity. Increased workload during the dive is commensurate with increased inert gas loading. It may be beneficial to be cold during the dive when you ongas the tissues because vasoconstriction reduces perfusion and, therefore, less inert gas uptake. Gas stays in the blood and is easily eliminated during decompression. No models have taken into account the redistribution of inert gas during or after decompression. This will remain difficult because we cannot accurately monitor the amount of blood flowing to specific tissue compartments to determine how much loading has occurred, how much comes back out and where it goes from there. Dive computer manufacturers should start thinking about this aspect. It is probably the slow tissue compartments (*e.g.*, skin and bones) that will cause us trouble by diving in cold conditions. Broome's description of skin bends and joint bends supports the notion of slow compartment involvement under cold temperatures. Long-term health effects of diving in cold could become exacerbated (*e.g.*, slow compartments are already prone to dysbaric osteonecrosis) but there is no supporting data yet. Cold temperature possibly impacts diver safety more than decompression issues.
- B. Stinton: At one point inner thigh temperature was considered to closely track mean body temperature. NEDU used four skin temperature points for weighting factors.
- J. Clarke: When the diver rose above the thermocline in the alpine lakes, the ambient temperature apparently nullified the effect of cold on decompression. How does Uwaterc model that in their algorithm (where did that come from) and how do they derive that correction factor?
- D. Long: Currently, the only device that determines whether the temperature is cold or warm is the dive computer itself. The computer reading is irrelevant in predicting how cold the diver is. He could have very cold hands and feet yet the sensor could register high inner thigh temperature. George Arnoux (Comex safety director) commented years ago on his observations of two commercial divers' gas consumption where one was working hard and the other was holding a close-circuit TV camera. None of the algorithms or tables take this discrepancy in exercise load into account.
- A. Brubakk: First, I agree that one of the weaknesses of the models today is that they do not take exercise into account. We need a model that actually describes the effects of physical exercise on the blood flow in the muscles and a mechanism to monitor perfusion. We know a lot about perfusion and that it is a main factor in the uptake and elimination of inert gas. The way we decided to monitor perfusion is by using heart rate. This has some weaknesses as well. We determined that there needed to be a change in heart rate over a given amount of time in order to call it exercise-related and that will be incorporated in the Uwaterc model. None of the models describes bubble formation which is a critical factor. Most of the bubble models are just supersaturation models that state that once you exceed a certain amount of supersaturation bubbles are formed. It is a very unsatisfactory, crude model.
- D. Long: It is quite complex how a diving physiologist would look at this problem but not the way a Diving Officer would look at it. Operationally the workload of the diver could be

determined and then decompression schedules adjusted accordingly based on experience versus letting the dive computer make the decisions.

- A. Brubakk: I agree with that but there are factors we don't understand and get surprised by. The "in" thing in diving now is deep stops. There are good reasons why deep stops would be functional. Then we tested deep stops in animals and found them to be good for longer bottom times but found them bad for short deep dives where it is better to ascend fast and stay shallow for a longer period of time. On short dives the body behaves like a supersaturation model not like a bubble model. Several institutions have attempted to scientifically study deep stops and failed miserably probably because the theory is wrong. Likewise we anticipated that deep stops probably worked and were surprised by the results in animals. Diver experiments are pending to confirm those results.
- J. Flinkman: What is a short dive and what is a long dive?
- A. Brubakk: In these particular studies a short dive had 30 minutes of bottom time and a long dive 70 minutes. This is only one dataset but we don't know for sure yet. We still need to demonstrate that this concept is correct. For shorter dives it appears that these bubble models are not very good.
- P. Mueller: For practical reasons it seems good to have as little activity as possible at depth to reduce perfusion and gas uptake. During decompression there should be much activity to increase perfusion and the elimination of inert gas. Is this practical in an operational setting?
- J. Flinkman: There's no getting around the fact that we are warm when we first suit up and jump in the water. During the ongoing phase of the dive we are warm and on ascent and during decompression, the offgassing phase of the dive, we are getting increasingly cold. In our team of ten trimix decompression divers those who are of lean build often get cold and develop skin bends where the rest of us have not had this problem. As Dick pointed out the computer monitors its own temperature. I would be annoyed if the computer told me to stay another 30 mins at 3 m if I were not freezing or cold. If I feel a bit cold or have hands that are a bit numb depending how I feel I stay a bit longer at 3 m breathing oxygen and might continue breathing oxygen at the surface.
- M. Sayer: Most, if not all, cases of DCS in the BAS diving program have been skin bends.
- J. Clarke: I agree with Alf that good models need to have as much physiology incorporated as possible. Juha's point is also well taken regarding the inability of dive computers to distinguish between divers of different body build. Navy physiological studies usually do not experience a wide variety of body morphs. Loss of body heat has a huge impact and a computer cannot pick that information up.
- J. Flinkman: Have any studies been done on tolerance of individuals to cold and decompression in relation to the amount of brown fat in the body? For example, with two individuals of the same size and build where one can tolerate cold and the other cannot?
- A. Brubakk: There is not much brown fat in the body. This probably has more to do with fat around the stomach and under the skin. In experimental animals even a small amount of difference in body fat content has a large effect on the amount of bubbles that are formed so it's very sensitive to body mass and fat count. Dive computers should be tailor-made for each diver and take these aspects into account.
- M. Lang: There is commercially available software that allows the diver to interface with the computer on variables such as gas mix, conservatism factors, altitude, etc. but much of this is not based on scientific data.

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- P. Mueller: One parameter that increases diver safety is the breathing of oxygen during decompression and staying within the air tables.
- M. Lang: Hydration level is important in general. In the tropics the diver sweats and the low humidity in polar environments also dehydrates.
- P. Mueller: There was nothing found in my literature search on cold and dehydration effects on DCS.
- S. Deweese: In the USCG we are only allowed to do no-decompression diving and do not use dive computers. Our divers experience high work loads and get cold frequently and the benefit of dive computers would be to maximize bottom time. Given that our dives are cold and strenuous it appears that dive computers would not be applicable to the kind of diving we do and, therefore, use of tables is the safest way to go.
- M. Lang: Comparing no-decompression limits for USN tables (*e.g.*, 60 fsw for 60 mins) and many dive computers (*e.g.*, 60 fsw for 52 mins) for single dives it is clear that computers are more conservative (*i.e.*, reduced NDLs). On a high performance automobile the speedometer may top out at 200 mph which does not mean that this speed must be reached on every occasion of a trip to the 7/11 convenience store around the corner. Because tables indicate an NDL of 60 mins at 60 fsw does not mean that the diver must use that entire NDL on every dive within a margin of 1 minute from required decompression which puts the diver on the edge. The diver's brain must still be turned on to introduce whatever factors impinge on a particular dive profile such as cold, gas consumption or workload. Tables and computers are merely a guide and provide information that we take into account to make informed decisions about our decompression status.
- S. Deweese: I accept that but USCG has relatively young divers doing this work and the control of the dive rests with the dive supervisor. He must have the tools and information to control the dive. I do not want to give control of the dive to the diver on the bottom.
- M. Lang: We acknowledge that there is a huge cultural difference in the operational approach to dives between the military/commercial communities and the scientific and recreational diving communities. Scientific divers on the bottom are responsible for monitoring and managing their decompression status based on their training and real-time nitrogen tracking using a dive computer.
- S. Deweese: My point is that dive computers might not be the best way to go for the type of dives we are doing not that there is anything wrong with computers in general.
- M. Lang: Dive computers also play a significant role and serve as an invaluable tool in the analysis of diving mishaps by creating a record of the dive profile which tables do not. Tables only provide a "shell" of the dive consisting of maximum depth and time and are mute on the number of ascents made, ascent rates and actual dive depths at intervals.
- J. Clarke: The Navy will actually use dive computers but with a military twist: next generation diving system. The diver will wear the computer with a datalogger but will not actually be provided with real-time information which is instead sent topside to the diving supervisor who is in charge of the dive. The guidance will ultimately come from the computer but be relayed from topside to the diver if none other than to satisfy the issue of multi-level diving where the tables are very inefficient. The supervisor will have tables available as back-up in case of computer malfunction.
- J. Flinkman: Diving cold water with tables the next deeper depth and/or time can be used but the same can be done with computers that allow for different conservatism level settings.

- M. Sayer: We don't use computers either for monitoring decompression and the real reason is the legal framework within which we have to work. In the UK the legal responsibility for the dive rests with the dive supervisor which gives him some control of the diving operations according to UK law.
- M. Lang: We all agree that from a DCS standpoint the high-risk portion of the dive is the ascent. Using tables, a watch and a depth gauge is primeval technology. Is there a possibility that dive computers could be phased in at least as ascent rates monitors?
- M. Sayer: Already done. Although computers aren't used for dictating the decompression schedule they're still used for the ascent and sometimes for the safety stop information the computers provide. The discussion then goes whether the tables are actually used for determining the dive profile. The bottom time is dictated by the tables and the ascent rate is dictated by the computer.
- M. Lang via email to S. Angelini: Monitoring the heart rate of the diver as a measure of workload is a useful variable that Uwaterc has included in its decompression model. A finite number of skin temperature monitoring sites would be another useful variable. Question: Clarify your comment on how the elevated temperature above the thermocline nullifies the effect of cold and how that is addressed in the algorithm and on what basis?
- S. Angelini via email to M. Lang:
Answer: The algorithm applies the temperature that it has remembered from the descent and applies it to predict the perfusion and saturation times that it will use during decompression. If the temperature is higher than at the bottom the penalization is much less as the results show. Does it apply to temperature in a straight way or does it account for some cooling of the body? Does the body need some time to recover from the cold at depth before it can fully benefit from the warmer temperatures in the shallows? The example shown is also not best for that because there is a difference in deco between the SmartZ and the Aladin locked at 25°C but there's also a temperature difference in that the real water temperature was a maximum of 18°C. The Aladin using instantaneous temperature: at first it applies reduced perfusion through longer halftimes than the predicted decompression and hence shows long deco times. As the water gets warmer though the computer compensates by accelerating the perfusion gradually and again shortening halftimes hence recovering from the effect of cold.
- D. Long: If the diver is in very cold water on the bottom and comes up into warmer water there is no place where the diver does not continue to lose heat or where the diver can take heat out of the environment to warm his body back up. The rate at which the diver loses heat might slow down a bit but it doesn't give him anything back.
- M. Sayer: The Swiss lake example may not be relevant to polar diving where such a temperature differential does not exist. However, what do you do when you get back to the surface and are still offgasing? Is it better to warm up quickly or slowly?
- P. Mueller: It may be good to warm up by physical exercise (walking or cycling but not lifting heavy weights). This theoretically warms the diver, increases perfusion and accelerates gas elimination which needs to be supported by experimental data.
- M. Sayer: This sort of contradicts everything we've taught divers and always used to be a good excuse to do their work as well.

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- K. Richardson: Are divers in hot water suits controlling their suit's temperature?
- D. Long: The hot water suits are kept around 93°F and will keep fairly uniform skin temperatures. Topside will only modify the temperature of the water sent to the diver by virtue of how many feet of hose are in the water. At the end of a surface-supported dive when the hose is being pulled out of the ocean the water temperature in the suit gets hotter so the temperature needs to be modified. If you're running a simple dive off the end of the KingsBay pier the supervisor would rely on what the diver tells him. In some operations water temperature sensors are located at the diver or at the bell. The main goal is to keep the water temperature in the suit constant.
- K. Richardson: Can you not decrease the temperature at the bottom to cool the diver and increase it during decompression?
- D. Long: You would need to be able to calculate what that temperature is. With the increased gas density at depth the margin by which the diver stays comfortable becomes narrower which would mean having very fine control over the temperature before the diver becomes miserable. The diver also wants to breathe gas that is cooler than his body otherwise he will not feel well.
- J. Clarke: Regarding hot water suit use in one Navy ballast experiment we dived the divers cold on the bottom and cold during decompression, warm/warm, cold/warm, and warm/cold. There's a horrible discrepancy between being warm on the bottom and cold during decompression and being cold on the bottom and warm during decompression. In this preliminary study results showed it was much safer diving cold and then turning up the temperature in the hot water suit. However, before we tell Navy divers that we are not going to give them hot water on the bottom we need more definitive data from further study.
- P. Mueller: The danger in hard work after dives lies in heavy lifting (such as heavy dive gear) where a right-to-left shunt can open. Lifting heavy weights, holding breath or increasing intrathoracic pressure causes a transient of bubbles that can cross to the arterial circulation and cause decompression sickness. Now that we now about patent foramen ovale (PFO) we can look at physical exercise as a way to increase perfusion to eliminate inert gas.
- J. Clarke: That is a brilliant approach because right now we are required to inform our divers that if they allow testing and are found to have a PFO this would not be entered in their medical record and would not affect their diving career. We need to come up with operational dive procedures where the PFO will not impact the dive or create unacceptable DCS risk to the diver.
- D. Long: Is having a PFO not considered disqualification from diving?
- J. Clarke: Absolutely not.
- M. Lang: The medical community is not in unison in its opinion on PFO. There are different degrees of patency (as in asthma different degrees of severity and onset, childhood versus adult) and thus potentially different effects on diving physiology.
- A. Brubakk: It is clearly established that it is the amount of gas as measured in the pulmonary artery or the gas bubbles you can see in the heart that is statistically related to the risk of severe decompression sickness. If one can produce operational procedures that reduce the amount of gas bubbles in the vascular system this will significantly influence the risk of DCS. There is, however, no way to monitor whether one procedure is better than the other. You can get an indicator by monitoring pulmonary artery gas. To know if one procedure is better than another you also need a large number of experimental dives (*e.g.*, 400-500) based

- on appropriate statistics. The increase of risk of DCS with a PFO is demonstrated but this risk can be reduced with appropriate dive procedures.
- B. Forbes: In healthy adults without PFO pulmonary shunts can also occur.
- P. Mueller: Yes. Cardiologists only look at the heart and see the PFO as a cause of right to left shunt. I prefer to speak of right to left shunting in general. It doesn't matter whether bubbles cross from the venous to the arterial circulation at the level of the heart or the lungs or somewhere else. It is an operational problem of bubbles crossing from where they are safe to a side of the circulation where they cause symptoms. It is how we dive that causes the transient of bubbles. Having a PFO or right to left shunt doesn't automatically mean you have an increased DCS risk as long as you dive within safe operational procedures. If we can teach divers safe procedures without transient bubbles then we probably don't have to look for right to left shunt and forget about screening procedures. This is still an unresolved issue.
- J. Flinkman: What is the opinion on using nitrox with air limits for cold water diving operations?
- M. Lang: Nitrox is universal now in the diving community, no longer a "specialty" and is readily available. The physiological advantages of having an increased pO₂ for offgasing are accepted. Not exceeding the maximum operating depth is of concern for open-ocean polar diving mitigated by the use of blue-water tether systems. The additional safety buffer is the use of air no-decompression limits.
- P. Mueller: As a standard technique we recommend for divers with proven right to left shunts who continue diving to use nitrox within air table limits.
- B. Stinton: The temperature of the diver is relative. We try to manage the thermal comfort of the diver. Surely we should not return to using wetsuits instead of drysuits to keep us cold on the bottom and then "warm" during decompression as the wetsuit material expands. These relative terms of "cold" and "warm" really mean that divers are not as thermally comfortable. Divers with high work rates can easily get heat stress. Looking to the future when active heating systems come online we need a management plan for their use.
- J. Clarke: Active systems will only be relevant to polar diving if coupled with surface-supplied diving.
- K. Richardson: If we accept that the tissues susceptible to decompression stress in the cold are slow tissues it also appears that skin becomes the coldest tissue as evidenced by skin bends. Are they peripherally distributed or is there any relationship between the skin temperature itself and where the skin bends occur, versus toe bends?
- J. Flinkman: The divers in our team have had the skin bends on the back of the forearms.
- M. Lang: From our exposure and incident rates going back to when ice diving started in our different programs we will also be able to provide a "DCS status" on where we are with polar diving.
- M. Lang: D. Andersen and E. Ochoa tried the DSI heat exchangers. The regulators worked fine and they reported no noticeable difference in breathing gas temperatures. We have had no freeflows in any regulators here yet.

Session 3: *Decompression Discussion*

- C. McDonald showed and narrated “Under Antarctic Ice” filmed by Norbert Wu in the 1999 and 2000 austral summer seasons and produced by PBS/Nature WNET. Oscar winner Hillary Swank narrated the movie. Norbert Wu (NSF Artists and Writers grantee), Dale Stokes and Christian McDonald did most of the diving and shot about 150 hours of HD video which was edited down to 19 minutes of underwater footage.

NORWAY'S POLAR RESEARCH: A SELECTIVE OVERVIEW

Haakon Hop

Norwegian Polar Institute
N-9296 Tromsø, NORWAY

Norway has polar research operations in the Arctic and the Antarctic. In the Arctic, marine research mainly involves Svalbard waters and is most often based from the Sverdrup Station or Kings Bay Marine Laboratory in Ny-Ålesund or the research vessels LANCE (Norwegian Polar Institute) and JAN MAYEN (University of Tromsø). Multidisciplinary ship cruises to the Marginal Ice Zone often involve scuba diving and diving projects have also been conducted in fjords on Svalbard. Most of the research projects conducted by the Norwegian Polar Institute, as well as other institutions in Norway, have international components with participating researchers. This paper presents an overview of some of the recently completed or ongoing Arctic research projects conducted by Norway, mainly in Svalbard waters or on Spitsbergen.

Norway's polar tradition

Norway has a long tradition in polar research, leading back to the early explorations by Fridtjof Nansen with his *FRAM* voyage (1893-1896). The expedition followed the transpolar ice drift across the Arctic Ocean and was fundamental to our understanding of polar oceanography and ice physics (Nansen, 1897). The foundation for the Norwegian Polar Institute (NPI) was laid by an expedition in 1906 led by Gunnar Isachsen and financed by the Prince of Monaco. The scientific focus of the early period was geology and oceanography and, in particular, on mapping of the Polar Regions. Norway is the only country in the world that has territories in the Arctic and maintains claims in the Antarctic. The Troll Station on Queen Maud Land in Antarctica was opened as a permanent Norwegian station in 2005. It has an associated ice airfield but no marine activities since it is located at 1270 m above sea level and 235 km from the coast. The Antarctic marine activities have been limited to cruises and there have been some diving activities associated with those.

Most of the Norwegian polar research has been concentrated on Svalbard and adjacent waters, including the Fram Strait to the west, Arctic Ocean to the north and the Barents Sea to the east. It is mainly based from the Sverdrup Station or Kings Bay Marine Laboratory in Ny-Ålesund or the research vessels *LANCE* (Norwegian Polar Institute) and *JAN MAYEN* (University of Tromsø). The Barents Sea is a relatively shallow-shelf sea, with a mean depth of 230 m. It receives warm Atlantic water from the south-west and cold Arctic water and ice from the north and north-east (Falk-Petersen *et al.*, 2000; Wassmann *et al.*, 2006). The warm and cold water masses meet in the Polar Front which also coincides with the maximum ice extent in April. One branch of the North Atlantic Current follows the shelf topography northward along the west

coast of Svalbard, as the West Spitsbergen Current, and carries warm water masses into the fjords on Spitsbergen (Hop *et al.*, 2006).

Ice-Free Kongsfjorden

The Kongsfjord-Krossfjord system is particularly suitable for studies of the effects of climate change on marine ecosystems because it is influenced by both Atlantic and Arctic water masses (Svendsen *et al.*, 2002). The fjord contains a mixture of boreal and Arctic organisms (Hop *et al.*, 2002). In warm years the influence of Atlantic water is strong, which causes a shift towards boreal zooplankton at the expense of the Arctic species in the inner part of the fjord.

The Scottish Association for Marine Science (SAMS) has maintained underwater observatories (moorings) in Kongsfjorden since 2002. The moorings measure temperature, salinity, currents, plankton movements, sediments (traps) and fluorescence. A similar mooring was installed in Rijpfjorden (80°00'-80°30'N, maximum depth 250 m), a fjord facing north on Nordaustlandet, in 2006. Continuous measurement records are critical to our understanding of the water mass dynamics in the fjord system (Cottier *et al.*, 2005) and has also helped to explain why there has been almost no ice in Kongsfjorden during the last two winters (Cottier *et al.*, 2007). The reasons for no ice formation are a combination of relatively warm air temperatures in early winter, close to 10°C above the 50-year mean in January, and an influx of warm Atlantic water across the West Spitsbergen Shelf and into the fjord systems in February-March. The prevailing wind pattern was important for the upwelling and cross-shelf transport of water masses and prevented ice formation when the temperature subsequently dropped in late-February-March. By this time there is also a large amount of heat in the fjord system and the entire water column remained above the freezing point after extensive wind mixing. The ice-free conditions, two years in a row, may be a strong indication of a climate-induced shift in environmental conditions for this fjord system; it is certainly unusual compared with previously recorded situations in late winter.

Zooplankton

Zooplankton research currently includes all aspects of modern marine sciences and the key topics concern: 1) understanding zooplankton natural biological dynamics; 2) zooplankton as potential food source for marine organisms; 3) identifying the role of zooplankton organisms in transfer of matter and energy (lipids) through food webs; and, 4) consequences of climate-induced modification of matter and energy transfer. Modern technologies for zooplankton sampling have included light (optical plankton counters, OPC) or sound (echosounders, sonars, acoustic doppler current profiler-ADCP). In studying fragile forms such as comb jellies, medusae or appendicularians, sampling by divers is necessary (Lundberg *et al.*, 2006).

The intrusions of warm water masses into the fjord system affects the zooplankton community in the fjord since Atlantic water masses bring in more boreal fauna (Basedow *et al.*, 2006; Willis *et al.*, 2006). The SAMS mooring has also proven useful in determining seasonal patterns in vertical movements of zooplankton in the fjord. Synchronized diel vertical migration of zooplankton species starts in the autumn, after the end of continuous summer sunlight, and the ADCP clearly shows this diurnal pattern (Cottier *et al.*, 2006). This also results in different

horizontal distribution of zooplankton since they will reach different water masses while migrating vertically. Zooplankton has been collected at least on an annual basis since 1996 by nets (e.g., Multi-Plankton Sampler with 5 closing nets), with associated oceanographic measurements (CTD), at stations along the length axis of Kongsfjorden to the shelf break (Kwasniewski *et al.*, 2000; Hop *et al.*, 2006).

Arctic marine food webs

Arctic marine web studies have been conducted during multidisciplinary cruises (2003-2005) in the Marginal Ice Zone around Svalbard, during the projects “*On Thin Ice? Climate influence on energy flow and trophic structure in Arctic marine ecosystems*”, and “*CABANERA - Carbon flux and ecosystem feed back in the northern Barents Sea in an era of climate change*”. All cruises have involved scuba diving to collect organisms and install instruments under drifting sea ice. The project “*MariClim - Marine ecosystem consequences of climate induced changes in water masses off West-Spitsbergen*” is currently being conducted in Kongsfjorden. It is presumed that climate change will affect the distribution of warm Atlantic and cold Arctic water masses of shelf and fjord regimes in West-Spitsbergen. This will alter the zooplankton composition and subsequently change the energy transfer within the pelagic food web with consequences for upper trophic levels.

Recent studies by SEAPOP (Norwegian Polar Institute/University Centre on Svalbard) have included zooplankton as food source for the little auk (*Alle alle*). The Arctic *Calanus* species are important food sources mainly because of their higher lipid (energy) levels. *Calanus hyperboreus* has 26 and *C. glacialis* 10 times as much energy as *C. finmarchicus* (Falk-Petersen *et al.*, 2007). In a warming climate regime it is expected that the transport of Atlantic water to the west coast of Svalbard will increase and that Arctic water masses with Arctic zooplankton will decrease. This little auk depends on large, Arctic *Calanus* species (*C. glacialis* and *C. hyperboreus*) and may disappear if the smaller Atlantic *Calanus finmarchicus* becomes the dominant zooplankton in Svalbard waters. From the bottom of the food web, primary producers may change to smaller flagellates utilized by *Calanus finmarchicus* and a third trophic level of pelagic fishes such as herring (*Clupea harengus*) will expand and prey on those. The fish then becomes prey for fish-eating seabirds and seals or Minke whales (*Balaenoptera acutorostata*) (Wassmann *et al.*, 2006).

The structure and energy flow in Arctic marine food webs has been studied by stable isotopes of carbon and nitrogen to determine carbon sources and trophic levels (Dahl *et al.*, 2003; Søreide *et al.*, 2006). Trophic transfer of energy from zooplankton to seabirds and seals has been studied by means of fatty acid trophic markers (Falk-Petersen *et al.*, 2002, 2004, 2007) which became carbon fixed during spring bloom and transferred as fatty acids to top predators within 6 months (Falk-Petersen *et al.*, 1990). Trophic levels, determined by stable isotopes, are used as a continuous variable against bioaccumulation of persistent organic pollutants (POPs) to determine their bioaccumulation potential in Arctic marine food chains (Hop *et al.*, 2002). Some compounds, such as trans-nonachlor and PCB-138 and PCB-153, show high food-web bioaccumulation factors, determined from regression slopes of TL against POPs (Hop *et al.*, 2002).

Ice algae

Ice algae are the primary producers in ice-associated food webs and consist primarily of diatoms (cells living in a glass house) but also include other types of algae originating from the pelagic (open-water) system (Hegseth, 1992; Gradinger *et al.*, 1999). Characteristic Arctic diatoms are *Nitzschia frigida*, *N. promare*, *Fragilariopsis oceanica* and *Thalassiosira bioculata*, whereas large strands of the ice diatom *Melosira arctica* are found in Arctic multi-year ice. Ice algae are sampled quantitatively by scuba using ring-frames with serrated edges that are screwed into the undersurface of the ice, where algae are vacuumed out by electrical suction pump (Lønne, 1988). Sub-ice communities are present in the Barents Sea from April to August. The communities are dominated by diatoms, from high to low biodiversity, depending on environmental conditions. Ice algae are sensitive to changes in the environment since they need low temperature water (-1.7/-1.8°C) to stay attached to the ice crystals. The maximum biomass, recorded in May, is 40 mg chlorophyll/m². It is higher in the Barents Sea ice than in other Arctic pack ice areas but lower than in Arctic fast ice areas. Primary production is measured with a production rig placed by divers below the ice. The maximum production is 55 mgC/m²/day and with a 3-months active growth season it becomes > 5 gC/m²/year. Ice algal production makes up 16-22% of total primary production in the northern Barents Sea (Hegseth, 1992).

Ultraviolet radiation (UVR)

Ultraviolet radiation (UVR) may have a negative effect on both pelagic algae and macroalgae in shallow waters (Wiencke *et al.*, 2000; Leu *et al.*, 2006a). The effects of UVR on lipids, fatty acids and nutritional quality of Arctic marine algae and zooplankton have been studied in Kongsfjorden and experimentally in Ny-Ålesund (Leu *et al.*, 2006a, 2006b, 2007). The aim of the project was to determine how recent and future changes of Arctic light climate affect the nutritional quality of phytoplankton, with a special emphasis on UV radiation. If the UV-radiation alters the lipids in phytoplankton these changes in food quality may be transferred to zooplankton. However, it was found that food quality is not the weak link in an Arctic food web exposed to UVR. Instead, hydrography determines the importance of light effects: Photosynthetic Active Radiation (PAR). Light stress might be of substantial importance for spring blooms at ice edges under strongly stratified conditions and rapidly changing light intensities. Trophic transfer of these effects is only likely under stable conditions, but may be of increasing importance because of climatic changes (Hegseth, 1998).

Rijpfjorden

This type of research will be continued in the CLEOPATRA project, a recently funded IPY-project (2007-2009). Climate effects on planktonic food quality and trophic transfer will be studied in Arctic marginal ice zones (MIZ) and a study site has been established in Rijpfjorden on Nordaustlandet, Svalbard. A weather station and web cam has been in operation there since February 2007 (<http://weather-iridium.unis.no>). A stationary mooring (maintained by SAMS) was also positioned in the fjord in September 2006 and scheduled for renewal in 2007. The aim of this project is to assess the role of light for timing, quantity and quality of primary and secondary production in the Arctic MIZ under decreasing ice cover, seasonally and spatially. Rijpfjorden will be a model system for the MIZ in Arctic Ocean and the onset of primary

production in an ice-covered system will be determined relative to the vertical distribution and stage composition of *Calanus* copepods. The role of light for autotrophic food quality will be assessed as well as the importance of food quality for *Calanus* reproduction. In the joint ICE-EDGE project, conducted in the same area, studies will include: the predation risk on *Calanus* by the Daubed shanny (*Leptoclinus maculatus*) and ice amphipods; the life cycle and lipid storage of the Daubed shanny (*Leptoclinus maculatus*) (Falk-Petersen *et al.*, 1986); and ecological and ecotoxicological studies of ice-associated amphipods.

Long-term monitoring of benthos

Long-term marine ecological projects are rare in Arctic waters but one project has monitored an Arctic macrobenthic community in relation to climate variability (Beuchel *et al.*, 2006). Two monitoring sites have been photographed annually by scuba divers since 1980: Kvadehuken in Kongsfjorden and a location in Smeerenburgfjorden on north-west Spitsbergen. Permanently marked hard-bottom areas at 20m depth are photographed annually by scuba divers (Fig. 1). Ten 0.25m² squares are photographed with stereo-photography (Hasselblad system, later digitally). At the start of the experiment all organisms were removed from "treatment" squares (5 out of 10 squares), and their recolonization was monitored over the subsequent years. Principles of image analysis included the use of Adobe Photoshop and the measurement toolkit Fovea Pro (Beuchel *et al.*, 2006). Changes in community composition (Shannon Wiener species diversity H') was related to changes in the North Atlantic Oscillation index (NAO; Hurrell, 1995) and its manifestations (Fig. 2).

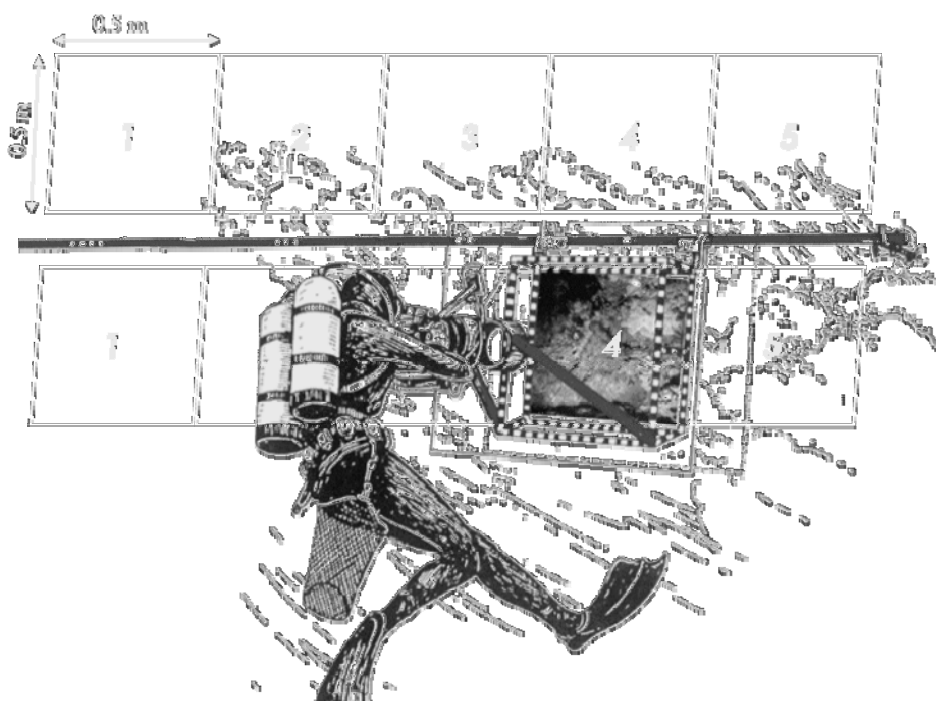


Figure 1. Permanently marked squares (0.25 m²) have been photographed annually at Kvadehuken in Kongsfjorden since 1980. The diver-operated camera rig is moved along a metal rod with notches, so that the photographs are taken from the same exact position each year. From Beuchel *et al.* (2006), with permission from author.

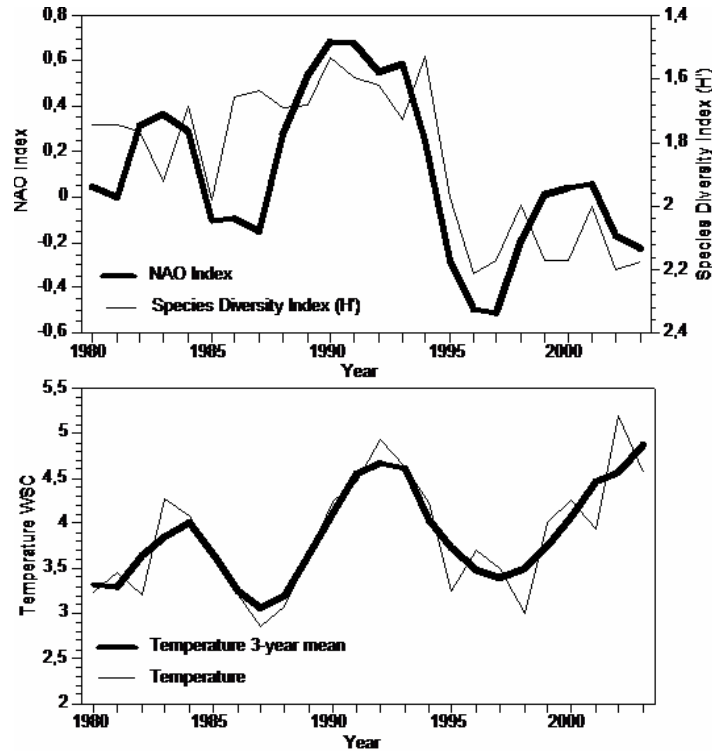


Figure 2. a) Correlation between North Atlantic Oscillation Index (3-year mean calculated from September-August) and Shannon-Wiener diversity index (H'); b) Mean autumn (August-September) temperature in the West Spitsbergen Current at about 79°N between 100- and 300-m depth. Data from Saloranta and Haugan (2001), Schauer *et al.* (2004) and V. Tverberg (pers. comm.). From Beuchel *et al.* (2006), with permission from author.

The NAO index is defined as the anomalous difference between the polar low and the subtropical high during the winter season, December through March (www.ldeo.columbia.edu/NAO). The Positive NAO index phase shows a stronger than usual subtropical high pressure center and a deeper than normal Icelandic low. The increased pressure difference results in more and stronger winter storms crossing the Atlantic Ocean on a more northerly track. This causes warm and wet winters in Europe and cold and dry winters in northern Canada and Greenland. The negative NAO index phase shows a weak subtropical high and a weak Icelandic low. The reduced pressure gradient results in fewer and weaker winter storms crossing on a more west-east pathway. They bring moist air into the Mediterranean and cold air to northern Europe (www.ldeo.columbia.edu/NAO).

The temperature in the West Spitsbergen Current was the most important link between the NAO and the benthic community, which is not surprising since the monitoring station at the mouth of Kongsfjorden is dominated by Atlantic water and, thus, Atlantic-boreal species. However, the severe changes in the benthic community observed between 1994 and 1996 coincided with a shift of the NAO from a positive to a negative mode. Multidimensional scaling (MDS) plots show that there is a strong coincidence between changes in the main environmental factors and benthic community structure. The increase in biodiversity after 1994 is accompanied by a decline of actinarians, a rapid increase of the sea urchin *Stongylocentrotus droebachiensis*

and brown algal cover. The linkage between large-scale, ocean-atmospheric climatic drivers and Arctic marine ecosystems are of particular interest as we try to understand the possible ecosystem consequences of warming in the Arctic (ACIA 2004).

Hard-bottom communities

The hard-bottom communities have also been studied spatially in Kongsfjorden (Gontar *et al.*, 2001). The spatial variations were addressed by comparing communities of benthic fauna and macroalgae in different parts of Kongsfjorden, from the inner to outer basins. The project's objective was to determine how the biodiversity of benthic communities in an arctic glacial fjord is structured by steep environmental gradients. The subtidal hard-bottom investigations were sampled quantitatively (duplicate 50 x 50cm frames, depth-stratified to 30m) by scuba diving at six stations from inner to outer fjord. Both the benthic fauna and macroalgae were sampled quantitatively in 1996 and 1998. Areal coverage by macroalgae was additionally determined by digital video recording of standard frames along transects at five stations and samples were also collected for taxonomic analysis. The project has already increased our knowledge substantially on how the biodiversity is structured in an Arctic glacial fjord (Hop *et al.*, 2002). The species records have been incorporated into the existing database for marine benthic macro-organisms at Svalbard (Gulliksen *et al.*, 1999). The spatial faunal data are being further analyzed as part of a Ph.D. project (A. Yu. Voronkov, Norwegian Polar Institute).

Clams as climate indicators

In a related project, which has involved collections by scuba divers, bivalves (clams) are used as long-term indicators of climate variability. Clams are basically "The Trees of the Sea," since they record and preserve biological and environmental information in their hard shells. This allows us to search for patterns and to reconstruct linkages between climatic phenomena and bio-responses (McMahon *et al.*, 2006). Types of information from bivalve shells include variations in growth rate, from local to pan-Arctic. Environmental conditions from constituents imbedded in the shell include signals related to temperature, salinity and food resources. Species studies have involved *Serripes groenlandicus*, *Hiatella arctica*, *Mya truncata*, *Macoma calcarea* and *Arctica islandica* (sub-Arctic species). The growth patterns show good correlation with the regional climate index, with high growth during positive anomalies and lower growth during negative periods (Fig. 3). Bivalve growth is linked to climatic forcing factors through variation in physical variables. A multiple regression model with different physical climate variables included (climatic oscillations, local weather variables, individuals, Barents Sea temperature, ice cover) has given good overall correlation for modeled and observed GSI for all years combined (1985-2002) (Ambrose *et al.*, 2006).

Glacial monitoring records

Kongsfjorden is surrounded by many glaciers, some of which calve directly into the fjord and are termed tidal glaciers (*e.g.*, Kongsvegen, Kongsbreen, and Blomstrandbreen). Some of the glaciers have been monitored over many years by the Mass Balance Program in Ny-Ålesund, conducted by the Norwegian Polar Institute. Austre Brøggerbreen (since 1967) and Midtre Lovénbreen (since 1968) are among the longest annually measured high Arctic mass-balance

time series, whereas Kongsvegen has a shorter time series (since 1987). A consistently negative mass balance has been recorded for small glaciers and the winter precipitation is also less variable than summer melt. No statistically significant trends are present in the balances but the last 5 years have the longest succession of negative net balances on record (J. Kohler, pers. comm.). Svalbard climate during the past ~1000 years has been determined from $\delta 18O$ ice core records (Isaksson *et al.*, 2003, 2005). The record from Lomonosovfonna suggests that temperatures during the early part of the record about 1100-1500 AD (medieval warm period) was at least as warm as the 1900s. However, the record ends in 1997, thus excluding the last exceptionally warm years (Isaksson *et al.*, unpubl.).

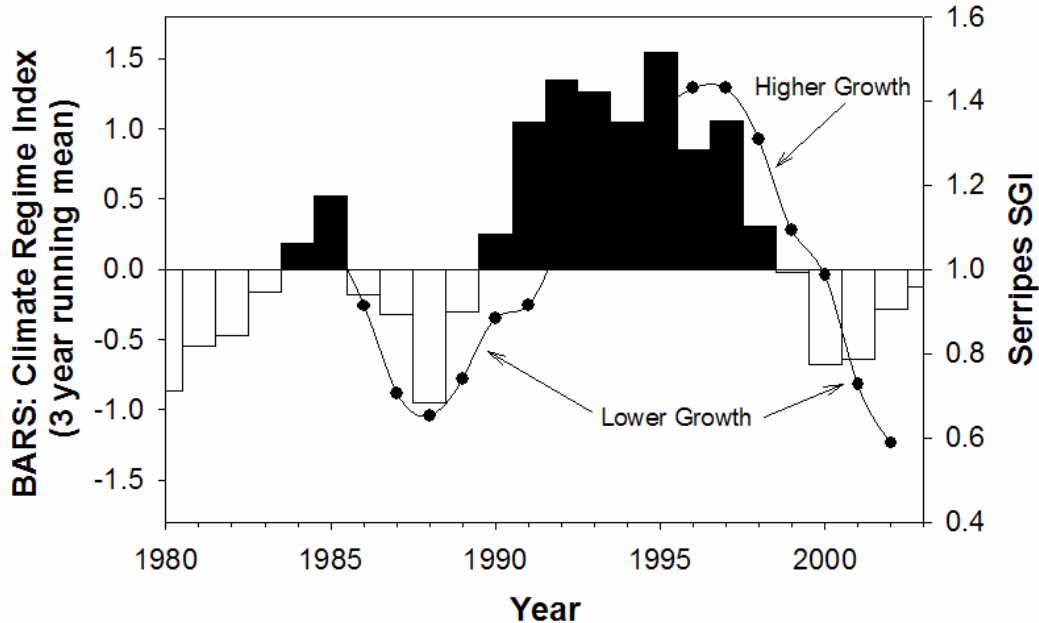


Figure 3. Svalbard *Serripes groenlandicus* somatic growth index (SGI) compared to Climate Regime Index – with a 1-year lag. All data are smoothed with a 3-year average function. From Ambrose *et al.* (2006), with permission from author.

Marine mammals pole to pole

Marine mammals have been extensively studied in Kongsfjorden (Hop *et al.*, 2002) as well as other areas in Svalbard (Kovacs, 2005) and now also in the polar IPY project “*Marine mammals exploring the oceans pole to pole – MEOP.*” The major goals for MEOP are: 1) assessment of marine mammal habitats; and, 2) oceanographic data collection to identify hot spots for activity. The project will use Argos satellite transmitters attached to different seal species. Diving profiles will be recorded in addition to physical data on temperature and salinity (Lydersen *et al.*, 2002).

ARCTOS network

Much of the Arctic marine research in the European Arctic is currently organized in the *ARCTic marine ecOSystem research network - ARCTOS* (www.nfh.uit.no/arctos). The vision of the *ARCTOS network* is to be the premier centre of Arctic marine ecology, oceanography, and

biogeochemistry for Europe and the pan-Arctic region. ARCTOS is currently a large network of 6 Norwegian, 6 Nordic and 22 international institutions. The network facilitates cooperation on basic and applied research and education, and is supported by a world-class Arctic research infrastructure. ARCTOS on-going projects consist of 30 international research networking and teaching projects headed by the different parent institutions. It includes some of the largest projects in marine ecology in Europe, and participates in two *European Networks of Excellence*: EUR-OCEANS and MARBEF. The *ARCTOS Applied Science Forum (AASF)* extends the basic research results derived through the ARCTOS Network activities to applied research goals and scientific outreach activities. The *Arctic Frontiers Tromsø* will be an annual event that takes place in January in Tromsø, Norway. The *ARCTOS PhD School*, University of Tromsø, provides comprehensive and contemporary education in Arctic marine science. About 30 PhDs, post-doc and master students are currently taking courses at the PhD School and take part in ARCTOS research projects. The components of the school include: ARCTOS Colloquium, ARCTOS Workshops, ARCTOS marine ecological research course / EUR-OCEANS floating University. The ARCTOS study area is the European sector of the Arctic and ongoing projects are: MariClim, ARCTIME, SEAPOP, PRACEAL, SAMS-NS, as well as new IPY-projects (Norwegian Research Council): SciencePub, iAAOS, COPOL, AESSAS. Other new projects include ARCWIN and Ice-edge. The ARCTOS network is currently linked with the Canadian ArcticNet (www.arcticnet-ulaval.ca) under the IPY-umbrella PanAME.

Acknowledgements

Thanks to the following individuals for providing information on the included topics.: Oceanography and Ice: Finlo Cottier, Mark Inall, Colin Griffiths, Kate Willis (Scottish Association for Marine Science, UK), Frank Nilsen (The University Centre in Svalbard, Norway), Sebastian Gerland, Vigids Tverberg, Arild Sundfjord (Norwegian Polar Institute); Harald Svendsen (Geophysical Institute, University of Bergen, Norway); Zooplankton: Slawek Kwasniewski (Institute of Oceanology, Sopot, Poland), Stig Falk-Petersen, Anette Wold (Norwegian Polar Institute); Ice algae: Else Nøst Hegseth (Norwegian College of Fishery Science, University of Tromsø, Norway); UV-Effects/primary and secondary production: Eva Leu (Norwegian Polar Institute, Norway); Hard-bottom benthos: Frank Beuchel, Bjørn Gulliksen (Norwegian College of Fishery Science, University of Tromsø, Norway); Clam growth: Michael Carroll (Akvaplan-niva, Tromsø), William G. Ambrose Jr. (Bates College, Maine, USA), Michael Greenacre (Pompeu Fabra University, Barcelona, Spain), Simon Thorrold, Kelton McMahon (Woods Hole Oceanographic Institution, Massachusetts, USA), Stanislav Denisenko (Zoological Institute, St. Petersburg, Russia), Andrey Yu. Voronkov (Norwegian Polar Institute, Norway); Glacial mass balance and climate change: Jack Kohler, Elisabeth Isaksson (Norwegian Polar Institute, Norway); and, Marine Mammals: Kit M. Kovacs, Christian Lydersen (Norwegian Polar Institute).

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UNDER SEA ICE DIVING OPERATIONS CARRIED OUT BY UK ORGANISATIONS IN SUPPORT OF SCIENTIFIC RESEARCH

Martin D.J. Sayer

NERC Facility for Scientific Diving
Dunstaffnage Marine Laboratory
Oban, Argyll, SCOTLAND PA37 1QA, UNITED KINGDOM

Keiron P.P. Fraser

British Antarctic Survey,
High Cross, Madingley Road
Cambridge, CB3 0ET, UNITED KINGDOM

Tracy M. Shimmiel

Jeremy P. Wilkinson

Scottish Association for Marine Science
Dunstaffnage Marine Laboratory
Oban, SCOTLAND PA37 1QA, UNITED KINGDOM

Introduction

Divers from UK scientific organisations have been diving under ice for many decades; the British Antarctic Survey (BAS) commenced diving operations in 1962/3. Predominantly diving has occurred through BAS Antarctic operations where a year-round diving capability is now maintained. More recently diving under ice has been conducted through the international Polar marine science laboratory at Ny-Ålesund, Svalbard, with additional diving programmes being undertaken mostly under open-sea ice in the north Polar region. This account details some of the scientific research that is being undertaken by scientists in the UK that is dependent on diving under ice. Diving under ice does entail an element of increased risk and equipment demands compared with most other forms of diving. The way in which diving operations under ice are now conducted by UK divers has changed markedly over the past few years. Although diving operations that take place outside of the UK's territorial limits do not have to comply with the UK Diving at Work Regulations, UK-based organisations are bound by the principals of duty of care to adhere, where reasonably practicable, to industry best practice. The current methods of diving under ice as employed by UK divers are outlined within the framework of risk assessment and risk management.

Current UK research programmes employing under sea ice diving

As would be expected, the predominant UK-based organisation with a requirement for diving under ice is the British Antarctic Survey (BAS). Although BAS dive in many locations in the Antarctic region (and have some research interests in the Arctic region as well), all of their

present under ice dives are conducted during the austral winter at the Rothera research station, Adelaide island, on the Antarctic Peninsula. Sea ice formation around the Rothera station is variable; however, diving under ice is conducted during most winters in support of the scientific objectives outlined below. In addition to BAS in the UK, the capability to dive under ice is also maintained by the Scottish Association for Marine Science (SAMS). Most of the SAMS work in Polar areas is concentrated in the Arctic region and has recently been strengthened through its association with the Ny-Ålesund research station in Svalbard. The SAMS diving programme at Ny-Ålesund is in the early stages of development, but some of the research themes that diving is likely to support are detailed below. SAMS also hosts a sea-ice research group jointly with the University of Cambridge that occasionally requires diving under ice in support of their studies. The group's research is mainly performed from ice breakers or ice camps established on the sea ice, and as such they are not usually linked to any particular research facility.

Ice-scouring studies (Antarctica, BAS)

Although ice scouring has been implicated as a highly significant factor in structuring Polar benthic communities, few studies have examined the effects in shallow Antarctic seas (Peck *et al.*, 1999). However, several studies have examined re-colonisation rates of scours on the deeper Antarctic continental shelf (Gutt, 2001; Gutt and Starbans, 2001; Gutt and Piepenburg, 2003), and in shallow Arctic waters (Conlan *et al.*, 1998; Conlan and Kvitek, 2005). Recently, the British Antarctic Survey have carried out a long-term project, measuring both the frequency and intensity of ice-scouring at shallow water sites adjacent to Rothera Research Station (67° 34' 07" S, 68° 07' 30" W; Brown *et al.*, 2004; Smale *et al.*, 2006). Iceberg impacts were recorded by monitoring the damage, or destruction, of purpose made impact markers laid in accurate grids on the substrate. Scuba divers resurveyed the grids at 3 monthly intervals and recorded the number of damaged and destroyed markers. Divers then carried out subsequent dives to replace the damaged or destroyed markers. During winter, resurveying of the sites was frequently carried out through winter sea ice. For the first time, we have estimated the scouring frequency of shallow-water Antarctic habitats. We have demonstrated that water depth, study site and season are all significant factors effecting scouring frequency. The number of days that fast ice is present has also been shown to have a highly significant effect on the total amount of ice scour damage over a year, as the fast ice tends to 'lock in' bergs, thereby reducing the frequency of ice scour events. In one of our study sites (North Cove), 60% of the impact markers were damaged or destroyed within 12 months, suggesting very high levels of disturbance (Brown *et al.*, 2004). At the same site, there was only half the number of bryozoan species with twice the mortality levels in comparison to a nearby, but less scoured study site (South Cove). A further study has found significant effects of ice scouring on species richness and abundance (Smale *et al.*, in press). It therefore appears that ice-scour has an important and highly significant role in structuring shallow water Antarctic communities.

Fish tracking (Antarctica, BAS)

To date there is little know regarding the local scale movements of Antarctic fishes. However, a recent study carried out as a collaboration between the University of Birmingham (Dr Hamish Campbell and Dr Stuart Egginton) and the British Antarctic Survey (Dr Keiron Fraser and Prof. Lloyd Peck), has used *in situ* hydrophones to track acoustic tagged fish (*Notothenia coriiceps*, the Antarctic cod) in the waters adjacent to Rothera Research station (Campbell *et al.*, unpubl.). A series of three hydrophones were attached to anchors and floated 4

m above the substrate, thereby allowing triangulation of each free-swimming fish. Real-time tracking of the tagged fish was carried out over an area of nearly 7000 m². The study ran for a period of 12 months, with regular year-round checking of the hydrophones by scuba divers. As part of the study a series of sea-cages were also used to examine *in situ* heart rates of *N. coriiceps*. Fish fitted with heart rate monitors were placed in sea-bed cages for periods of several months, before recovery by divers to allow logger download. The project involved a significant amount of year round diving activity and the achievement of complex underwater tasks at water depths of up to 35 m.

Seasonal Ecological Studies (Antarctica, BAS)

The majority of national Antarctic operators do not regularly carry out year round diving programs and hence their scientists are restricted to working on animals during the austral summer. The British Antarctic Survey are extremely fortunate in having the facilities to allow year round diving operations, both at our current facility at Rothera Research Station and previously at Signy Island and South Georgia. As a result, BAS has carried out a wide range of year round studies on the physiology and ecology of specific marine species or animal groups (*e.g.*, Barnes and Clarke, 1994; Stanwell-Smith and Barnes, 1997; Brockington, 2001; Brockington and Peck, 2001; Brockington *et al.*, 2001; Fraser *et al.*, 2002ab; Fraser *et al.*, 2004; Bowden, 2005; Bowden *et al.*, 2006). These studies have required considerable amounts of diving to collect animals for physiological experiments, or to allow *in situ* observations or photography. In turn these studies have provided important insights into how Antarctic ectotherms are adapted to living in an environment characterised by a stable thermal regime, but a highly variable food supply.

Carrion scavenging (Antarctica, BAS)

Although a number of studies have examined seasonal feeding in Antarctic marine organisms that filter feed, deposit feed or graze, very little is known regarding the feeding ecology of scavengers (Barnes and Clarke, 1994; Brockington, 2001; Brockington *et al.*, 2001; Fraser *et al.*, 2002ab; Fraser *et al.*, 2004). A recent study has utilised an underwater, tripod mounted digital video camera, to record the seasonal foraging behaviour of scavenging animals (Smale *et al.*, unpubl.). The camera was baited with a fish fillet, and the sequence of species arrival, time spent at the bait and overall bait consumption recorded. The camera was deployed from a boat using divers to ensure correct camera placement. Comparative summer and winter studies were carried out, and these included deployments through fast ice.

Studies of the transport and fate of pollutants in the Arctic (Arctic, SAMS)

The Arctic region is a seemingly pristine, remote environment, yet there is increasing evidence that it is greatly impacted by anthropogenic metal contamination. The source of contaminants primarily lies outside the Arctic region, with sediments potentially providing a major sink for these anthropogenic inputs. Heavy metals are attributed to adverse effects on the health of biota and indigenous populations, because of their toxicity and bioaccumulative tendencies within the environment. Two metal contaminants of major concern are lead (Pb) and mercury (Hg). Both are ubiquitous anthropogenic pollutants with elevated concentrations being reported throughout the Arctic environment (Shimmield *et al.*, unpubl.). Lead is unique in that the source of lead can be determined by its isotopic ratio. The ²⁰⁶Pb/²⁰⁷Pb isotopic ratio of western sources of anthropogenic Pb has a value of approximately 1.14, with Eastern Europe and

Eurasian sources represented by a higher value of 1.18. Research in the Kongsfjordregion of north-west Svalbard has concentrated on detailing pollutant distribution. The research was based on core profiles of heavy metal concentrations and stable lead isotopes from the fjord along with a fresh water lake (Lake Ossian) and Brandallaguna, a brackish lagoon near Ny-Ålesund. Results showed varying sedimentation rates between cores, with some metal profiles characteristic of significant anthropogenic input. In the lake, large increases in the Pb concentration were clearly seen, with values rising from 15 mg/kg to 40 mg/kg. The lead isotope ratio decreased, which is indicative of a change in the source of lead associated with the long range transport of contaminants. The fjord in comparison showed a consistently lower Pb concentration, which possibly resulted from high sedimentation rates from glacial inputs and sediment mixing. Although the cores for this study were obtained using coring techniques based on surface dispatch, future work may be based around obtaining the cores using divers. There are many practical advantages to using divers for this type of work as they can obtain high quality cores without causing sediment re-suspension; there is no need to construct or transport any surface structures to support the coring; and many cores can be obtained from a relatively small area.

Sea ice research (Arctic, SAMS)

Over recent decades the Arctic has warmed more than any other region of the world (ACIA, 2005). This warming has been accompanied by a reduction in the amount of perennial (multi-year) ice within the Arctic Basin (Johannessen *et al.*, 1999, Comiso, 2002); a decrease in the extent of sea ice of about 15% (Francis *et al.*, 2005) as well as a decline by some 40% in the thickness of summer sea ice (Rothrock *et al.*, 1999, Wadhams and Davis, 2000) with an accompanying reduction of some 73% in the frequency of deep pressure ridges (Wadhams and Davis, 2001). This reduction is set to continue with coupled models predicting the disappearance of summer sea ice extent by 2040 (Holland *et al.*, 2006). The near-seasonal disappearance of sea ice will influence among other things, ocean-atmosphere feedback, ocean stratification and vertical mixing. This in turn will affect primary productivity, ecosystem function and carbon cycling.

Understanding the dramatic and significant changes that are presently occurring within the Arctic region and their effect on global climate is beyond the scope of any one nation. The European Union encourages member states to form consortia to address major climate change issues. The Sea Ice Group at SAMS was funded for three Arctic Framework-5 programmes:

- (1) GREENLAND ARCTIC SHELF ICE AND CLIMATE EXPERIMENT (GREENICE). GreenICE, co-ordinated by SAMS, was a 6-partner study of the ice thickness distribution in a little-observed region north of Greenland and Ellesmere Island, combined with a coring-based investigation of past ice conditions.
- (2) SEA ICE THICKNESS OBSERVING SYSTEM (SITHOS). The objective of SITHOS was to develop a European monitoring system for sea ice thickness and related parameters for climate change detection, and to support sea transport, offshore operations and environmental protection in Polar regions.
- (3) ICE RIDGING INFORMATION FOR DECISION MAKING IN SHIPPING OPERATIONS (IRIS). IRIS investigated the mechanics of sea-ice ridge building and ridge structure, and the relationship between ridging parameters and ice resistance forces on vessels.

The Group presently has two active Arctic Framework-6 programmes:

- (1) DEVELOPING ARCTIC MODELLING AND OBSERVING CAPABILITIES FOR LONG-TERM ENVIRONMENT STUDIES (DAMOCLES). DAMOCLES aims to (a) identify the on-going changes concerning sea ice, atmosphere and ocean in the Arctic; (b) evaluate the capability to simulate these changes and to improve the level of confidence for predicting extreme events affecting the Arctic environment; and (c) evaluate the socio-economic impacts of a drastic retreat of the Arctic perennial sea ice or even its disappearance in a near future.
- (2) UNDERSTANDING THE IMPACT OF A REDUCED ICE COVER IN THE ARCTIC OCEAN (RECARO). This multidisciplinary programme, co-ordinated by SAMS, involves 20 partners from 10 European countries plus Japan and the USA. RECARO aims to quantify the changes in the oceanographic structure within the Arctic Ocean caused by the reducing ice cover.

Through participation in these and other Arctic programmes it is becoming increasingly clear that if we are to understand the Arctic, or Antarctic, system we need to have a synoptic scale multidisciplinary measurement programme, as well as smaller focused campaigns. In both instances divers can play a crucial role in determining whether a field campaign is successful or not.

Over the past few years a number of free drifting and moored instrument packages have been deployed under the sea ice as part of the EU DAMOCLES or the USA funded SEARCH programme. It is not feasible, for logistic or budgetary reasons, to have manned stations scattered across the Arctic Ocean. We are, therefore, reliant on autonomous systems. The cost of deploying and recovering mooring under sea ice is extremely expensive. It is, therefore, essential that the instruments and the valuable data are recovered safely and efficiently. One way to ensure this is through the use of divers. This technique is employed by our American colleagues in the turn around of their North Pole Observatory moorings.

Another example of divers playing a crucial support role is in the deployment and recovery of Autonomous Underwater Vehicles (AUV) in ice covered seas. The use of AUVs in the Polar oceans is growing, and will continue in the foreseeable future (Wilkinson, 2007). We have in the past used divers in the deployment and recovery of AUVs (Fig. 1). Whilst most AUVs do not need divers for deployment or recovery, divers could play a key role in the retrieval on an AUV should it become stranded under sea ice.

We have seen in the previous sections the varied use of divers in the pursuit of science. This need will continue if we are to understand the detailed changes that are occurring in the Arctic, especially in the fields of sea ice physics and biology. As robotic technology advances, (remotely operated vehicles and AUVs), the need for divers will reduce but at present there is a distinct requirement by the Polar community for divers in both a scientific and support role.

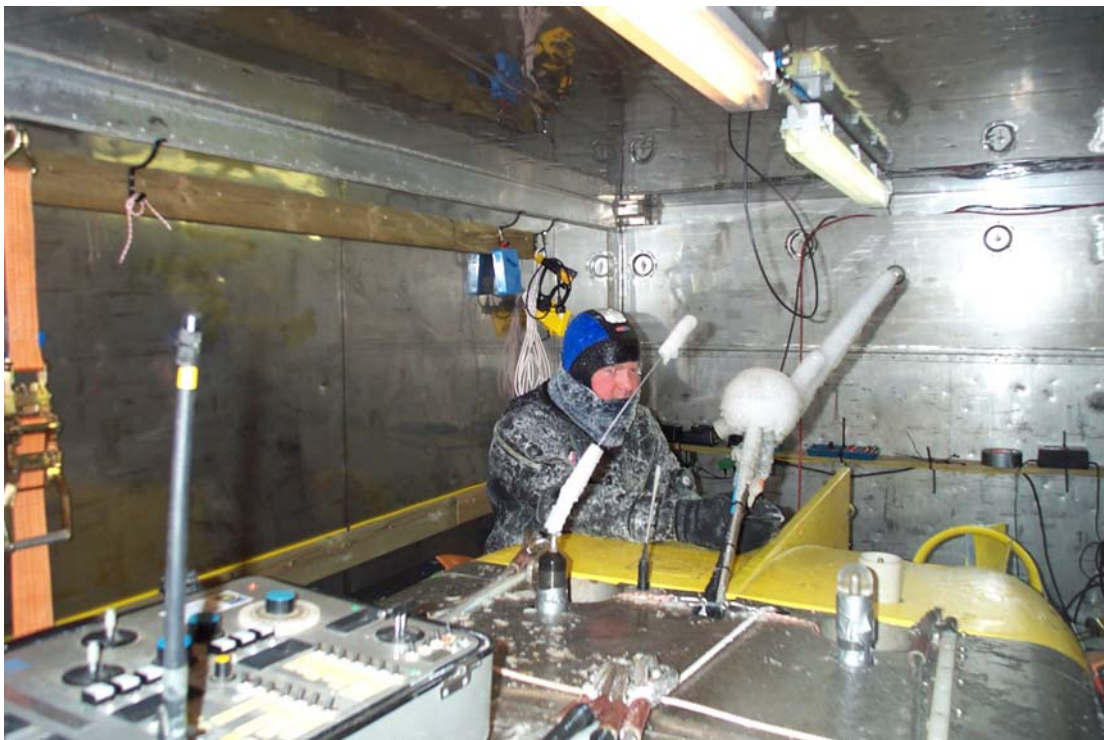


Figure 1. A diver in the Arctic with an AUV recovered recently from under the ice and now under cover.

UK Diving Under Ice Procedures

Although it is conceivable to undertake diving under ice in the UK, all current diving under ice operations occur outside the UK. Diving while at work in the UK is administered by the 1997 Diving at Work Regulations (DWR97) but these regulations only apply in law up to a limit of 12 nautical miles offshore; diving off UK-registered ships is covered through The Merchant Shipping (Diving Safety) Regulations 2002 (Sayer, 2004). However, many scientific employers accept the principles of “duty of care” for their employees and where this includes diving overseas then the DWR97 are recognized as industry best practice and are adopted as the preferred practice for diving where it is reasonably practicable. The DWR97 conform to a set of generic goal-setting rules and are implemented through the process of risk assessment and management (Sayer 2004). The procedures for diving under ice for UK employees, therefore, have been generated through the process of quantifiable risk assessment and management. In 2003, while snorkelling at Rothera, the UK scientist Kirsty Brown was drowned by a leopard seal (*Hydrurga leptonyx*; Muir *et al.*, 2006). Since that incident, the protocols for diving in Antarctica have been modified further and are discussed below.

The diving procedures employed by all UK divers when diving under ice have many common elements because of the desire to adhere to the DWR97 where reasonably practicable. However, there are differences in how some organisations interpret or implement the DWR97 and also organisational differences that are influenced by the ambient environmental conditions, indigenous predators or the remoteness of the diving operation.

Under the UK DWR97 there must be a Diving Contractor identified for each diving at work operation. The Diving Contractor will usually be the employer of those divers. There are instances where there is a practical reason for the Diving Contractor being at an organisational level that allows for more direct contact between the Diving Contractor and the person in charge of diving operations. The Diving Contractor has a legal responsibility to ensure that all diving operations comply with their own interpretation of the UK DWR97 (Sayer, 2004).

The number of people required to undertake any diving operation will be dependent on the type of diving being undertaken. In general, all diving operations will be controlled by a diving supervisor who must be appointed in writing by the Diving Contractor and reconfirmed by the person or persons who have been appointed by the Diving Contractor to oversee diving operations on their behalf. In order for that appointment to be made, the diving supervisor must be competent to supervise all elements of that diving operation. So, for example, if the diving operation is based on using mixed gasses then it is essential that the diving supervisor has the appropriate knowledge and proven competence to oversee a mixed gas diving operation. It is standard practice that all UK divers diving under ice employ lifelines to the surface. Therefore, for every diver there is a requirement for a dedicated tender and, even if employing a combination of a single main lifeline with a subsidiary buddy line running off the main line, a one diver to one tender ratio is recommended to aid kitting up and de-kitting of the divers. The final team member must be dedicated to being alert of the presence of any potentially dangerous animals in the vicinity of the diving operation. In the Antarctic the animal watch is initiated at least a half hour before the diving operation starts. Any presence of leopard seals or orca (*Orcinus orca*) in the vicinity of the diving operation will result in that operation being cancelled. If a leopard seal or orca is sighted during the diving operation then that operation has to be terminated. In the Arctic, the main risk is from polar bears (*Ursus maritimus*) and the observer must be armed and must be dedicated to task of looking out for bears. Again, any sightings of polar bears in the vicinity of the diving operation for 30 minutes beforehand and/or during the operation itself would result in the dive being aborted. Orca are also a potential threat in the marginal ice zone around the Arctic. So the team size for a diving operation should be a minimum of four: two divers, a tender, and a diving supervisor who will also act as the second tender. Where and when there is the requirement for a dedicated animal observer, the minimum team size will be five.

The DWR97 are based on a series of goal-setting regulations that are implemented through processes of risk management and risk assessment. These processes are outlined in detail by Sayer (2004) and are, therefore, only summarized here. Each diving operation must be identified as part of a diving project plan. The project plan is essentially a summary of all the diving operations that make up the project and may consist of a number of site-based and task-based risk assessments. In addition, there is a generic risk assessment for scuba diving that examines the minimum requirements for undertaking a diving operation employing scuba equipment. The specific potential risks associated with scuba are: the suitability of the individual diver (minimum training / certification levels; the medical certification required; the day by day dive fitness of the individual); the standard of equipment used and the performance of that equipment (maintenance and service requirements for equipment; the assessment of all equipment prior to a diving operation by a competent person to ensure that it is suitable, compatible and functional; guidelines under which to terminate a diving operation if there are any concerns over equipment

performance; guidelines on the standards of breathing gases and recommended volumes and rates of supply); the suitable size and make up of the total dive team (the minimum dive team for scuba; modification required to the basic dive team based on remoteness of location or specific tasks); the standard of the overall supervision of the diving operation and, specifically, the requirements and duties of the Diving Supervisor; the methods and suitability of communications over the whole operation (the suitability of communications between the Diving Supervisor and the dive team; the suitability of communications between the Diving Supervisor and third parties; the methods of indicating that a Diving Operation is underway to other water users, and more specific requirements if the diving operation is being undertaken in a port or harbour); the adoption of safe decompression procedures (the method of calculating decompression; any agreed limits or penalties on the chosen method of decompression calculation; guidelines on the use of computers for deriving decompression schedules; allowances for physical factors such as altitude, atmospheric pressure and temperature); the adoption of an evacuation plan in the event of an emergency (the provision of an agreed emergency plan for each diving operation; the standards of medical training and the numbers/posts within the dive team that require medical training; the provision of sufficient oxygen supplies for any diving operation; the availability and content of a medical supply kit; the availability of and transfer requirements to the nearest recompression chamber to the site of the diving operation); the safety of diver ingress and egress from the water (the acceptability of the ingress/egress routes; the guidance on diving from boats); the provision of suitable personal protective equipment (the types of protective equipment to prevent excessive environmental exposure; additional care for areas of potential contamination risk); and the assessment of manual handling risks through the specific provision of specific manual handling risk assessment for scuba diving. Because of the requirement to maintain the scuba risk assessment as generic to all diving operations, the content is also generic and only outlines the basic principles, guidelines and reference sources for diving at work for that specific institution. In order for specific diving operations to be planned and managed, the assessment of risk needs to be more precise.

The location of the diving operation will influence greatly the basic assessment of risk for scuba diving. An assessment of risk at a specific location is broken down into the following divisions:

Location: The assessment gives full details of where the diving operation is to be undertaken, making full reference to the ease of travelling to and from the site. Where the location is either remote or travelling times between the site of operation and a 'safe haven' are relatively long then this will influence how managing the risks associated with the operation is approached and the eventual make up and size of the dive team.

Tidal conditions: The location is assessed on the likelihood versus the severity of outcome of excessive water movements caused by tidal influences. A heavily tidal location will determine the times at which the diving operation can be undertaken in order to minimise risk. Again, the level of risk attached to the location because of tidal influences will determine the methodology of the diving operation as well as the membership of the diving team.

Ice dynamics: Sea ice near the coast or within a fjord is usually immobile because of it being pinned by coastal features; this ice type is known as fast ice. However, most of the ice in the Polar regions is under constant motion and, therefore, the dynamics of the ice needs to be taken into consideration before a dive. Even in the central Arctic, where ice concentration is at 100%, sea ice can drift at speeds above 1 m s^{-1} and higher speeds are possible at lower ice

concentrations. The drift of sea ice is driven predominately by the local wind conditions and, therefore, the drift of the ice may not necessarily be in the same direction as any underlying currents. Owing to the differential movement of sea ice within the Arctic Ocean it is constantly undergoing deformation. The ice can tear open to form leads or be forced together to form pressure ridges, both scenarios can be problematic during dive operation. It is not possible at present to predict when or where leads or ridges will occur and, therefore, observers on the ice surface should be vigilant. Dive operations occurring near an ice edge (within 200 km) should take into consideration the ocean swell. An increase in the energy of the incoming wave spectra could lead to the fracture of the ice cover, again putting the dive operation at risk.

Air/Water Temperatures and Weather Exposure: When planning Polar under ice diving operations the assessment of risk has to include the conditions for the divers below water as well as the conditions for the divers and the rest of the dive team above water. Obviously the temperature of the water in which the diver is operating will influence greatly the types of diving equipment used. However, in areas of extreme climatic conditions, the risk assessment should also consider the additional influences of likely surface conditions and the potential consequences of change. The assessment should also consider the personnel on the surface who may be more likely to be affected. The severity of outcome may increase concomitantly with the remoteness of the location and the duration of transport between the diving location and safe areas.

Underwater Hazards: The types of underwater hazard that could influence the risks associated with an under-ice diving operation should include underwater entrapment, iceberg grounding, iceberg collapse, no clear surface, water visibility, water depth, harmful biological life, and pollution.

Access to the Water: A number of considerations need to be made about how divers enter and leave the water when diving under ice. The main influencing factors will be the thickness and stability of the ice and the prevailing surface conditions. Ice conditions will influence surface transport which, in turn, will influence pre-dive exercise. Extreme exposures to cold weather prior to and following diving can alter the integrity and functionality of the equipment.

Recompression considerations: At present, DWR97 is highly prescriptive in how a diving operation should be planned with respect to emergency recompression. For dives with no planned in-water decompression that are less than 10 metres water depth then the legal requirement is to identify the nearest suitable operational two-person, two-compartment chamber within 6 hours travelling time from the dive site. For dives of between 10 and 50 metres water depth with either no planned decompression or up to 20 minutes planned in-water decompression, then a suitable two-person, two-compartment chamber should be identified within 2 hours travel time. Where in-water decompression of greater than 20 minutes is planned then there is a requirement to have a recompression at the site of the operation. Transport of a diver to a recompression facility within the above time frames is the main factor to be assessed and will be influenced by the remoteness of the location and the methods of transport available.

On completion of the above sections of the location risk assessment then an overall assessment of risk is made. There are a number of outcomes from that assessment: the location may influence the size and members of the dive team; the location may influence how or if the task of the diving operation can be conducted safely; and the overall assessment should generate an emergency protocol that would state clearly how, in an emergency, the diver would be

retrieved, what the on-site treatment would be, how transfer for on-going treatment would be achieved and managed.

Although there is no specific requirement under DWR 1997 to assess the risk of performing a specific underwater task, it is obvious that the task will influence the overall management of the diving operation. Effectively, a risk assessment for task re-analyses the issues addressed under the risk assessment for location (location, tidal conditions, air/water temperatures and weather exposure, underwater hazards, access to the water, surface traffic, recompression considerations) within the context of how the task to be carried out may alter that initial assessment. Similarly to the location risk assessment, the task assessment will inform the team size and the qualifications and experience of the team's membership. The task assessment should conclude with an overall task protocol that defines the stages within the planning and execution of the task along with the specific personnel responsible for each stage.

A significant problem associated with the process of risk assessment is that it can be viewed by operators as an administrative task rather than a dynamic tool for guiding the management of an operation. Although the DWR97 regulations state that every diving operation must be risk assessed, it was never the intention that this would result in numerous, repetitious and largely meaningless risk assessments. Conversely, there were concerns that the use of a single risk assessment to cover a large number of similar diving operations may result in diving supervisors overlooking day- or site-specific differences to the overall assessment. There is a legal responsibility on the diving supervisor to review all relevant risk assessments prior to the diving operation taking place. This ensures that the person with ultimate responsibility for the safety management of the diving operation is fully aware of the risks associated with the type of diving employed, and the location and task of the operation. By providing summaries of the work to be carried out, any manpower or procedural limitations on the operation and the protocols to employ in the event of an emergency, the site and task risk assessments provide the diving supervisor with easily accessible information covering the whole diving operation. The DWR97 state that there should be an entry on the diving operation record to confirm that the diving supervisor has read the appropriate risk assessments. In order to allow for any on-site occurrences that may differ from the original risk assessment, there is also a legal requirement for the dive supervisor to note in the diving operation record any differences and how they affected the safety management of the diving operation.

In line with the requirements of DWR97, the minimum qualifications for a UK scientific diver are set at an equivalent CMAS 3 star level that does not differentiate between professional or recreational qualifications. In addition, all divers must have an annual UK Health and Safety Executive Diving at Work medical and should obtain a First Aid at Work qualification. There are no real differences between these minimum qualification levels between diving under ice and other forms of scientific diving. However, because some divers are in position for more than 12 months in the Antarctic then a similar medical to the HSE one is implemented through the doctor on base. It is acknowledged that the procedures used for diving under ice do differ to other forms of scientific diving. For that reason, and in order to comply with the requirements for demonstrating competence, some form of training or familiarisation in the under ice procedures are usually undertaken before departure. The main competencies are use of full-face masks including emergency bail-outs, the use of life-lines, the use of voice communications and some

basic instruction on equipment protection and maintenance in the ice environments. In addition, it is standard UK practice that all divers who are employed in either Polar region are familiar with recompression chambers and their use. It is recognised by all UK diving operators that divers employed on any sustained scientific programme under ice or in extreme cold water conditions require an ongoing programme of familiarity with working in these conditions. If this familiarity is not maintained on an annual basis then divers should have one or a series of familiarisation dives in the Polar regions or in conditions approaching relevancy.

The actual form of diving employed under ice is illustrated in Figures 2 and 3. In Figure 2 it can be seen that the diver is kitted out with a standard drysuit configuration. In this example the diver is wearing neoprene wet gloves; gloves are usually of individual choice and can be wet, integrated dry or external dry. The diver is wearing an *Interspiro Divator AGA* full-face mask and the lifeline to the surface can clearly be seen; *Poseidon cyclone 5000* are used as the regulator first stages. Figure 3 gives a close-up view of the mask configuration. The main difference between the masks used by the UK scientific diving community and others is the modification of a manually operated bail-out block on the side of the face plate. This permits simple needle valve operated regulation of low pressure air into the system if required from a separate pony-mounted bail-out cylinder. Voice communications are usually through-water (although hard-wire systems exist and have been employed under ice) and work through a push-to-talk facility at the front of the mask that communicates through the transmitter/receiver unit that can be seen over the divers left ear in Figure 3. These through-water voice communication units permit communication between divers as well as between the individual divers and the supervisor at the surface.



Figure 2. The typical equipment configuration for a UK scientific diver diving under ice. Note the use of full-face masks and lifelines.



Figure 3. A close-up of the full-face mask configuration with manual bail-out side valve connected to a rear-mounted pony cylinder and push-to-talk voice communications with ear-mounted transmitter/receiver.

The use of lifelines for diving under ice in UK diving operations is mandatory. A number of lifeline configurations can be employed and the type of usage is determined by the process of risk assessment and management. The basic configuration can either be individual lifelines per diver, or a single lifeline per diving pair whereby the second diver is attached to the main lifeline through a secondary, usually sliding, buddy line. The variety in employment is determined by the environmental conditions and the work that is required to be undertaken and so could be any combination of positive, negative or neutrally buoyant lifelines and/or buddy lines. The weight and thickness of the lifeline has to be such to support and retrieve the diver/divers; it also has to be of a thickness that is practicable for handling with heavy hand protection. It is essential that the surface end of the lifeline is secured to the ice, usually by an ice screw, in order that the end is not lost in error. Attachment of the lifeline to the diver is a compromise between ensuring that it cannot become detached by accident but that it is also able to be released if needed. The usual method of attachment is by a lockable carabiner. Although voice communications are employed as standard on all lifeline dives, it is essential that the diver and tender are competent and continually trained in the use of manual rope signals in the event of a loss of voice communications.

The use of the AGA full-face mask does require a degree of discipline in order to maintain performance under ice. In particular the diaphragm cartridge traps water, either seawater from the dive or freshwater from the washing process. Therefore, the cartridge needs to be dried between dives (see Fig. 4). With the AGA this is a very straightforward operation that can be achieved easily and quickly. However, it is essential that the diver and supervisor check the locking ring on the diaphragm cartridge before each dive to ensure that it has been tightened appropriately. Another simple method of protecting the masks is to construct lined wind and

water proof bags for the masks (Figs. 5a and b). The masks are kept in the bags during transport and only removed at the final moment before commencing the dive. As with all diving under ice, avoiding purging the regulator before or during the dive reduces the potential for free-flow. Because of the full-face nature of these masks, there is also added thermal protection to the diver.



Figure 4. The between-dive routine maintenance for the AGA masks consists of opening up and drying the diaphragm cartridge which traps water easily.



Figures 5a and 5b. The full-face mask is protected during transit out onto the ice with a lined wind- and water-proof bag (a). The mask is inserted into the bag (b) with the draw string tightened and kept in the bag right up to the final point of kitting up.

All diving under ice operations employ decompression tables to manage the dive profile. It is normal practice for the dive plan to outline the maximum permitted depth and then the supervisor to state the time allowed for that dive. The tables used tend to be the DCIEM tables in the Antarctic and the Bühlmann 1986 tables elsewhere. The DCIEM tables were introduced to BAS following several cases of suspected cutaneous decompression sickness. Their introduction has resulted in no further cases. The DCIEM tables do produce very conservative dive profiles and their development was based on cold-water diving (Lippmann and Mitchell, 2006). When

employing the Bühlmann tables a further level of conservatism has to be added by the diving supervisor in order to compensate for cold but also for atmospheric pressure differences. In general an altitude penalty is employed for all decompression planning. Dive computers are used but only to monitor depth and time and to provide records of the dive profile where necessary. Dive computers will also permit the use of altitude penalties.

Discussion and Conclusions

The UK scientific diving sector has a good safety record that is comparable with other scientific diving groups around the world (Sayer and Barrington, 2005; Sayer, 2005). There is nothing in the statistics to suggest that diving under ice produces proportionately any more incidents than other forms of scientific diving. However, it is acknowledged that diving under ice does carry the potential for increased risk and challenges and it is suggested here that the lack of any significant elevated incident rates for under ice diving is because of the extra precautions taken for diving in under ice environments. Although probably directly linked to the use of snorkelling, the leopard seal attack in the Antarctic has resulted in a more rigorous approach to dealing with the threats from large top-predators in both Polar regions with set protocols and risk assessments. As with all diving in very cold water the performance of regulators under water continues to be a major operational concern. By adopting more disciplined approaches to maintaining, drying and protecting the regulators used, regulator malfunction is now a relatively rare occurrence in UK scientific diving operations under ice. At present, the UK ice diving community is continuing to employ full-face masks with alternative bail-out cylinders and valves, life-lines and voice communications. In addition it is unlikely that the UK community will move from planning and executing dive decompression schedules using decompression tables that are either conservative in design or in their use.

Acknowledgements

The authors acknowledge the valued input, comment and images from current and previous Field Diving Officers at the Antarctic Rothera Research Station: Kelvin Murray, Matt Brown and Hugh Brown.

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METHODS AND CONSIDERATIONS FOR SCUBA DIVING BELOW ANNUAL PACK ICE IN ANTARCTICA

Langdon B. Quetin

Robin M. Ross

Marine Science Institute

University of California at Santa Barbara

Santa Barbara, CALIFORNIA 93106 U.S.A.

Introduction

Three types of pack ice can be delineated: seasonal, perennial and marginal ice zone (Eicken, 1992). During the annual growth and melt cycle the proportion of each type varies which, in turn, means that the ecological habitats provided by each vary in space and time. Seasonal pack ice is a circumpolar environment that grows each fall, and shrinks each spring, covering a vast area at its greatest extent. In the winter and spring seasonal pack ice has phytoplankton/ice algal standing stocks that are 1 – 3 orders of magnitude higher than in the water column immediately below. This annual phenomenon thus provides a source of food for grazers (microheterotrophs, copepods, euphausiids) during times in the annual cycle when food resources in the water column are low. The process of formation of seasonal pack ice involves frazil ice formation scavenging particles from the water column, congelation into pancake ice and aggregation into ice floes. Once the floes are 0.5 to 0.7-m thick, the annual ice only thickens by processes of deformation, particularly over-rafting. The seasonal pack ice, particularly the zone of highly over-rafted ice, is a favored habitat of Antarctic krill (*Euphausia superba*) in winter (Marschall, 1988; Smetacek *et al.*, 1990; Quetin *et al.*, 1996; Frazer *et al.*, 1997; 2002). The perennial pack ice, in contrast, is a mixture of annual and primarily second year sea ice and the water column below perennial pack ice tends to have even lower phytoplankton concentrations than that of seasonal sea ice due to the increased light attenuation.

For decades, investigators have noted the coherence between the northern limit of the seasonal sea ice zone and the northern extent of the habitat of Antarctic krill, with the exception of krill around South Georgia (Marr, 1962; Laws, 1985; Siegel, 2005). This coherence led investigators to postulate a key role for seasonal pack ice in the life cycle and population dynamics of Antarctic krill. Over the years, three facets of the influence of seasonal pack ice on the population dynamics of Antarctic krill have emerged: (1) the annual retreat and melting of the seasonal pack ice sets up the conditions for diatom blooms in the austral spring, thus providing an important and timely food resource for female krill to bring them into spawning condition; (2) the presence of sea ice microbial communities (SIMCOs) in the winter provides larval krill, that are not resistant to starvation (Elias, 1990; Ross and Quetin, 1991; Quetin *et al.*, 1996), an alternate food source during a time when food in the water column is at an annual low; and, (3) the pattern of sea ice retreat in the austral spring may influence the pattern of distribution

of Antarctic krill during the following summer, as it is postulated that the adult krill follow the retreating ice edge during the early spring months.

The pack ice environment is dynamic, on both seasonal and shorter time scales, which creates challenges for investigators. Scuba diving and observations of both the habitat and its inhabitants has played a key role in revealing the mysteries of the seasonal pack ice habitat. Some of the earliest observations of Antarctic krill under the pack ice were made by United States Coast Guard (USCG) scuba divers during fall (March 1986) and spring (November 1983) cruises in the Weddell Sea for the Antarctic Marine Ecosystem Ice Edge Zone (AMERIEZ) program (Daly and Macaulay, 1988; 1991). Subsequently, Kottmeier and Sullivan (1987) reported larval krill feeding in the under-ice habitat in late winter 1985 west of the Antarctic Peninsula during the first of a series of six winter cruises (WinCruise I). O'Brien (1987) observed both Antarctic krill and ice krill (*Euphausia crystallorophias*) in the under-ice habitat in austral spring of 1985. Hamner *et al.* (1989) found larval krill in the austral fall 1986 associated with newly forming sea ice. In all cases, the investigators observed larval krill in higher abundance associated with the sea ice than with the water column and also observed larval krill feeding on SIMCOs (Fig. 1). Complimentary observations were made from investigators on board ships both west of the Antarctic Peninsula in September through October (Guzman, 1983) and in the Weddell Sea in spring (Marschall, 1988).

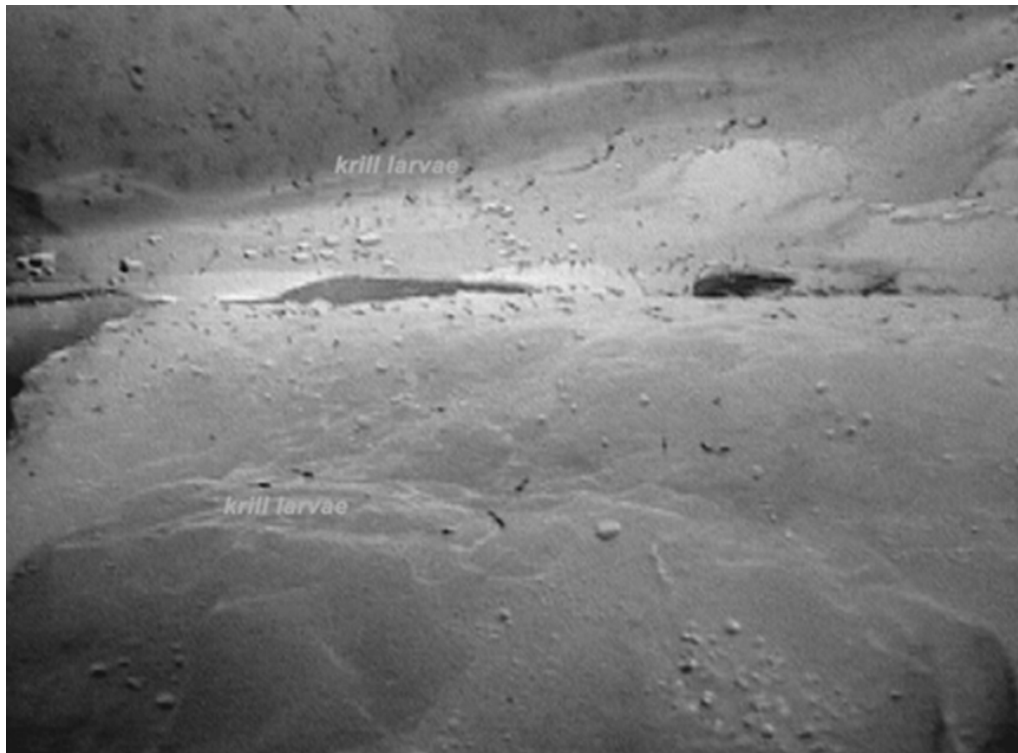


Figure 1. Larval krill feed in the pack ice environment. Note the 2 larvae feeding on the upward facing surface (above lower label) and the three larvae feeding on the downward facing surface (above upper label). Photograph by Langdon Quetin.

Our involvement started with a series of cruises we coined “the WinCruise series” when the Office of Polar Programs, National Science Foundation, first chartered the *R/V Polar Duke* (Fig.

2). This ice-strengthened ship allowed us to operate more consistently in winter than in the past. On the WinCruises we were encouraged to invite participants from other funded programs so the cruises were multidisciplinary in nature but oriented toward pack-ice work since our primary aim was to explore the interaction of krill with this environment. The first pack-ice diving and observations of larval krill under the ice on these cruises took place during WinCruise I in 1985 when a team of two divers, Richard Moe and Todd Roberts, working with Dr. Neal Sullivan, dived to investigate the SIMCOs associated with the underside of the ice. Our diving work began on WinCruise II when we began work on physiology and distribution of krill larvae found on the underside of the ice. Since 1987, we have participated in many additional cruises where pack ice diving has been a primary tool used in our research (Table 1).



Figure 2. Divers, Dick Moe and Todd Bates, prepare to dive from an ice floe in 1985 (WinCruise I, Table 1) with the R/V Polar Duke in the background. Note the two-hose regulators and lack of a tether setup. Dive tenders are out of the picture. Photograph by Skip Owen.

Table 1. Diving Projects by the authors at Palmer Station and on cruises in the Southern Ocean. W - WinCruise krill studies to Ross and Quetin, K - krill studies to Ross and Quetin, L - Palmer Long-Term Ecological Research project, A - Antarctic Pack Ice Seals research project .

Pal Sta	Year	Cruises												Ship	
		fall			winter			spring			sum				
		A	M	J	J	A	S	O	N	D	J	F	M		
	1985				W	W									<i>R/V Polar Duke</i>
	1986														
	1987			W	W										<i>R/V Polar Duke</i>
	1988														
	1989				W										<i>R/V Polar Duke</i>
	1990										K				<i>R/V Polar Duke</i>
L	1991		K			W									<i>R/V Polar Duke</i>
L	1992														
L	1993	L	L	W			L								<i>R/V Polar Duke</i>
L	1994			W	W										<i>R/V Polar Duke</i>
L	1995														
L	1996														
L	1997														
L	1998														
	1999			L											<i>ARSV L. M. Gould*</i>
L	2000										A	A			<i>RVIB N. B. Palmer*</i>
L	2001				G	G	L	L							<i>LMG (GG) NBP (LL)</i>
L	2002					G	G								<i>ARSV L. M. Gould</i>
L	2003														
L	2004														
L	2005														

*ARSV Laurence M. Gould, RVIB Nathaniel B. Palmer

The goal of this report is to describe some of our diving practices and the considerations underlying the evolution of those practices whether it be the experience of the divers, the science questions and, of course, the nature of the particular pack ice environment being studied. We hope that others will gain from and build on our diving experience in pack ice when developing safe and productive programs in the future.

Diving Environment

Ice types

In this report we are discussing our diving experience with seasonal pack ice encountered mostly between the southern Bransfield Strait and Alexander Island west of the Antarctic Peninsula. Our diving experience ranges from diving below recently formed pancake ice to highly over-raftered pack ice with keel depths to 20 m (Fig. 3). However, most of our diving experience has been in 50 - 100% ice cover with floe drafts caused by over-raftering less than 7 m.

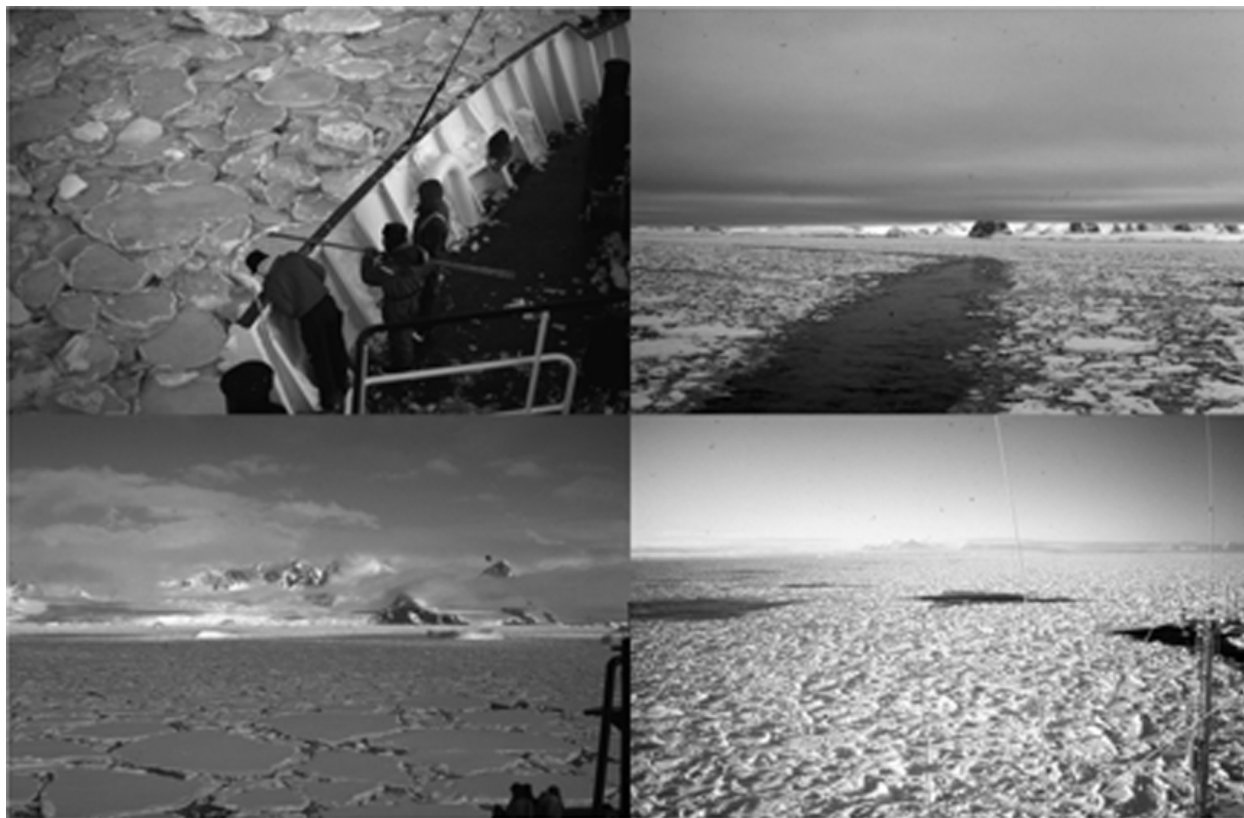


Figure 3. Examples of different pack ice encountered during diving operations. UL - Pancake ice starting to over raft. UR - Ship's track through loose pack ice in early spring. Ice algae appears as dark areas in the over-turned ice at the edge of the ship's track. LL - Searching for the most suitable dive entry among ice floes. LR - Highly over-raftered ice cover with open areas suitable for diving.

Visibility

Optimal diving with natural light during winter west of the Antarctic Peninsula is from 1000 to 1500. Depending on the science activity, these hours can be extended with the use of the ship's spotlights. Generally, visibility in the water is greater (often much greater) than 50 m during winter and need not be much of a concern during a dive unless diving early or late in the day. However, during spring phytoplankton blooms visibility can be restricted to less than 2 m and is of concern. Generally, we do not dive, even when tethered, to distances beyond our ability to discern, even if vaguely, the entry hole if multiple exits do not exist in the vicinity, since a break in the tether would leave us with no redundancy.

Weather

Assessing the effect of weather on the particular pack ice area prior to and during a dive is the most important consideration when pack ice diving. There is no one answer or limit to dealing with weather conditions since different types of pack ice respond to weather differently. Generally, smaller floes with shallower drafts respond much more quickly and to less severe weather conditions than larger floes with deeper drafts.

a. Wind Velocity

When ice is pushed through the water by wind, it drags some water along with it. The result of this drag is a current relative to the ice that increases with distance from the ice keel because of a decreasing drag effect. This limits the usefulness of setting absolute limits for diving conditions and places more emphasis on assessing conditions prior to, and during, a dive. For example, diving below pancake ice is difficult in 10-15 kt winds but diving below the edges of large perennial floes, kilometers in diameter and with deep keels found in the eastern Ross Sea, can occur in 40 kt winds. Further, if wind changes velocity during a dive larger floes may lag in their response long enough for the dive to finish. West of the Antarctic Peninsula we cannot operate in the high wind conditions described above because the floes are much smaller than the large perennial floes in the eastern Ross Sea. If diving in any moderately strong but acceptable current relative to the entry hole, the diver and dive planning need to keep in mind that the current 5 to 10 m and further below the ice may approach the swimming limits of the diver. Another point to consider is that in some situations ocean currents may create a strong current relative to the ice in low wind conditions if there is not much ice movement. This places added emphasis in heavy pack ice conditions of assessing the current relative to the entry hole immediately prior to diving and at the beginning of a dive. The key to pack ice diving is to constantly assess the effect of wind velocity on the ice relative to diving conditions during the cruise.

b. Wind Direction

Similar to the discussion of wind velocity, wind direction also needs to be monitored closely prior to, and during, a dive. Smaller floes and loose pack respond more quickly than larger floes to changing wind direction. Switches in wind direction may be magnified if the new wind direction opposes a prevailing ocean current. West of the Antarctic Peninsula winds from the northeast generally compact the pack ice; winds from the southwest loosen it. Ice is more compact on the weather side of an island than on the leeward side. Similarly, icebergs often move with the prevailing ocean currents and plow through pack ice creating, in effect, a weather and lee side regarding the compactness of the ice. During winter it is common to cross loose pack channels created by the movement of icebergs through the pack ice.

c. Distant Effects

Pack ice may change at times without warning. More locally, this can happen when icebergs plow through pack ice toward a dive site, creating a pressure front on the ice caused by the relative difference between a current-induced direction of the iceberg opposing the wind-induced direction of the pack ice. The pressure wave in front of the iceberg is much more of a concern to a diving operation than the trail through the ice left by the berg. Also, and more distant, strong storm fronts far from a dive location experiencing light winds may also loosen or compact the ice without warning. Though this happens rarely, it reinforces the need to always be aware of the larger weather picture and of conditions at the dive hole during a dive.

d. Precipitation

Snow and sometimes rain are a feature of pack ice cruises and gear needs to be kept dry and dive tenders kept warm. Generally, on cruises we bag the second stages of our regulators before loading to leave the ship. This keeps them dry and helps prevent freezing prior to, or when starting, a dive. In addition, we tape the ends of our dry suit inflator hoses with electrical tape to

keep snow from clogging the open end making sure there is an adequate 'tag' end for easy removal. The inflator hose for the buoyancy compensator is connected prior to transport off the ship.

Regarding precipitation increasing wind chill, divers should keep in mind that topside conditions are more difficult and often colder for the dive tenders than the divers who are diving in water at a relatively balmy -1.8°C , while the tenders may be sitting in temperatures of -25°C with winds of 20 kts.

Diving Platforms

a. Ships

We have never used a ship as the primary diving platform in pack ice. But ships do deserve separate mention since the capability of the ship to penetrate pack ice during a cruise will dictate the maximum pack ice conditions the divers will experience. Our experience and observations have been limited to three ships that are not powerful icebreakers (Table 1), an important point to keep in mind considering our ice-diving experience.

b. Zodiacs

The Mark V zodiac is our primary diving platform (Fig. 4). Even in heavier pack ice it is generally easier to launch and recover a diver from the zodiac than directly from the ice. It is much easier to lean over a zodiac pontoon than from the edge of an ice floe to help the diver and retrieve samples. A motor on the zodiac is useful only in loose pancake ice or diving in large leads. In all other ice conditions we remove the motor from the zodiac to prevent it from getting damaged by ice floes. Compression also occurs when the ship moves floes during its approach to retrieve the zodiac and divers.

We have found the MKV zodiac a very reliable platform from which to dive. It provides enough room for science and diving equipment and four to five people, keeps dive gear snow-free, is soft-sided and easy to exit and enter and provides good flotation if conditions change and compress the ice, which is generally true when the ship arrives to retrieve the team in 7-10/10 pack ice.

c. Ice Floes

During early cruises we often dived directly from floes but soon found diving directly from a Mark V either partially on, or beside, a floe much more advantageous (see above).

d. Ice Holes

If the pack is consolidated enough to form floes of 50 m or greater diameter and the ship can remain stationary at the edge of the floe, we often will dive through holes cut through the floe. The effort spent opening the holes pays off if the holes are to be occupied during a series of dives and preferably over many days. Holes are cut in the pack ice with thicknesses of less than 1 m with a chain saw. The shape is a triangle approximately 3.5 m on a side, enough room for two divers and making it easy for the diver to rest in a corner and for a tender to assist. A series of manageable ice blocks are cut to open the hole. An ice screw is attached to each ice block which

then can be lifted easily from the hole by two people on either end of an attached line. The ice blocks are used to mark the hole and make good benches near the hole for divers and tenders.



Figure 4. Diving from the Mark V zodiac. UL - Divers and tenders being lowered to the water from the rail of the ship. UR - Dive tenders collecting samples and taking notes from divers. LL - Ship moving into position to pick up the dive team. LR - Ship standing off from the divers during a dive in heavy pack ice.

Sampling Requirements

Sampling requirements will vary widely depending on the science involved. Our activities included:

- swimming beneath ice floes with a hand-held light meter attached to a surface computer;
- deploying sediment traps;
- monitoring nets fishing below an ice floe;
- the use of suction samplers to vacuum the underside of floes to assess the SIMCOs at the ice/water interface;
- the use of meter tapes to quantify krill larvae along 30-m transects;
- measuring the draft of ice floes with an air tube;
- the use of pneumatic drills;
- the use of still and video cameras; and,

- using our most-used tool, a 3-inch aquarium net to catch krill larvae.

With use of any type of equipment in a blue-water ice diving situation, consideration needs to be given to minimizing the impact of the equipment on the buoyancy of the diver and ensuring that it can be used effectively while the diver is on a tether. In some instances, the diving conditions may dictate whether a specific piece of equipment can be used safely and effectively. For instance, a diver with a tethered light meter cannot dive in as strong a current as a diver with only an aquarium net or camera; it is of little use to use a camera when the visibility is low. Most importantly, when diving in an overhead environment, exhaust bubbles need to be managed so as not to impact the measurements or observations.

Ice diving

Equipment

Throughout the years we have striven to restrict variability in our equipment to minimize the number of spares, and thus the cost, and effort needed for a season or cruise. Thus, the equipment used may not be the most current or even the best but we have consistent experience with it. We use Viking Pro dry suits. Originally, the suits came with the inlet valve at waist level and these have been moved up to the sternum which makes them more accessible and unobstructed. For head protection we use a polypropylene hood covered by a neoprene hood that is covered by the latex hood attached to the dry suit. The latex hood can fill with air if the diver does not properly manage exhalation but this is easily remedied by rolling to one side and burping the hood. Some of our divers prefer to punch a hole to the latex hood and have it vent freely; we leave this to personal choice. We provide a variety of fins and glove arrangements since these items often involve personal preference and are important to the comfort and warmth of the diver. Glove arrangements vary from 1-2 pairs of liner gloves covered by a thin, 5-finger rubber glove to thicker 5-finger insulated gloves that impart less dexterity. We use Zeagle buoyancy compensators with a soft backpack but more out of tradition since they were the first we purchased. Buoyancy compensators with a hard backpack are much easier to don and doff and hold the cylinder better.

We have made several changes over the years based on experience. We switched from Scubapro regulators to Sherwood Maximus regulators when the diving statistics at McMurdo Station found that the Maximus had the lowest probability of freezing. Our experience has been similar to the results at McMurdo and this move was obviously a very important improvement to both diver safety and getting the job done. We also switched from weightbelts to Diving Unlimited Incorporated (DUI) weight harnesses. These harnesses not only hold the weight more securely and allow for dropping half the weight at a time but are much more comfortable for the diver. We have also added wrist straps that lie over the outer glove at the wrist seal to better keep the wrist rings in place during entry. This arrangement helps keep the wrist rings from coming off which, in most situations, leads to termination of the dive. Along these same lines, we insist that divers use fin keepers, since losing a fin is not trivial when on a tether dive and often in a current.

Divers and Training

Most of our divers are volunteers, upper-division university students or recent graduates, have taken a university scientific diving course and have some scientific diving experience off the coast of California (Fig. 5). They are, therefore, used to diving in cold water when encumbered by wetsuits and some lack of dexterity from neoprene gloves. They are also used to diving in surge, low visibility and in kelp forests. All of the above gives them some advantage when adapting to the conditions of pack-ice diving. However, not all of our divers have had this experience and the most important attribute we are look for in divers is their comfort in the water, especially with the equipment and techniques they will be using in pack ice.



Figure 5. Dive volunteers on the winter 2002 cruise of the Southern Ocean GLOBEC program. Left to Right: Karina Johnston, Allan Willis (behind), Charles Boch and Eric Hessel (U.C. Santa Barbara Dive Safety Officer).

Most of our divers have no drysuit experience and diving in Antarctica will be a first. Because of this, and the need to assess them in the water prior to deployment, we conduct a drysuit-training course. During this course we are able to bring our group together and go through a progression that ensures they are competent in the suits and familiar with the scientific equipment that will be used in the field. The key to this progression is to introduce the divers to our operation in an unimposing sequence of steps and allow them time to get comfortable with each step.

We first meet to explain the diving program and guidelines set by the Office of Polar Programs for Antarctic diving, fit divers into drysuits and explain the dive gear they will be using. We also note that we work together, meaning that we help each other when donning the drysuits, help adjusting neck seals, and help each other putting on gear and attaching hoses and clips prior to a dive. There is no more dangerous diver than an experienced diver with unfamiliar gear who thinks he needs to show independence. Following the diving and drysuit orientation are pool sessions. In the pool sessions we follow a progression, insisting that the diver be comfortable with each step before progressing to the next activity. The first pool dive is with the divers in drysuits and without gloves. During the initial orientation to the suit and equipment we stress that buoyancy control during a dive is done only with the drysuit, with the buoyancy compensator empty. We stress the fact that controlling two buoyancy sources is difficult and the buoyancy compensator should only be used if the drysuit is incapacitated and to float the tank removed at the end of a dive. First dives are solely about buoyancy control using the drysuit and divers generally master this in 1-2 dives. We then add gloves, similar to what will be used when diving in pack ice, and go through the same exercise again. After that, we introduce the divers to the tether system and equipment they will be using in the field. Generally, with our divers, the tether system presents more of a problem than adjusting the nuances of buoyancy control with a drysuit. During training with the tether we create an overhead surface and do many of the activities we will do in the field. Another exercise is to tangle the divers in the tether. The key to this exercise is to ensure that, even when tangled, divers maintain their buoyancy first and then slowly work toward freeing themselves or seeking help. There is no bottom to rest on when diving in the open ocean.

Pool sessions are complete when the divers are comfortable and easily maintain their buoyancy with the drysuits, glove arrangements, tether system and simulated science tasks. We purposely set no timetable for the completion of pool sessions so the divers feel free to explore the nuances of our operation without the pressures of a time constraint but divers are usually bored with the pool after three half days. Ocean dives from a boat are next so the divers can adjust to diving the drysuits to depths of 15 - 20 m in more realistic conditions. These dives have always been uneventful but serve to give the divers more experience and mold the group together.

Diving Methods

Prior to beginning diving west of the Antarctic Peninsula we generally do dives at Palmer Station to adjust weights and experience polar diving for the first time (Fig. 6). This is the first time the divers are in full undergarments so some weight adjustment is usually required and some may want to change their glove arrangement for greater warmth. These dives are at the Palmer Station dock, in loose pack ice (many exits) and from a zodiac tied to shore beside the dock. Divers enter the water in 3-5 m of water and can swim down to 15 m. These dives are limited to around 25 min so the divers can test the limits of their glove arrangement without getting too cold. We dive only one novice diver at a time with a diver experienced with polar conditions and progress at the new diver's pace, first with weighting and buoyancy control and then exploring deeper water. Divers usually come up from this first dive amazed at how warm they feel and excited about their experience but often wanting to adjust their glove arrangement since their hands start getting cold towards the end of the dive. Divers usually need only one dive to feel comfortable enough to begin working but some take longer and, in a few instances,

the polar orientation dive has indicated that the new diver will not be comfortable with pack ice diving.



Figure 6. Pack ice in front of Palmer Station during winter.

a. Palmer Station

Pack ice diving at Palmer Station is done in many different ways depending on ice conditions. We dive from a zodiac tied to shore, from fast ice over a bottom if less than 30 m, from fast ice over depths greater than 30 m and from a zodiac in a pack ice field over deep water.

When diving from a zodiac tied to shore we dive in loose pack on an incoming tide and in calm conditions. The key words here are loose pack meaning exits between floes and calm weather. If the weather is variable then dives either need to be shortened or have more frequent communication with the surface in case conditions change. Deploying a zodiac, even if tied to shore, makes these dives much easier, especially when collecting samples.

When diving from fast ice we try to position the hole to be within range of the pack ice inhabited by larval krill. If the dive hole is over water less than 30 m deep we will drop a down line with flags and strobes to mark the hole but will not be on a tether if we can see the bottom. If the bottom is at greater depths than 30 m, or we cannot see the bottom from the dive hole, we will dive with a tether. When on tether we do not dive further from the hole than we can orient to the hole without the tether. In rare cases, *e.g.*, east of the Ross Sea in the austral summer, we have had to terminate the dive because of 3-4 m visibility.

b. Cruises

During cruises we always dive on the tether system mentioned above. Dives on cruises are over deep water and visibility is usually around 200-300 m. The system we use is based on the experience of blue-water scientific divers with some modifications specific for our requirements (tether system, Fig. 7). The system consists of a 1.2-cm braided-nylon down line that is tied to a swivel at the apex of a stainless steel horse shoe. This line is secured at the other end to the zodiac or an ice screw if diving through a fast-ice hole. In addition, a float is secured through a loop in the down line to ensure that the suspended horse shoe remains at a constant depth (usually 3-4 m) and offers redundancy to maintaining the tether system should the knot at the surface come loose. An 80-g weight is attached to each leg of the horseshoe and at the end of each leg is a 2.5 cm I.D. stainless steel ring that swivels and through which runs a 3-mm diameter 30-m long Dacron tether line. The line is kept thin to minimize drag. At one end of the tether is 80-160 g of weight and a plastic disc which keeps the line from going through the ring. At the other end of the tether is a 2.5 cm I.D. stainless steel ring (that cannot go through the ring on the horseshoe). Each diver is attached to the tether by a spinnaker shackle with a quick release. This shackle is attached to the left side of the diver and can be opened with either hand if necessary. Generally, divers swim with the tether line extended (still attached to the spinnaker shackle) with their left hand to keep it free from their fins. The weight at the opposite end of the line keeps light tension on the line to make it manageable. Divers quickly become accustomed to the tether system after a few pack-ice dives.

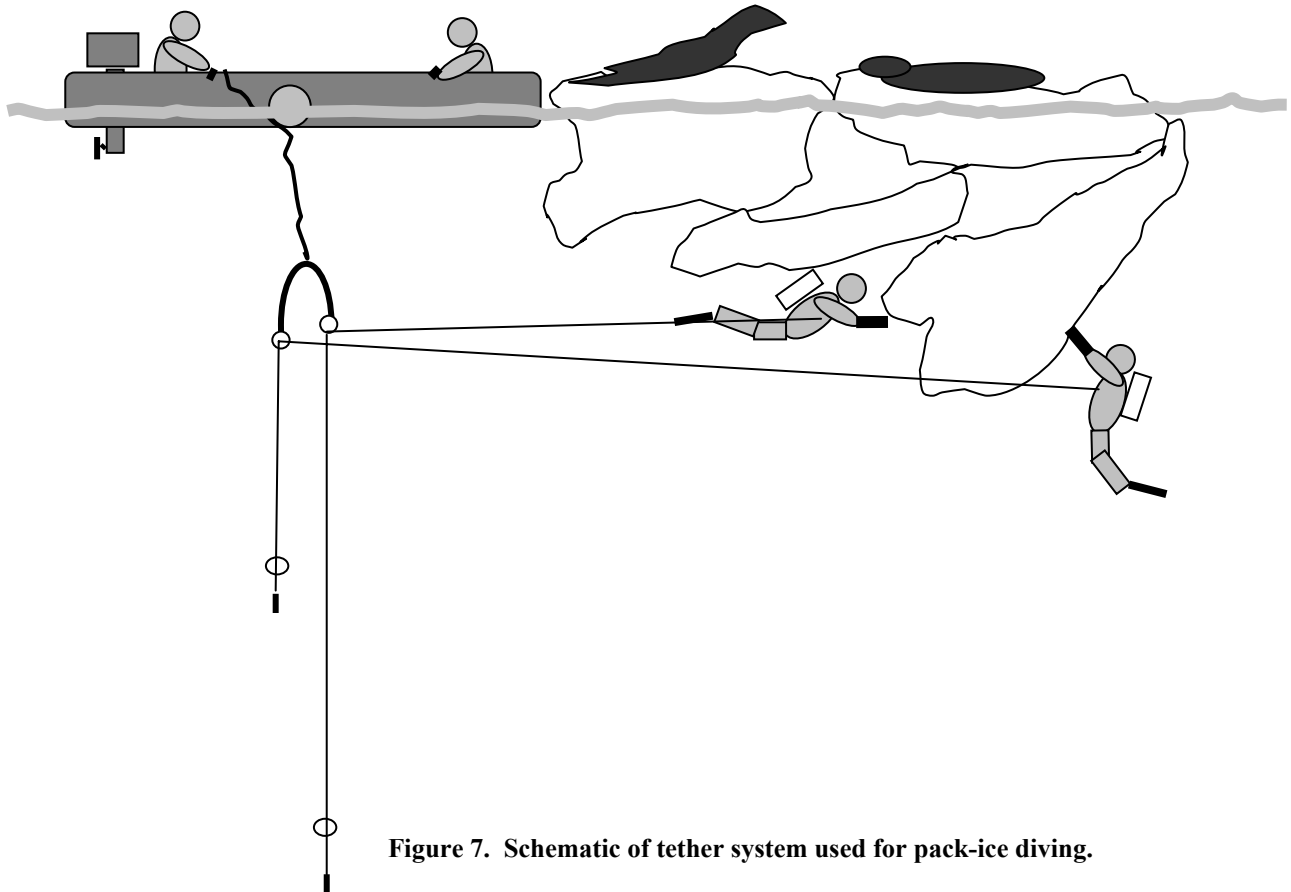


Figure 7. Schematic of tether system used for pack-ice diving.

Note that the tether system accommodates only two divers, the minimum number needed for a dive. We consider using the minimum number of divers during a diving operation a safety issue since divers may need to be retrieved from the water quickly should conditions change rapidly. If the need arises to put more divers into the water, we would recommend using an additional dive team of 4 people.

Diving Operations

a. Ship Operation

Since the most important part of any dive in pack ice is picking an adequate location and monitoring topside conditions prior to, and during, the dive, a good working relationship with the captain and bridge officers is essential. We have been most fortunate in this regard and the captains and officers of the ships we have sailed on have been strong partners in our success. A dive day begins with assessing weather conditions far and near with the captain and assessing the local ice conditions. If the weather window looks suitable we begin looking for a suitable dive location. Most often this is not difficult but in heavy pack finding a suitable dive entry can sometimes be tedious since we search for a particular floe configuration. We search for a configuration where three floes form an entry that is roughly triangular and which will not close easily with increased pressure as will a small lead between two floes. Note, however, that although we never dive in pack ice when there are not multiple exits, we consider that the use of an alternate exit is a serious mistake on our part and have been fortunate to never need one.

Depending on ice conditions, we have used many different configurations between the ship and divers. Least desirable is to move the ship forward, drop the zodiac by the side of the ship and have the ship back down. If there is little pressure on the ice the resulting jumble left in front of the bow is suitable for diving but the wash of the ship when backing down disturbs the pack ice community. Early in our experience we dived on the inside edge of a circular ship wake. After dropping off the divers the ship made a circle and stood bow toward the divers at a distance of a few hundred meters. Diving in this manner left an undisturbed environment under the ice since the ship's thrust was vectored toward the outside of the circle. More recently, we have found that the ship's thrust (partly caused by shrouded propellers) is very localized and that dive operations can be carried out within a crane's length of the ship with no disturbance to the pack ice community. In fact, as we will discuss later, when diving from an ice hole in consolidated pack the stern of the ship can serve as an additional safety exit.

Not enough can be said about the importance of keeping an eye on weather when pack ice diving. Rapid weather changes that cause shifts in the pack ice are the greatest worry. During preparation for a dive, and during a dive, we ask the bridge to notify us if the wind shifts by 10° or increases by 5 kts. Thus, the bridge serves not only as an early warning system that weather, and therefore ice, conditions may be changing but also provides redundancy to the dive tenders who are also monitoring ice conditions at the entry point.

b. Zodiac Operation

During all of our ice diving activities, none has been more controversial (but essential at times) than deploying and retrieving divers by lifting the team in a MKV zodiac (Fig. 4). Early in our experience with pack ice diving we found that in many situations the zodiac needs to be

swung over the ice with the diving team aboard and placed at an appropriate entry site. We also found that during retrieval the ship may have difficulty closing on the zodiac and we needed an approach for picking up the dive team easily and quickly at some distance from the side of the ship. Early in our pack ice diving experience we worked with captains and crew to ensure that the MKV could be picked up safely with the dive team aboard and, since those early trials the zodiac lift has been an essential element of our diving success, incurring no mishaps in over 300 lifts. Our current method when the zodiac lift is needed is to load the zodiac on deck, board it at the rail of the ship with the team spreading to the four attachment points of the harness, lower the zodiac to just above the ice and swing it outboard toward a suitable dive location in the pack ice. Retrieval is the reverse procedure. To help ensure safety we add a soft line (cargo strap) and hook to the heavier hook of the crane and attach a tag line to the hook, making it easier and safer for those aboard the zodiac to guide the hook to the lifting harness during retrieval. We have continually modified the system and now replace the 3/8" eyebolts in the zodiac with 1/2" eyebolts with larger backing plates at both the transom and thrust board. We also attach cargo straps to the harness that crosses beneath the zodiac at the stern and bow as added protection. We have never had to depend on these straps; it is important with this method to have the zodiac fully inflated.

We most often use the zodiac lift in 7-10/10 pack ice when moving the ship too close to an entry point will force the selected entry/exit hole closed. We also always deploy with the harness arrangement even if not used, since if conditions change, or we need retrieval quickly, the zodiac lift may be the quickest and safest method of retrieval.

c. Dive Tenders

On cruises, at least one dive tender is always one of the divers who has been shown the procedure of deploying the down line, keeping the entry hole free of brash ice and being aware that a change in conditions means instant retrieval or discussion with the divers. For each dive, the dive team goes through what we are trying to accomplish and what to expect of the divers, such as how often we will return with samples or notes, what to have prepared for us to take when we return to the zodiac or dive hole and how to treat the samples. Early in the cruise we are careful to explain our dive operation and the importance of keeping an eye on ice pressure and weather conditions to everyone, divers and non-divers alike. We also explain that the tether system is not only to aid the divers under water but serves as a mode of communication from the tender to the diver. After much trial and error we have settled on one line signal. If the tenders want the divers to return to the entry hole they pull the tether rig in slowly until the divers appear. The key here is to pull in slowly and constantly so the diver can swim to the hole once he is aware of the constant tug on the line. We do this if topside conditions deteriorate or if we see a leopard seal in the area. A diver is not to dive if their hands are cold prior to a dive and if a wrist ring is dislodged it likely means the end of a dive since it may be too difficult to fix aboard the zodiac without someone getting cold hands. We also reinforce to the divers that if they have a glove leak they should terminate the dive immediately before their hands get too numb to operate their suits efficiently. We also advise them to return immediately and swim fast (once shallow and at a constant depth) to the dive hole without trying to notify their partner if they have a regulator free flow. We have purposely planned the length of the tether and the dive to ensure that, should a free flow occur, the diver can swim to the dive hole safely. Soon the safety information is known by all who have tended but do not make the mistake of adding a novice

tender midway through the cruise without providing a detailed account of what is expected of them. At the mid point of a cruise, when all is running smoothly, this is easily forgotten and can create issues.

Dive tenders are an additional safety resource since they prepare and stow equipment aboard the zodiac to ensure it is not plugged with snow or broken, they check as they help the divers put on their gear and their primary responsibility is assessing conditions during the dive. The tenders often experience cold and wind chill much worse than the divers. In some instances we have had topside conditions (wind chill) and/or tender issues that have terminated a dive, so care must also be taken to ensure tenders dress warmly enough and can help the diver with gloved hands. However, we also encourage tenders to realize that they often have the raw end of the deal and to terminate a dive if they themselves cannot tolerate the conditions. This has been an infrequent occurrence.

d. Beasts

We have had very few encounters with marine mammals during our pack ice dives and fewer that have led to termination of a dive. We have encountered Minke whales, crabeater seals, Weddell seals and leopard seals on pack ice dives (Fig. 8).



Figure 8. Preparing to dive through a dive hole at an ice camp. A crabeater seal is mouthing our tether float in the foreground.

On several occasions, divers swam with Minke whales (one pregnant) and returned ecstatic. Quetin has been in a group of 30-40 crabeater seals during three passes they made from him to the ship 100-200 m distant. During visits by the group of curious seals, some would literally "sniff" over his shoulder at the aquarium net in use. We do not terminate dives in the presence of the above marine mammals except for leopard seals. On two dives when we were in the water with leopard seals we eventually terminated, mostly because of our inability to concentrate on the science. During the first dive, the tenders did not see the leopard seal and it nudged the cylinder of a diver conducting line transects. He turned, saw the seal and tried to keep working but concentrating on the task at hand proved difficult and he returned to the zodiac. On another occasion, the tenders, pulling in the down rig, alerted the divers to a leopard seal in the water and the divers returned without incident to the zodiac. At no time did the divers feel immediately threatened by the leopard seal. On both occasions we returned to the ship and dived later in the afternoon without incident.

On a cautionary note, we have had a crabeater seal mouthing the fins of a diver while at a dive hole. After that incident we have kept a regulator in hand when at the dive hole if crabeater seals are at the dive site, just in case a nudge becomes a submersion.

e. Typical Dive in 80-90% Pack Ice

The lead diver meets with the captain to assess the weather, discuss the plan for the dive and pick a suitable dive site, looking for one that is more resistant to closing than a straight split between two floes in an area where there are multiple exits. Prior to this, the divers and tenders have discussed the plan for the dive, discussing the order of tasks so that distant tasks are accomplished early in the dive, who will do what tasks and who will be on what side to prevent crossing the tether lines. Generally, dives are conducted 'upstream' and at the furthest extent of the tethers (if needed) early in the dive. Once the site is picked and the decision to proceed made, the divers start dressing while the captain finishes final maneuvers of the ship. While the divers dress (including dive gloves), but without weight harnesses, cylinders, fins and masks, the tenders load and secure the oxygen, spares box, down line, divers' gear and science equipment in the zodiac. They also ensure that the zodiac is fully inflated and the lift harness is set. The tenders then dress completely for the excursion themselves, including a radio for each for communication with the bridge. Once the divers are ready, the zodiac is lifted over the rail and brought close so the divers and tenders can climb aboard. The zodiac is then lowered and positioned at the selected dive hole. One tender starts deploying the down line while the other tender begins helping the divers don their weights, cylinders, fins and mask as needed. Tenders check the divers over prior to the divers entering the water. If possible, prior to entry, a tender looks at the down line to see if the tethers are streaming. If they are, he alerts the divers that there will be a current. The divers then slip into the water with one hand holding a line on the zodiac, being careful to keep wrist rings from being dislodged and regulators from starting to free flow. The divers slowly descend the 3-4 m to the end of the down line, carefully adjusting buoyancy and assessing any current, and then attach themselves to the tether. They then resurface to get any equipment they require and begin sampling. Dives for our research often require many trips to the entry hole during a dive. Repeated visits also serve as an added safety measure since the divers can be more often informed of topside conditions, *i.e.*, "getting slightly harder to keep brash out of the dive hole," "bridge called with a slight change in wind direction," or "the tenders hands are getting colder." When the dive is over the divers release themselves

from the tether at the down line, slowly ascend, inflate their suits at the surface, pass their cylinder and buoyancy compensator to the tenders, then pass their weight harness and finally kick up into the zodiac. The ship is notified, the crane swung over, the harness attached, the zodiac brought to the rail, personnel climb out and the zodiac is brought on deck to be offloaded.

f. Ice Camps

The evolution and development of pack-ice diving techniques is far from complete and will continue to evolve. Long-term ice camps have been occupied in the perennial ice of the Weddell Sea on floes of much greater dimension that we describe below (Melnikov and Spiridonov, 1996). Most recently in our diving evolution we developed the ability to dive from small (> 50 m) consolidated floes west of the Antarctic Peninsula repeatedly for periods up to 9 days (Fig. 9). Diving on floes for periods of days enabled us to explore local variability in the pack ice community associated with an individual floe over time as the floe drifted within the pack ice.

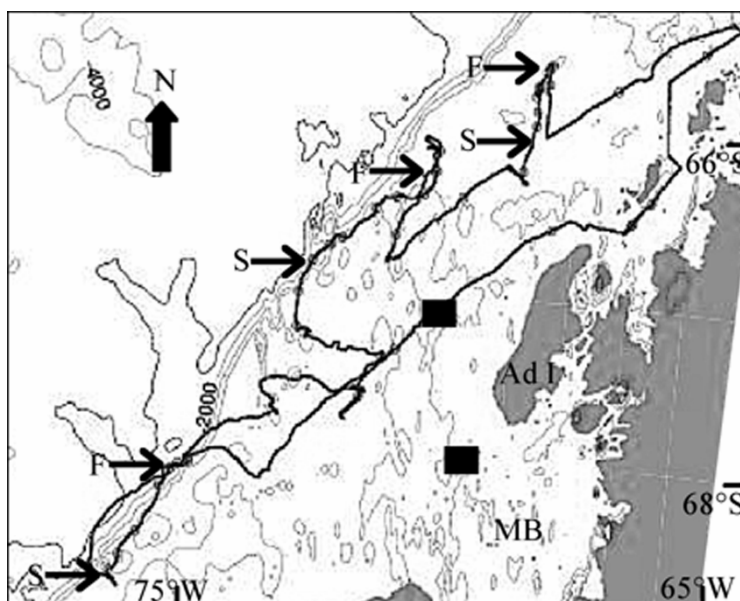


Figure 9. Tracks of the ice camps occupied during the Southern Ocean GLOBEC cruises during the winters of 2001 and 2002. Ad I - Adelaide Island, MB - Marguerite Bay, Bathymetric contours in meters, S and F - start to finish of each ice camps during 2002, Black boxes enclose meandering track of each ice camps during 2001.

Our diving techniques below water when diving on a larger floe (consolidated pack ice) do not vary from diving in looser pack ice. However, topside there are differences from diving in looser pack ice. We worked closely with the captain of the ship to ensure we tried different approaches in a stepwise and safe manner as we developed the techniques.

Positioning the Ship

We did not recognize immediately the best ship position for operating continuously from small floes. Initially, we positioned the ship so wind would be on the port beam of the ship, thus keeping the ship hard against the floe for deploying to starboard. But with the wind directly abeam of the ship, the floe often cracked and had to be abandoned. With persistence, we found that in order to minimize stress on the floe and keep the ship stationary against the floe the best

position for the ship was with the wind 10-15° to port of the bow and with enough way on to keep the ship from slipping sternward. Obviously, this requires a great deal of cooperation with the ship's officers. They managed this position with the use of the port screw only, which led to some other advantages which will be explained below.

Dive Holes

Dive holes need to be used when diving from a consolidated pack-ice floe without the luxury of multiple exits. Two triangular dive holes approximately 1.5 m on a side were spaced approximate 20 - 30 m apart, one acting as a primary hole and the other as a safety hole should the primary hole be blocked or close (Fig. 8). Each hole could easily accommodate two divers and the triangular shape made assisting a diver much easier. Ice thickness at the dive hole was never greater than 1 m and more often approximately 70 cm. Since annual pack-ice floes are often smaller floes that have frozen together during calm periods, our hole locations are often located in the refrozen leads between floes. In most instances, the ice is too thick and over rafted to locate a dive hole in the middle of a floe. The underside of any dive hole should not have over-raftered ice below that might close it. Another consideration is that dive holes are most often located in a refrozen lead, one of the weakest areas of a consolidated floe. The secondary hole should be located in a different lead than the primary hole to help ensure the holes do not close simultaneously if pressure on the ice increases.

Diving Near the Ship

The ships we have used have shrouded propellers that narrowly direct the thrust of the propeller. After seeing our two dive holes collapse one night during a strong wind, and a hole generated by the ship remain open, we experimented with the idea of possibly using the hole at the stern of the ship as a last resort for retrieving a diver. We tested this possibility by placing a lightly weighted line at the starboard edge of the stern hole when only the port propeller was operating and found that the current was weak enough to permit a diver to exit. Operationally, if the primary and secondary holes closed with divers in the water, they would swim for the stern hole while the tenders notified the captain so he could reduce pitch while the divers were being retrieved, a matter of minutes. Using a stern hole for diver retrieval should obviously only be used as the last option but should be discussed as an aspect of the diving program. Note here, that we have as yet to need our secondary hole during any of our dives.

Dive Tent

A Scott tent placed over half of the dive hole greatly facilitated our work. The tent kept the divers and tenders much warmer prior to, and during, the dive. Generally, divers exited the hole at the end of a dive outside the tent. We always had one tender stationed outside the tent, not only to assist divers at the end of the dive, but also to monitor the condition of the primary hole, the secondary hole should a diver surface there, and the wind.

Summary and Risk assessment

Diving in seasonal pack ice is blue-water diving in an overhead environment that is rewarding scientifically, entrancing and stunningly beautiful. It is an environment on the move that can change to the detriment of the diver. The water is often as cold as it gets when diving. Surface conditions can change quickly. Managing the risks associated with diving in pack ice is similar to managing risks associated with other types of diving and other activities with a known,

inherent risk. All can be done safely. Training, planning, environmental awareness, good communication, individual responsibility and caution are all essential elements for the safe conduct of any such activity. Most important is the ability to say, "No, not today", and to take the longer view.

Hopefully, our experiences shared in this report will prove useful to others following their curiosity into the pack-ice realm.

Acknowledgements

Our pack ice studies have been supported exclusively through many grants from the Office of Polar Programs, National Science Foundation. Bill Hamner provided Quetin with his first diving opportunity in Antarctica, initiating our ability to investigate krill in the pack-ice realm. Over the years many, many people, too numerous to name individually, assisted and participated in developing the techniques mentioned in this report. We thank all of you for sharing your experience, for considering new ways of operating in the field, for your assistance and to our divers for diving safely.

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U.S. ANTARCTIC PROGRAM SCIENTIFIC DIVING PROGRAM

Michael A. Lang

Smithsonian Institution
Office of the Under Secretary for Science
PO Box 37102, MRC 009
Washington, DC 20013-7012 U.S.A.

Rob Robbins

Raytheon Polar Services Company
7400 South Tucson Way
Centennial, COLORADO 80112 U.S.A.

Introduction

The first dive by Americans in Antarctic waters was probably made just after New Year's Day in 1947 as part of Operation Highjump, the United States' first major post-war Antarctic venture. Lieutenant Commander Tommy Thompson and a Chief Dixon used "Jack Brown" masks and Desco® oxygen rebreathers. The first Antarctic open-circuit scuba dive was probably made in 1951. Early scuba divers braved McMurdo Sound's -1.8°C water with wet suits and double-hose regulators. Equipment advances since then has led to the use of variable volume drysuits, buoyancy compensators, and dive computers. Because of their resistance to freezing, however, double-hose regulators were used almost exclusively in the McMurdo area until 1990. Since then, single-hose regulators have been identified that also resist freezing failure, and these are now in use. From 1947 to 1967, research diving operations fell under the control of the U.S. Naval Support Force, Antarctica (NSFA). 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 polar regions for the National Science Foundation (NSF) Office of Polar Programs. The NSF/OPP Diving Safety Officer's responsibilities include, with the U.S. Antarctic Program (USAP) Diving Control Board, promulgation of diving safety standards and procedures, evaluation and training of prospective divers and authorizing dive plans. The USAP *Standards for the Conduct of Scientific Diving* are based on the standards published by the American Academy of Underwater Sciences (AAUS). USAP researchers understand that polar diving demands the acceptance of responsibility for an increased level of risk and diver preparation. Antarctic conditions are more rigorous and demanding of divers and their equipment than most other diving environments.

Table 1. Milestones of U.S. Antarctic Dive Program (adapted from Brueggeman, 2003)

- 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.

- 1961-62: Verne E. Peckham (Donald E. Wohlschlag project, Stanford University) logged 35 science dives tended topside on occasion by Arthur Devries and Gerry Kooyman.
- 1962-63: John S. Bunt (Donald E. Wohlschlag project, Stanford University) logged 7 science dives.
- 1963-64: G. Carleton Ray (New York Zoological Society), Elmer T. Feltz and David O. Lavallee logged 10 scuba dives.
- 1963-64: Gerald Kooyman started diving under ice with Weddell Seals with Paul K. Dayton tending topside.
- 1963-64: Willard I. Simmonds (Jacques S. Zaneveld project, Old Dominion University) logged 45 tethered science dives.
- 1964-65: Gerry Kooyman, Jack K. Fletcher and James M. Curtis logged 71 science dives.
- 1965-66: David M. Bresnahan (NSF OPP) and Leonard L. Nero dived on Zaneveld's project.
- 1965-66: G. Carleton Ray, Michael A. deCamp, and David O. Lavallee diving with Weddell seals
- 1967: NSF-SIO agreement for polar research diving
- 1968: Paul K. Dayton benthic ecology project divers Charles Gault, Gerry Kooyman, Gordon Robilliard. Dayton has logged over 500 hundred dives under McMurdo ice.
- 1978-79: 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.)
- 2001: NSF-Smithsonian Interagency Agreement for polar research diving.
- 2007: International Polar Diving Workshop, Svalbard (Lang and Sayer, eds.)

Scientific Ice Diving Authorization

Once a research project requesting scuba diving capability has been funded by the National Science Foundation, the Principal Investigator (PI) is required to upload a dive plan and diver applications onto POLARICE (USAP's project management database). The dive plan is reviewed by the PI's home institution Diving Officer, subsequently by the support contractor (Raytheon Polar Services Company) Scientific Diving Coordinator (SDC) Rob Robbins, and final dive plan authorization is issued by the OPP Diving Safety Officer (DSO) Michael Lang on behalf of NSF. The dive plan includes information on proposed number of dives, depths and times, dive sites, and diving objectives.

The USAP diver applications include diving training and history, depth certification, diving first aid training (Lang *et al.*, 2007) and drysuit experience, certified by the home institution DSO. Minimum qualification criteria for entry into the USAP diving program include:

- 1-year diving certification
- 50 open water dives
- 15 drysuit dives
- 10 drysuit dives in past 6 months

The NSF DSO may require that the proposed diver undergo additional training prior to authorization. Ice diver training curricula considerations were described by Somers (1988). A pre-dive orientation and check-out 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

Lang and Robbins: *USAP Scientific Diving Program*

in an “apprentice” mode. However, divers must become proficient with the gear and techniques they will be using prior to deployment.

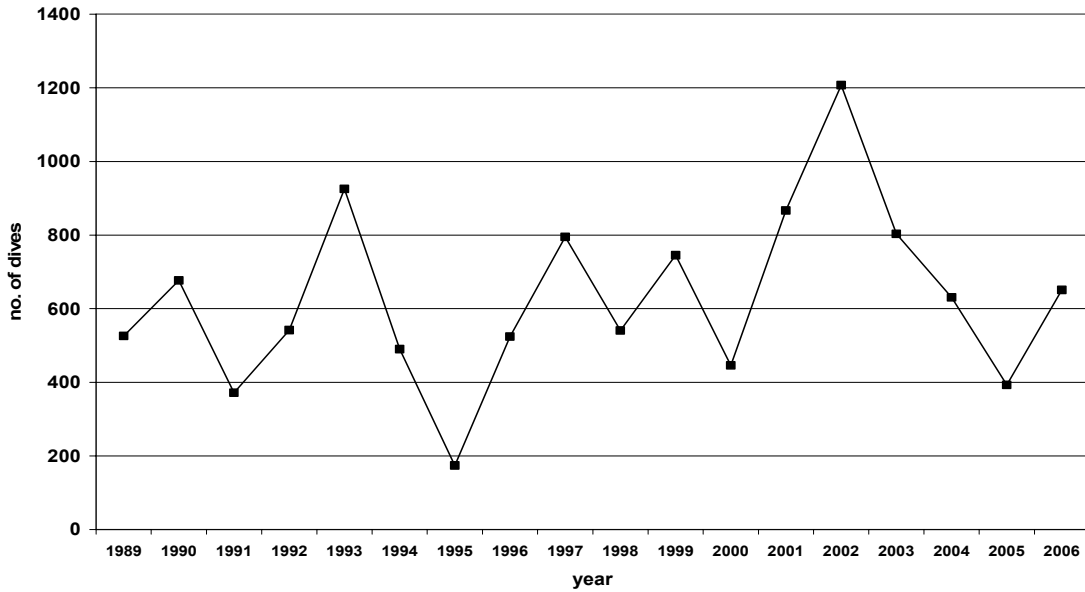


Figure 1. USAP dive summary 1989-2006.

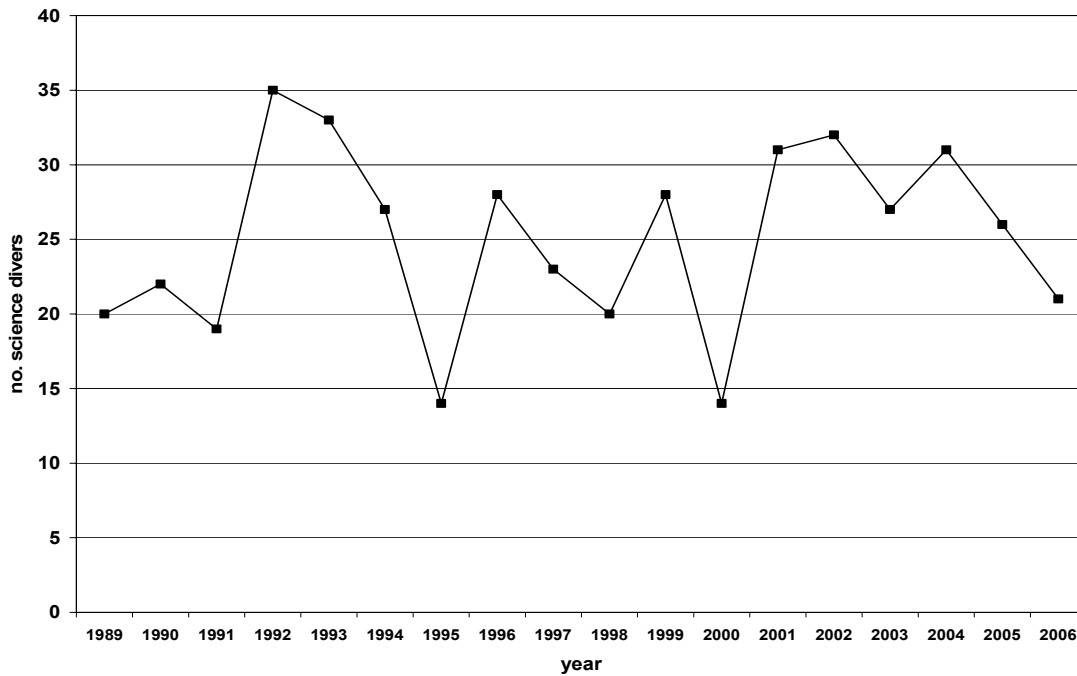


Figure 2. USAP authorized diver summary 1989-2006.

The Antarctic Diving Environment

The SDC conducts a pre-dive orientation briefing for each McMurdo research dive team. This briefing covers dive locker procedures and dive safety emergency procedures, including use of oxygen kits. At Palmer Station and on the research vessels, this briefing is conducted by the Palmer Station Laboratory Supervisor and by the vessel Marine Projects Coordinator, respectively.

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. If calm conditions persist, this ice 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,” which consists of roughly circular, porous slabs with upturned edges. These slabs may be 0.5 m to several meters in diameter. 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 in origin, becomes a solid surface joined to the shoreline, it forms “fast ice.” Fast ice forms a nearly unbroken cover across McMurdo Sound during the winter, spring, and summer months, from the Ross Ice Shelf to Cape Byrd on Ross Island and from Ross Island to the continent at Granite Harbor.

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 platelet layer continually solidifies by freezing, thus increasing the thickness of the ice sheet. The unfrozen platelet layer can be a few cm to several m thick. The platelet layer is interesting for several biological reasons. It forms a substrate for the growth of microbial communities dominated by microalgae and it serves as a home for other organisms that feed on the microalgae and each other (*e.g.*, amphipods and icefish). This ice is also of diving safety concern since positively buoyant divers buried in a thick platelet layer may become disoriented and experience difficulty extricating themselves. Abundant platelet ice, dislodged by divers, may also float up and plug a dive hole. Ice may also crystallize on the benthos. This “anchor ice” generally forms at depths of 15 meters 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

At McMurdo Station, diving conditions are typified by solid fast-ice cover for most of the austral diving season. Fast ice also occurs briefly at Palmer Station, and it may be present during diving operations conducted from USAP research vessels. Diving conditions in the Dry Valley Lakes are also typified by thick fast-ice conditions. Both unique benefits and hazards are associated with fast-ice diving. A solid fast-ice cover helps provide for a calm, surge-free diving environment and it offers a stable working platform free of surface wave action. Fast-ice strength varies by time of year and ambient temperature. An ice thickness that will support a

diving operation in October may be insufficient for a similar activity in December. The under-ice topography varies dramatically by dive site, time of year, microalgal activity, ocean current, age of ice, and other oceanographic, biological climatic factors. When viewed from below, a fast-ice sheet may appear relatively homogenous as a hard, flat surface forming a lid over the ocean. In places, the ice sheet is punctuated by cracks and open leads that appear as bright lines in an otherwise dark roof. Areas of thick snow cover will appear significantly darker than snow-free regions. If platelet ice is present, the underside of the ice appears rough and uneven. Areas of multi-year ice are darker because of increased ice thickness. Where pressure ridges and tidal cracks are present, the under-ice topography is more heterogeneous. 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 may be several m in length and may appear singly or in clusters. They most often occur near cracks or other breaks in the ice sheet. Fast ice thicknesses:

- McMurdo: annual 2 m; multi-year > 4 m.
- Dry Valley Lakes: > 6 m.
- Palmer Station: < 30 cm.

Underwater Visibility

Visibility varies dramatically depending on dive location and time of season. In the McMurdo region, visibility may be up to 300 m in August and September. As solar radiation increases during the austral summer, an annual plankton bloom develops and diminishes visibility. In mid-November, the visibility may be 100 to 200 m but by mid-December, the visibility drops quickly, and can be as little as one meter. Visibility on the west side of McMurdo Sound may remain 30 m or more well after the visibility on the east side has dropped to near zero. Divers have reported 60 m visibility at New Harbor in late December. In the Palmer region, visibility from August through early December is usually about 30 m.

As the summer phytoplankton bloom develops, visibility will drop to 3-5 m. Glacial melt also contributes to reduced visibility. This typifies diving conditions until March, when visibility usually improves. Throughout the austral summer season, wind conditions and temperature will affect visibility to the extent that they contribute to glacial melt. In general, northeast winds lead to bad visibility, while southwest winds cause visibility to improve. Visibility in the open waters of the Antarctic Peninsula may vary from 300 m to less than 3 m, depending on location, time of season, and phytoplankton and zooplankton densities. The visibility values and seasonal limits presented here are approximate and may vary from year to year depending on climate, weather, sea state, and other conditions. As glacial or sea ice melts, the resulting water may form a brackish water lens over the seawater in some areas. Visibility within these lenses is markedly reduced, even when the visibility in the water below is still good. Because of this, divers should be aware that it may be possible to lose sight of the entry hole even when they are near the surface.

Cold

Cold ambient temperature is the overriding limiting factor on dive operations, especially for the thermal protection and dexterity of hands. Dives should be 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 leading to hypothermia. Monitoring the following symptoms 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

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 at ambient temperature initially and chills from expansion as it passes through the regulator. Air consumption increases as the diver cools, possibly resulting in additional cooling with increased ventilation. Significant chilling also occurs during safety stops while the diver is not moving. Cold-water diving requires greater insulation, its bulk decreasing general mobility and increasing the potential for buoyancy problems. This also means increased drag and swimming effort, doffing and donning of equipment, all of which increase fatigue.

Surface Cold Exposure

Dive teams should be aware that the weather can change quickly in the Antarctic. While they are in the field, all divers and tenders should have in their possession sufficient cold-weather clothing for protection in any circumstance. In McMurdo, possible circumstances may include loss of vehicle power or loss of fish hut caused by fire. At Palmer, boat motor failure may strand dive teams away from the station. 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 should be 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 breathing filtered, dry, compressed air, Antarctica is an extremely low humidity environment 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.

Dive Access Through Pack Ice

Tidal action, currents, and other forces produce open cracks and leads which divers may use to enter the water. Accessible tidal cracks may be found between the fast ice and the shore or between fast ice and a floating glacier. Divers working from USAP icebreakers and research vessels often use the leads cut by the vessel for their access to the water (Quetin and Ross, 2007). Areas of open water known as polynyas have also been used.

A hydraulically operated mobile drill is available at McMurdo to cut 1.3-m diameter holes in ice that is >5 m in thickness. Dive groups often request that two or more safety holes are drilled near the primary dive hole. At least one safety hole is required. The mobile drill is limited to the vicinity of McMurdo Station, as far north as Cape Royds if ice conditions permit. It is not available for use at New Harbor or the Dry Valley Lakes.

Hole melters, consisting of coiled copper tubing filled with hot circulating glycol or alcohol, are used to open holes in the thick ice cap that covers the freshwater Dry Valley Lakes (Andersen, 2007). A submersible pump is used to pump water out of the hole as the ice melts. Melters provide a clean one-meter-diameter hole, but they are slow. Actual melting time, depending on ice thickness, air temperature, and efficiency of heat source, may be anywhere from several hours to several days.

Chain saws can be used to cut an access hole through ice that is 15 to 60 cm thick. Cutting a hole through ice thicker than 60 cm is possible but not recommended. Welding a chain saw is dangerous at any time, and this danger may be magnified when the researcher is forced to lean over a deep hole. Standing in the hole as it is being cut also exposes the researcher to high concentrations of exhaust fumes. When a chain saw is being used, the ice should be cut away in chunks small enough to be easily handled, and these chunks should be removed as they are cut free. Access holes may be cut into square or triangular shapes and should be large enough to accommodate two divers in the water simultaneously. Some divers maintain that entry and exit are easier from triangular holes. At Palmer Station, divers have used Jiffy drills to make holes in ice 15 - 30 cm thick, then used saws between the holes to create a large dive hole. Attaching ice anchors to the chunks of ice allows them to be easily removed once they've been sawed free.

For ice 15 - 25 cm thick, ice saws and breaker bars (2-m lengths of steel pipe or solid bar with a sharpened tip) may be used to cut and break away the ice to form a hole. No dive operation should be conducted on ice thinner than 15 cm.

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. In cases where explosives are the only choice, divers should plan on several hours of clearing ice from the hole before a dive can be made. In addition, transport requirements for explosives are stringent and require significant advance planning. Explosives are not used at the Dry Valley Lakes. In some cases, the distance from the working surface to the water may be substantial. Freeboard from a dive hut floor to the water may be as much as one meter. Exit from the water in these instances is simplified by lowering a ladder into the dive hole.

During times of the year when air temperatures are extremely cold, dive holes freeze over quickly. Several techniques can be used to keep holes open and accessible. These techniques mainly apply to the McMurdo vicinity, where most fast-ice hole diving takes place.

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. This has proven to be an excellent method of keeping the hole open for extended periods of time. Wind blowing under a dive hut can increase the rate at which the dive hole freezes. After the hut is positioned, the bulldozer used to move it can, at the divers' request, push snow up to the edges of the hut to block the wind. Additional snow may be removed from the area around the hut to improve ambient light underwater. Once the hut is positioned, snow and slush can be used to construct a step. The step will freeze overnight, permitting easier and safer access to the hut when carrying heavy scuba gear. Portable shelters also provide for diver and tender comfort and permit diving in adverse weather conditions

Dive holes for which no hut is available may be covered with insulated covers. These covers are made with 5-13 cm of foam insulation sandwiched between layers of plywood. If possible, divers should allow a thin film of ice to freeze over the hole before installing the cover. This will prevent the hole cover from freezing in.

Even with the intervention methods described above, ice will continually form on the surface of a dive hole during the coldest months. If left unattended, the hole will quickly freeze over. Safety holes should be chipped open once per day, if possible. A week of neglect during spring and early summer may render a hole unusable, even if the hole has been covered. Safety holes that are allowed to freeze at the surface are hard to tell from viable holes while diving under the ice. Down lines must mark all holes available for use on each dive. Divers should be instructed to ignore unmarked holes. Congelation ice, frazil ice, floating anchor ice, and platelet ice dislodged by divers can quickly fill a dive hole. This combination is often called "brash ice," and it must be continually cleared by tenders. If platelet ice is allowed to accumulate in a dive hole while divers are in the water, it may be difficult or impossible for returning divers to reach the surface. Caution should be used when the platelet layer around the dive hole is thicker than one meter. When explosives are used to make a dive hole, large blocks of ice may be displaced under the surrounding fast ice. This large debris may choke an exit hole if it becomes dislodged and floats up into the hole. Tenders should remain alert to possible ice buildup and try to keep the hole as free of ice as possible. Tongs, nets, and shovels can be used for ice removal.

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 the thickness of the ice will also attenuate light transmission. Microalgal blooms and increasing zooplankton during the austral summer will reduce available light. Low light conditions may make 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 potential loss of the access hole or lead. Access holes, leads, and cracks in the ice are often highly visible from below due to daylight streaming through them. However, conditions of darkness or covering them with portable shelters may make the holes difficult to see. Therefore, a well-marked down line is required for fast-ice dives. Divers should always maintain positive visual contact with the down line during the dive; they should not become 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 more serious, since a vertical ascent is impossible except when a diver is directly under the access hole or lead. If the diver has lost visual contact with the dive hole, the problem becomes extremely serious. Safety holes ameliorate the danger of losing the primary dive hole. 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 should be marked with a down line.

Thin Ice

In cases where the ice is too thin to support a diving operation (less than 15 cm), divers will have to open a hole near the shore and swim to their work site. This condition should be treated procedurally as a solid-ceiling dive, since the divers may have to struggle to break through the ice in an emergency. Accordingly, at least one safety hole should be opened and the divers should not swim farther from their access hole than is safe. Each diver should also have two independent regulators, and a spare air source (pony bottle) should be carried along. Divers in this environment should follow the “Thirds Rule” (*i.e.*, divers should plan dives to use 1/3 of their air volume for the excursion, 1/3 for the return trip, and keep 1/3 of their air as a reserve). A tether line may be required.

Pack Ice

Pack-ice diving offers benefits and challenges quite different from those of fast-ice diving (Quetin and Ross, 2007). The broken ice cover of the pack environment usually eliminates the need to cut access holes for diving. Easy and ubiquitous access to the surface generally makes a down line unnecessary, though one may be used to mark the exact entry point for convenience. The pack-ice environment tends to be much 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. As in most open-water diving, wave action and currents must be considered. In cases where the pack ice is forced against the shore and is solid but unstable, divers will have to open an access hole near shore in shallow water. This dive should be treated procedurally as a fast ice dive, since additional access to the surface may not exist. Divers must also take into account tidal fluctuations which may alter the size of their dive holes or vary the depth under the holes.

Divers may 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. Depending on the

density, stability, and thickness of the ice, transit to and from a dive site via inflatable boat may be time-consuming. This factor should be considered in the dive plan. In early spring, broken ice around Palmer Station makes Zodiac operations, and therefore diving, nearly impossible.

Pack-Ice Diving Hazards

Pack ice is inherently unstable. Pack ice conditions can change rapidly, based primarily on 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 waters when divers entered the water. Therefore, the possibility always exists that the access area may become covered or blocked. Similarly, increased wind pressure on pack ice may make Zodiac travel more difficult or impossible. Under a jumble of pack ice, the topography is reminiscent of cave diving. Condition of the pack must be continually monitored by both divers and tenders for changes that may affect dive safety. The entry area must be kept clear. Also, down lines and tethers can be disturbed by shifting pack ice. Dive tenders must be alert to keep these lines free of moving ice.

Surface swells, even if only light to moderate, may cause pack ice to move up and down several feet. 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 should avoid diving under pack ice if the clearance between the ice and the benthos is 3 m or less.

Lighting may be dim under a heavy pack-ice cover. Ice thickness, snow cover, phytoplankton bloom, increased zooplankton, glacial flour and melt water will all contribute to light attenuation and low visibility.

Open water may develop in the McMurdo Sound region 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 frequently defines the diving environment after early December. It should be noted that these are approximate dates. Climatic conditions can and will cause variation in annual ice conditions. Divers operating in open water and from small boats should fly a “diver down” or “Alpha” flag when other boat traffic in the area is likely. When diving from small boats in areas where leopard seals are known to exist, a rapid exit from the water into the boat may be necessary. Because this can be difficult when fully laden with gear, some divers have suggested hanging lines with clips from the side of the boat. The diver can then temporarily secure gear in the water while he or she enters the boat. A ladder may also facilitate diver exit from the water.

When diving in blue water, California Sea Grant College Program (CSGCP) *Blue Water Diving Guidelines* (Haddock and Heine, 2005) generally apply. Divers should be tethered and wear buoyancy compensators. It may also be useful to deploy a down line if conditions warrant. Divers operating below pack ice in blue water should be aware that perceived current often increases with increasing depth. Wind action causes the pack to move, which in turn moves the

water directly below. 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. Ice-edge divers should watch for dangerous marine organisms. In particular, leopard seals may pose a hazard to ice-edge divers. Leopard seals have been 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. If, on the other hand, penguins are swimming calmly next to the ice edge, it is unlikely that a leopard seal is present. Killer whales may also pose a hazard at the ice edge.

Remote-site diving operations carry increased risks and responsibilities. Medical care and logistical assistance may be several days away. Dive groups planning on remote operations must have sufficient dive gear, backup gear, medical supplies, and oxygen.

The following is a partial list of diving areas in Antarctica that may be regarded as contaminated water environments:

- The region between the southern tip of Hut Point and a point approximately 200 meters from the shoreline on the annual ice runway road.
- The region in front of McMurdo Station includes the sewage outfall and all of Winter Quarters Bay. In general, this area is considered contaminated because of the high levels of *E. coli* bacteria that have been measured, up to 100,000/100 ml. However, the plume of highest contamination may shift.
- The region near the Palmer Station sewage outfall. This area runs from the seaward side of the pier to Gamage Point.
- The hydrogen-sulfide layer in Lake Vanda

These environments require special consideration and should be discussed with the SDC prior to beginning operations. Diving with standard scuba or band mask, where a diver may be exposed to the water, is prohibited in these areas. Surface-supplied/contaminated-water diving equipment is available for the McMurdo area. The equipment ranges from Heliox-18 bandmasks, for use with any vulcanized rubber drysuit, to Superlite-17 helmets that mate to special Viking suits. Equipment requirements will depend on the type and level of contamination.

Dangerous Marine Life

Few Antarctic animal species are considered dangerous to the diver. Generally, only some large mammalian predators pose any risk and common sense should prevail in any interactions.

Southern elephant seals (*Mirounga leonina*) and Antarctic fur seals (*Arctocephalus gazelli*) may become aggressive during the late spring/early summer breeding season. According to some researchers, elephant seals, while aggressive toward people on the surface, are generally nonthreatening in the water. Antarctic fur seals, on the other hand, are very aggressive during the breeding season, in and out of the water. Diving in areas with fur seals during that time should be avoided.

Crabeater seals (*Lobodon carcinophagus*) have demonstrated curiosity toward divers but have not shown behavior in the water that could be construed as aggressive. It should be noted, however, that even playfulness or curiosity on the part of a seal or group of seals may pose a hazard to a diver. Crabeater seals have shown 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 is described by Muir *et al* (2006). Dives should not be conducted when leopard seals are nearby. If a leopard seal approaches divers in the water, the divers should apply similar techniques to those used against sharks. If the divers are in midwater, they should face the seal, hold any available tools out in front of them as a barrier and swim slowly toward the dive boat or toward shore. Divers on the bottom should stay close to the bottom if possible and head toward shore, always keeping eyes on the seal. Movements should be slow and deliberate. At no time should divers swim quickly away or give the appearance of flight. Such behavior mimics prey behavior familiar to the seal and may entice the animal to attack. If divers are operating from a small boat, and they have hung lines with clips in the water, each can guard the other while they temporarily secure their gear to the clips. Then both divers can enter the boat quickly and simultaneously. If a leopard seal approaches too closely and appears to be inclined to attack, it may be helpful for divers to feign aggressiveness, charging at the seal as it charges them. These charges can be accompanied by loud exhalations of air and exaggerated arm waving. This protean behavior is unlike anything the seal expects from a potential prey and may confuse it or encourage it to retreat. However, divers should always consider the possibility that aggressive behavior on the part of a leopard seal may be the result of territoriality rather than hunger. Consequently, aggressiveness on the part of divers should be considered as a self-defense last resort and only if an attack appears imminent and escape seems impossible. At all times during a leopard seal encounter, divers should stay close together and act in concert. If a diver is bitten, prompt and careful attention must be paid to the wound. Beyond the obvious need to stop bleeding and minimize tissue damage, seal bites can be extremely infectious and should be thoroughly cleaned as soon as possible. Prophylactic antibiotic treatment may be required. Encounters with all of the aforementioned animals are usually restricted to areas of open water, ice edges, or pack ice. Most encounters have occurred near Palmer Station or in other areas of the Antarctic Peninsula. However, two attacks by leopard seals on a human have occurred in McMurdo Sound. Divers and other researchers working at the ice edge or other areas where leopard seals may be present should maintain constant vigilance.

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. Most of the time the seal will vacate the hole once it has taken a few breaths and replenished its oxygen stores, particularly if divers are approaching from below and preparing to surface. Divers should, however, approach such a seal with caution, since an oxygen-hungry seal may aggressively protect its air supply. During the breeding season (October through mid-November), a male Weddell seal may stake a territorial claim to a dive hole and prevent divers from surfacing. In these cases, a safety hole may have to be used. If no open safety hole is available, the seal will have to be enticed out of the hole. Letting exhalation bubbles come up under the seal is usually the simplest and safest means of doing this. Weddell seals protecting

their surface access will often invert into a head-down, tail-up posture to watch for rivals. If exhalation bubbles don't work, gentle prodding by the surface tender of the seal's hind flippers will usually entice it to leave. 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. At least one diver has had his fin bitten in this way. It is best to avoid areas of high seal concentration during the breeding season, particularly if surface access is limited. Adult and subadult male Weddells may show aggressive behavior toward divers in the water, even when the dive hole is not the seal's objective. This can be particularly true of peripheral males in non-breeding areas. Aggressive behaviors include posturing, "thumping" (a low frequency staccato vocalization), and charging. As with leopard seals, divers should keep their eyes on an aggressive seal and make their way back to the dive hole, without giving the appearance of flight. In those rare cases when a Weddell seal has become too bold, arm waving and counter charging have caused it to retreat. However, these techniques should again be considered a last resort. Typically, however, Weddell seals are not noted for aggressive behavior toward humans, except for the time frame noted above, and divers generally need not be concerned about their presence. Like all pinnipeds, though, they may bite if provoked.

No incidents of killer whale (*Orcinus orca*) attacks on divers have been recorded in the Antarctic.

Diving Operations

A down line is required on all untethered dives conducted from fast ice or any other stable overhead environment with limited surface access. The purpose of the down line is to clearly mark the access hole from below and must be securely attached at the surface to prevent accidental loosening. A down line is not required on tethered dives. A down line is sometimes required for attaching heavy loads for later retrieval. However, to avoid entanglement, tethered divers using a down line should plan to work in a single direction from the hole with the down line placed on the opposite side.

Down line characteristics include:

- a rope of sufficient length to reach either the bottom under the dive hole or a depth 50 percent greater than the proposed working depth;
- preferably Nylon construction because of its strength and flexibility in the cold;
- sufficient diameter to allow easy grasping by gloved or mitted hands;
- weighting at the bottom with 5-10 kg. In addition to stabilizing the line, this weight serves as a safety device for divers experiencing buoyancy problems on ascent;
- anchoring with the weight suspended just off the bottom to reduce damage to the benthos;
- clear marking by highly visible flags (*e.g.*, black and white checkers) placed at regular intervals along its length;
- clear marking with two to three underwater strobes attached to the line just under the ice and near the bottom or at the working depth;
- equipping with a 13.7-cubic-foot or larger reserve cylinder with regulator and submersible pressure gauge at about one-half the working depth of the dive, keeping the regulator out of the mud and making the air supply more readily available to a diver in an

emergency ascent. The cylinder is attached securely with a carabiner to a loop in the down line, a system that also allows the cylinder's ready removal by a diver.

Other hole-marking techniques to further protect against loss of the dive hole:

- snow removal: straight lines radiating outward from the dive hole that are very visible from under water.
- benthic lines: marked 30-m lines laid out on 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.

Fast-ice environment diving requires one or more safety holes in addition to the primary dive hole. The main function of these safety holes is to allow easy surface access in case of emergency. They also allow continued dive operations and surface access in cases where a Weddell seal appropriates the primary dive hole. In cases where the divers are securely tethered and the loss of the dive hole is essentially impossible (such as when diving with surface communications in the seal-free Dry Valley Lakes), no secondary hole is required.

Each diver must conduct a functional check of all equipment before a dive. Particular attention should be paid to regulators and inflator valves. If leakage or free flow is detected in these items the dive must be postponed until the malfunction is corrected. If a regulator or inflator valve is found to be free flowing on the surface, it is a virtual certainty that it will free flow at depth. One spare regulator should be kept available for every dive. All divers should be able to disconnect the drysuit low pressure hose from the drysuit inflator valve with gloved or mittened hands. Otherwise, a drysuit inflator free flow in the water could result in an uncontrolled ascent.

Because a drysuit must be inflated to prevent "suit squeeze," it is most efficient to regulate buoyancy at depth with the drysuit. Drysuits must be equipped with a hands-free exhaust valve (Lang and Egstrom, 1989). Buoyancy compensators (BCs) should be 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. Air in a drysuit also serves as thermal insulation. Weighting should be sufficient to enable the diver to achieve neutral buoyancy with a comfortable amount of air in the suit. Buoyancy compensators and drysuits should *never* be used as lift bags. When heavy items must be moved underwater, separate lift bags designed specifically for that purpose should be 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.

University of Michigan Sea Grant "HUGI" tables and Canadian Defence and Civil Institute of Environmental Medicine (DCIEM) tables have been used in the past as effective alternatives to the U.S. Navy tables. 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. Currently, the decompression status of all divers through USAP is monitored through the use of dive computers (UWATEC Aladin Pro) and data loggers (Sensus Pro) issued

at McMurdo by the Scientific Diving Coordinator. Battery changes may occur more frequently because of higher discharge rates in extreme cold. Dive computer advantages over tables is 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 submitted for consideration to the USAP Diving Control Board. Divers must be conservative and incorporate safety factors into their dive plans. Cold and the physical exertion effort required to deal with heavy gear in ice diving can increase the risk of decompression sickness. Furthermore, because of the polar atmospheric effect, the mean annual pressure altitude at McMurdo Station is 200 meters (650 feet). Under certain conditions, pressure altitude may be as low as 335 meters (1100 feet) 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 decompression sickness.

Based on cave diving protocols, it is recommended that divers operating beneath fast ice that prevents direct access to the surface maintain at least twice the volume of air necessary to return to the dive hole or access point. This amount of air is in addition to a recommended reserve minimum of 20 cubic feet.

Safety stops of three to five minutes at 10 to 30 feet are required for all dives (Lang and Egstrom, 1990).

Tenders assist divers into their gear and into the water, hand the divers collection and photographic gear, handle tether lines, maintain communications with base, receive samples and specimens and help divers out of their gear and out of the water when the dive is completed. In case of accident, tenders are on hand to pull an incapacitated diver from the hole and begin emergency procedures. A minimum of one tender per dive is required. Tenders are usually members of the research team. Additional tenders can sometimes be drawn from the science or support communities of the research base or vessel. Because they are a critical part of the dive effort and are the first responders in case of accident, tenders should have diving first aid training (Lang *et al.*, 2007), radio use and communication procedures, knowledge of scuba gear operation and vehicle or boat operation (if used to support the dive). The SDC trains volunteer tenders in the previously listed skills as needed.

Dives conducted under fast ice where there is a current, in reduced visibility, in blue water, or where the water is too shallow to maintain visual contact with the dive hole require a tether. The tether must be securely attached at the surface in such a way that it cannot accidentally come loose and be lost into the water. Dive groups operating in blue water from a USAP research vessel have used tethering systems based on those described in the *CSGCP Blue Water Diving Guidelines*. Tethering each diver individually increases the danger of entanglement, but allows for more efficient work. Use of the T-shaped system makes it difficult for line-pull signals to be effectively communicated between divers and surface tenders and is discouraged. The L-shaped system (tether and buddy line) is modeled after the system described in the *Blue Water Diving Guidelines*, where one diver serves as a safety diver, controlling the tether line and preventing

entanglement, while the other “working” diver performs the required task. It is also the safety diver's responsibility to maintain a positive communication link to the surface. With this system, line pull signals are easily transmitted between the safety diver and the surface tender, as well as between divers. The disadvantage with the L-shaped tether is that only one diver is fully available for work at depth. The surface tender must 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 divers. The following signals, taken from the U.S. Navy Diving Manual, are considered to be an industry standard:

Tender to Diver:

- 1 pull = Are you OK?
- 2 pulls = Go down or change direction.
- 3 pulls = Prepare to come up.
- 4 pulls = Come up.

Diver to Tender:

- 1 pull = I'm OK.
- 2 pulls = Give me slack.
- 3 pulls = Take up slack.
- 4 pulls = Haul me up.

Line-pull signals should be practiced in advance of dive operations. It should be noted that single pulls may be mistaken for inadvertent tugs on the line by a moving diver. Tethered divers should pay close attention to each other and constantly monitor each other's position and status. Divers should never assume that a tether relieves them of normal buddy-diving responsibilities. Tethered divers working in a current should always swim and conduct work up-current unless returning to the dive hole.

Dive Equipment

Particular care should be taken in the selection and maintenance of diving equipment for use in the Antarctic (Lang and Stewart, 1992). 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 malfunctions may be more frequent. Diving under total ice cover also imposes safety considerations that are reflected in the choice of gear. Years of testing and use by researchers and other Antarctic divers have demonstrated the reliability of some equipment items and the inappropriateness of others. In addition, specific care and maintenance regimens have been developed to ensure the reliable operation of the equipment.

Divers are required to have two fully independent and functional regulators attached to their air supply whenever they are diving under a ceiling. Regulators (modified Sherwood Maximus SRB3600 models, Fig. 3) are issued at McMurdo by the Scientific Diving Coordinator. Modifications include installation of a heat retention plate and detuning to an intermediate pressure of 125 psi. These units are rebuilt at the beginning of each season and with over 7,000 dives have a free-flow incident rate of 0.3%. Proper use and proper pre- and post-dive care can improve the reliability of the regulators used substantially. Regulators should be kept warm and dry before a dive; divers should not breathe through the regulator before submersion, except to

quickly ensure that the regulator is functioning. This is particularly important if the dive is being conducted outside in very cold air temperatures. During a dive, a regulator should never be 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 should always be attached to the back-up regulator in case the air supply to the primary regulator must be turned off to stem a free flow. The backup regulator second stage should be attached to the cylinder harness or buoyancy compensator such that it is readily accessible and easily detached. Loops of surgical tubing or velcro tabs have been used effectively for this purpose. 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 if required. After the dive, the regulators should be rinsed and allowed to dry. During the rinsing, care should be taken to exclude water from the interior regulator mechanism. The diver should ensure 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 in the McMurdo area is water within the mechanism that freezes once the regulator is used. 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.



Figure 3. Sherwood Maximus SBR3600 second stage with heat retention plate.

Inflator valves are also subject to free-flow failure, again because of water in the mechanism. Drysuit and buoyancy compensator inflators should be kept completely dry. Inflator hose connections should be blown free of water and snow before attachment to the valve. When inflating a drysuit or a BC the diver is advised to use frequent short bursts of air. Inflator buttons should never be depressed for longer than one second at a time otherwise rapid air expansion, adiabatic cooling and subsequent condensation and freezing may cause a free flow.

Buoyancy compensators should allow unimpeded access to drysuit inflator and exhaust valves. Water should be removed from the BC bladder after diving and rinsing. Freshwater in the bladder may freeze upon submersion of the BC in ambient seawater. BC use in the McMurdo

area is not currently required when the dive is conducted under a fast-ice ceiling. A BC should never be used to compensate for excess hand-carried weight. Steel cylinders instead of aluminum cylinders are used for durability in cold temperatures and their buoyancy characteristics.

Divers must wear sufficient weight to allow maintenance of neutral buoyancy with a comfortable amount of air in the drysuit; over-weighting should be avoided. Because of the amount of weight and potential for accidental release, weight belts are not allowed. A number of diving equipment manufacturers have developed weight and trim systems that retain the benefits of a harness while still allowing full or partial dumping of weight underwater. It also 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, requirement for ease of motion and on the options available with each suit. Vulcanized rubber suits must be used when diving in contaminated water because of decontamination requirements. Drysuits must be equipped with hands-free, automatic exhaust valves. Over inflation 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 a drysuit, because it is the underwear that provides most of the thermal protection. Many divers wear an under layer of expedition weight polypropylene with an outer layer of Thinsulate®. Dry gloves or mitts are used with the drysuit. These three-finger mitts will work properly only with the Viking ring system and latex seals. Divers who use these mitts place a small piece of tubing or cord under the wrist seal to allow for warm air equalization into the glove at depth. Like the drysuit, the Viking mitts require an inner liner to provide thermal protection. Diving Unlimited International's (DUI) zipseal dry gloves are very effective. A disadvantage of most dry-glove systems is the complete lack of thermal protection if the gloves or mitts flood although this is an uncommon occurrence.

Severe cold may compromise O-ring seals. All O-rings exposed to the environment should be cleaned and lubricated frequently. Proper compressor care and operation are necessary to ensure a reliable supply of clean air. Compressors should be kept warm or should be adequately warmed before starting. Cold starting attempts will drain batteries and may unduly strain compressor components. A log of compressor hours must be kept to ensure that a proper maintenance schedule is maintained. Air filters and crankcase oil are scheduled to be changed on a regular basis. Air quality tests must be conducted at 6 month intervals. The cleansing capacity of portable compressor filters is usually limited, so air intake hoses should be positioned upwind and well away from compressor engine exhaust. When the compressor is in operation, manual condensate drains should be purged frequently to prevent moisture contamination of the filter. When charging cylinders, it is important to always purge the cylinder valve of moisture before attaching the fill whip.

All diving gear, including cylinder valves, should be rinsed in fresh water after every dive (except as otherwise noted) to reduce salt buildup and corrosion.

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 the 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.

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.

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. 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.

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 used rarely for scientific diving operations. 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.

Environmental Protection

All researchers in the Antarctic must avoid degrading the integrity of the environment in which they work. In particular, divers working in the Antarctic should:

- Avoid over-collecting. Because knowledge on Antarctic faunal growth rates is limited, divers should assume that recovery and recruitment rates are slow, particularly for rare or uncommon organisms. Over-collection could severely deplete an organism's abundance and alter the ecology of a research site;
- Avoid undue disturbance of the benthos. Whenever possible, divers should maintain neutral buoyancy when working on the bottom to avoid kicking and stirring up the sediment. When negative buoyancy must be used, divers should take care where they place their knees, hands, and feet. At McMurdo, divers should take particular care to avoid stirring up the contaminated sediment in Winter Quarters Bay;

- Minimize mixing of water layers, such as haloclines. Water layering occurs in many Dry Valley Lakes, such as Lake Vanda in the Wright Valley;
- Limit the use of explosives for opening dive holes. Explosives should never be used when seals are near enough to be injured by the concussion. The injury perimeter of an explosion is greater underwater than on the surface;
- Exercise care with oil, gasoline, and other chemicals used with machinery or in research. Limit or prevent spillage as much as possible. At Palmer Station, dive operations that promote further oil or fuel release from the shipwrecked *Bahia Paraiso* should be avoided. In the McMurdo region, divers may sometimes need to use Weddell seal holes or open leads in breeding areas for access to the water. Seals in these areas should be respected and given as wide a berth as possible. 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. Because seals will avail themselves of anthropogenic holes in the ice, dive operations will always disturb natural behavior to a certain degree. However, if it appears a dive operation will unduly disrupt natural behavior (*i.e.*, by causing seals on the surface to become agitated, to move, or to leave the area), the dive should be aborted or its location changed. Furthermore, dive groups should avoid Weddell seal breeding areas during the breeding season, unless they have a compelling reason to dive there and a permit to do so.

Dive Emergencies

Several possible emergency situations specific to the Antarctic, and particularly to the fast-ice environment at McMurdo, are discussed. The best method to mitigate scuba emergencies is through prevention. Divers should halt operations any time they become unduly stressed because of cold, fatigue, nervousness, or any other reason. Similarly, diving should be 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; they generally result from the accumulation of two or more minor problems. For this reason it is best to terminate a dive before problems multiply. In any emergency situation, it is important not to panic. Maintaining the ability to think clearly is the best preparation for the unexpected. Most dive emergencies are best handled with the assistance of the dive buddy, reinforcing the importance of maintaining contact between buddies while in the water.

If, during the course of a fast-ice dive, a diver loses contact with the dive hole and cannot locate a safety hole, the first action should be to locate the buddy. The buddy may be able to point the way. If both divers have lost the hole, they may be able to retrace their path. A suspended silt layer in the water column will indicate where divers have kicked along the bottom. Scanning the water column for the down line should be 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. In their search for the dive hole or for an alternate access, lost divers will have to constantly balance a desirable lower air consumption rate in shallow water with the need for the wider field-of-view available from deeper water. Following

established USAP diving procedures and maintaining a safe proximity to the surface access point makes losing the dive hole an extremely unlikely occurrence.

Loss of the tether on a dive requiring one is one of the most serious Antarctic dive emergencies, particularly if the dive is under fast ice. If the dive is not under fast ice and if the tether line cannot be reconnected, the diver should terminate the dive and surface. Exercising reasonable care (especially by paying careful attention to how the tether is attached to the diver) makes a loss of tether emergency unlikely.

If one diver comes off the tether line in limited visibility, this diver should make an attempt to locate the line or the buddy in the immediate area. If neither can be located, the diver should ascend to the underside of the ice and assume a vertical posture, extending one or both arms over the head. This presents the largest possible target. The tethered buddy will run a circular search pattern by swimming 15 to 30 m farther away from the hole than the divers were working and sweeping in a clockwise or counterclockwise direction just under the ice. The tether line should catch the untethered diver. The lost diver should keep one hand on the ice and should watch the water below his or her feet. A rescue line passing just under the ice or a few feet below the diver will be caught or seen. If both divers become disconnected from the surface tether, they should immediately establish contact. If they are still connected by a safety line, they should initiate a circular search pattern for the surface tether. In this pattern, one diver remains stationary while the other swims to the limit of the available line and does a sweep. If the tether cannot be found, the divers should ascend to the underside of the ice and initiate a similar search pattern for the dive hole. Multiple patterns may be run provided the ability to return to the initial position is maintained. Staying shallow will conserve air supplies. If the surface tender realizes that the tether line has become disconnected from the divers, he or she should immediately deploy a down line if one is not already in place. The tender should also immediately inform the base of operations that divers have been lost. Under some conditions, it may be possible to deploy a search-and-rescue dive team. 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 one diver becomes disconnected from the tether in a current under fast ice, and the tether cannot be reconnected, the dive should be terminated. The diver should attempt to make physical contact with the buddy's tether. If the divers are in the water column, and have been working up current as they should, it may only be necessary to drift back to the down line. If the divers are down current it may be necessary to crawl along the bottom to the down line. It is always advisable to deploy a down line on tethered fast-ice dives made in a current.

When one or both divers lose the tether in shallow water, where the access hole is not readily visible, they should first establish contact with each other. If the tether line cannot be found or reattached the divers should attempt to retrace their path to the hole. Barring this an alternate access may have to be located. No dive should be made in such a situation without clearly marking the access hole. There are several ways to do this:

- 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 some other obvious and highly visible object on the substrate just below the hole;
- Shovel surface snow off the ice in a radiating spoke pattern that points the way to the dive hole. Such ice-free areas are generally very visible from below.

The under-ice platelet layer can be several meters thick in places. It is possible for an over-buoyant diver to become trapped within this layer to the extent that he or she is unable to see and becomes disoriented. The best and most obvious solution is to dump air from the drysuit to achieve negative buoyancy. If this is not possible, and if 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. The over-buoyant diver can then orient to the position of the dive hole and buddy.

Fire is one of the greatest hazards to any scientific operation in the Antarctic. 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. Heaters should never be left on at a high level particularly when the hut is unattended. All dive-team members should be familiar with fire prevention methods and fire extinguisher operation. If divers recognize during the dive that the dive hut is burning they should terminate the dive and ascend to a safety hole. If no safety hole is available the divers should ascend to the under surface of the ice next to the hole (but not below it) in order to conserve air. Divers who have followed proper air management procedures should have enough air to wait out a rapidly burning hut. Complete destruction of the hut may take only 15 or 20 minutes.

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ANTARCTICA NEW ZEALAND DIVING OPERATIONS

Steve Mercer

National Institute for Water and Atmospheric Research

Private Bag 14901

301 Evans Bay Parade, Hataitai

Wellington 6021 NEW ZEALAND

Introduction

New Zealand has conducted scientific research in Antarctica since 1957. New Zealand's operation is run from Scott Base and is focused on the McMurdo Sound area of the Ross Sea. The Base, located at Pram Point, 77° South on the southern most point of Ross Island, supports a summer population of approximately 75 staff and scientists, and is administered by Antarctica New Zealand, a division of the Ministry of Foreign Affairs and Trade. Access to New Zealand's Base is by air to the adjacent McMurdo Station and then by ground transport for 3 km. A strong relationship has been established with USA operated McMurdo Station, which enables New Zealand to operate a well-supported polar operation with frequent and regular air transport compared with many other countries with claims on Antarctic territory.

History

Scientific diving from Scott Base commenced in 1985 when a group of Auckland University fish physiologists included direct observations on platelet ice fish activity in their Event (or Programme) objectives. Until then New Zealand's Antarctic research had focused on geological and ice investigations with limited biological investigation activity. In those times the NZ Antarctic organisation took a very cautious approach to all new field activities. They sought technical advice from military experts and approached the Navy seeking a protocol and volunteers from the Operational Dive Team to manage the scuba diving. Unfortunately, their request coincided with the sabotage and sinking of a Greenpeace protest vessel in Auckland Harbour and the Navy was unable to release staff. They then sought advice from the Fisheries Division of the Ministry of Agriculture and Fisheries (MAF) which had a team of 100 divers and an established training regime. It was agreed that MAF would develop the diving protocol and provide training and supervision of the first diving Event. This first expedition was successful and, while the 4 divers made only 18 dives in the first season, further diving Events followed and a comprehensive training programme and diving manual was developed over the next few seasons. The diving manual is reviewed annually and has been issued since to all divers taking part in Antarctica NZ diving Events.

As the first Antarctica NZ Diving Officer seconded from MAF the author has continued in this capacity for 22 years though his employer has transformed to a trading arm of the NZ government called NIWA (National Institute of Water and Atmospheric Research).

Training

In 1986 a two-day ice diving training exercise was established as part of the familiarization exercises already required for participants in Antarctic activities. This exercise has proven to be an invaluable preparation for ice diving Events. It is conducted at an alpine lake adjacent to a major ski field close to Queenstown which has excellent accommodation, services and an international standard airport. Divers are required to attend with all the personal diving equipment they will be using in Antarctica. Despite the fact that the main Tekapo training exercise was permanently terminated in the early 1990s the ice diving training has continued for all new and lapsed Antarctic divers. The exercise is regarded by all diving supervisors as an essential component in preparing divers for Antarctica.

New Zealand is a temperate country and scuba diving is a very common recreational activity. Sea water temperatures rarely drop below 10°C in winter so few divers have experienced sub-zero air or water temperatures. Many candidates even expect to be able to use their New Zealand dry suits and unmodified diving equipment under the ice. Hence, the training exercise provides an opportunity to ensure all divers have equipped themselves with suitable gear.

Prerequisite qualifications for ice diver training are that the candidate must be a registered NZ occupational science diver. If they are collaborating from another nation they must hold national equivalent certifications. The trainees are made up of new ice divers and lapsed divers taking a refresher course which always provides a large enough group to make the training economical.

On the first evening the group is briefed on what to expect when operating out of Scott Base and they are shown field clothing, survival bags, tents and the layout of Scott Base. They also receive ice diving fundamentals and are introduced to lifeline signals. Those with substandard dive gear are given the opportunity to exchange or replace it. Day 1 involves travel to the dive site usually by road to the ski field car park and from there the equipment is sling-lifted to the frozen lake by commercial helicopter. Duties are allocated and a camp is established with one or two shelter tents. Sounding holes are bored to establish appropriate depth (around 18-20m) before a triangular hole is cut with chainsaw and chippers. This can take up to two hours through 500 mm thick ice.

The first orientation dives are made one at a time with the Antarctica New Zealand Diving Officer. Both divers are on lifelines and basic signals are sent and responded to. This dive serves as a skills check-out and to establish that the diver has sufficient thermal protection. A second dive is then conducted with buddy pairs of candidates diving under lifeline instruction. At the end of diving, heavy equipment is secured in the tents and debriefing and further training is conducted during the evening.

The following morning diving resumes and ideally all diving candidates achieve four dives. In practice this is rare as candidates underestimate the difficulty of resurrecting frozen diving equipment (a most important lesson is learned about allowing equipment to become frozen). While the dive time might be limited, the experience of transport over snow and ice, the cold

topside conditions and the difficulty of diving through ice, provides a useful message of how necessary it is to obtain the correct diving suit and gear for polar diving. Being able to stage the training in August permits Event Managers sufficient time to consider over-ambitious expectations and replace any inadequate and inappropriate equipment.

Operations

A Diving Manual is issued to all Event diving staff prior to travel to Antarctica and a Diving Supervisor – independent of the science party - is appointed by Antarctica New Zealand. The Principal Scientist and the Diving Supervisor will have together written the Diving Operations Manual, a diving logistics/risk assessment/risk management document, prepared before departure and approved by the Antarctica NZ Diving Officer. A template and example are available in the Diving Manual.

The standard operational limitations on New Zealand diving Events are detailed in the Diving Manual. The fundamental rules for diving are that:

- All diving is to be conducted using lifelines with individual tethers;
- The maximum depth is 30m unless special permission is sought from the Diving Officer on an individual basis;
- The maximum number of dives per 24 hour period per diver is 2;
- The maximum dive duration is 40 minutes;
- All dives are planned based on the DCIEM tables;
- The minimum team size is 5;
- Each diver must enter the water with two independent, winterized regulators;
- The diver must wear a dry suit;
- Open water diving is discouraged;
- All dive holes will be drilled in pairs not greater than 50 m apart to serve as safety holes in case of seal occupancy during the dive; and,
- Divers must have a rest day from diving after 5 consecutive days of diving.

On arrival at Scott Base all new arrivals and regular visitors who have had more than a 3-year absence from Scott Base must undergo a two-day Antarctic Field Training (AFT) programme with snow survival instructors stationed at Scott Base. This program includes an overnight stay in a snow shelter of their making. Once AFT has been completed the Event group must be briefed by Base staff and resources allocated and preparations made before any field work can commence. While all New Zealand Events operate independently of outside support, contact with McMurdo Station staff is required to be maintained with regard to any hazardous field activity so that, in the event of an accident, the emergency services can be called in.

For all approved diving Events Scott Base staff prepare the dive sites including melting ice holes and transporting heated huts or tents to the dive sites. The melting of holes is the longest process in setting up a dive camp - Scott Base engineers have constructed a unit that will melt one hole through 2.5m thick ice in 9 hours. Other hole making systems used in McMurdo Sound are quicker but require the presence of heavy machinery which may not be appropriate at some of the more remote locations such as on Victoria Land.

Most diving is conducted through floor holes in heated huts. When conditions are suitable, diving has been achieved through holes in the open but any wind above 5 knots chills the surface support to the point where the standby diver becomes ineffective. In Oct-Nov 2003, Event K081 from NIWA successfully dived from a “light-weight” camp of tents at Cape Evans. A Polar Haven was used as the Dive Hut/Laboratory and an Endura for the mess hut for 6 team members. It was a tight squeeze but as a trial run for a long range expedition it proved surprisingly efficient as a mobile dive camp and would require fewer vehicles than a hut-based convoy.

Range of Diving

Diving operations have been completed from Cape Adare at approx 72°S to Pram Point at 77°S during the Latitudinal Gradient project. However, the greatest number of dives have been completed in the 30 km embayment between Cape Evans and Cape Armitage (Table 1.) There is an ongoing collaboration between US and New Zealand scientists diving in the Taylor Valley and New Zealand divers spent 3 seasons in the late 1990s diving at Lake Vanda in the Wright Valley. The Taylor and Wright valleys form a major part of the Dry Valleys system of Southern Victoria Land.

Table 1. Diving Events 1985 – 2006

Event	Month/Year	Organisation	Focus	Area	Divers	Dives
K021	Oct/1985	Auckland Uni	Fish	Cape Armitage	4	18
K029	Nov/1987	TVNZ/Cant Uni	Bioprospecting	Cape Armitage	6	47
K054	Oct-Nov/88	Canterbury Uni	Bioprospecting	Cape Armitage	8	162
K161	Nov-Dec/89	Water Quality Centre	Soft sediments	New Harbor	1	17
K062	Oct-Nov/1989	Otago Uni	Algal physiology	Cape Evans	3	48
K201	Oct-Nov/1991	Canterbury Uni	Bio prospecting	Cape Armitage	5	117
K291	Oct-Nov/1992	TVNZ	Documentary	Pram Point – ErebusTongue	5	30
K081	Dec 1997	NIWA	Algal physiology	Lake Vanda	3	30
K081	Dec 1998	NIWA	Algal physiology	Lake Vanda	3	36
K081	Dec 1999	NIWA	Algal physiology	Lake Vanda	3	24
K059	Oct 2001	Canterbury Uni	Biodiscovery	Cape Armitage	5	54
K081	Oct-Dec/2001	NIWA	Biodiversity	Cape Evans New Harbor	7	182
K059	Jan-Feb/2002	Canterbury Uni	Biodiscovery	Cape Armitage	4	60
K081	Oct-Nov/2002	NIWA	Biodiversity	Cape Evans Dunlop Island	8	96
K068	Nov/2002	Otago uni	UV/Ice studies	Cape Armitage	8	34
K059	Oct-Nov/2002	Canterbury Uni	Biodiscovery	Cape Armitage	7	82
K081	Jan 2003	NIWA	Biodiversity	Terra Nova Bay	5	20
K068	Oct-Nov/2003	Otago Uni	UV/Ice studies	Cape Armitage	3	38
K081	Oct-Nov/2003	NIWA	Biodiversity	Cape Evans	5	34
K068	Oct-Nov/2004	Otago Uni	UV/Ice studies	Cape Armitage	4	61
K083	Jan-Feb/2004	NIWA	Biodiversity	Cape Adare – Terra Nova Bay	4	16
K068	Oct-Nov/2005	Otago Uni	UV/Ice studies	Cape Armitage	3	47
K082	Oct-Dec/2006	NIWA	Biodiversity	Terra Nova Bay	5	43
Total					110	1,296

First-time diving Events are restricted to dive locations within two hours ground transport of Scott Base and are not usually permitted beyond the McMurdo Station – Scott Base delimitations. Once field operations have been given final approval by base staff, Event members usually complete a shake-down dive through a dive hole very close to Scott Base or McMurdo. Diving operations south of the Erebus Ice Tongue may be conducted by day travel from Scott Base but daily travel to Cape Evans is considered time consuming and impractical except on an opportunistic basis.

Open water diving has been attempted by divers engaged in film making but this is an unusual activity at Scott Base. Boating operations have been considered but, as the Event would have to fund the purchase of at least two capable boats and open water conditions are unpredictable, it would be a major undertaking for any Event to establish.

Issues

Several potential issues merit discussion in this forum. The first relates to the risk posed by fierce competition for funding for Antarctic activities and the pressure to realize savings in dive-based Events.

Non diving support: For most diving Events the logistics of training, transport, establishing and maintaining dive holes and then the limited amount of dives and dive time, makes diving a relatively unattractive and expensive tool for Antarctic research. However, even though there are an increasing number of alternatives to direct sampling (drop cameras, grab samples ROVs) there is still a need for the deployment of instruments, collections of specific organisms and direct observations to be carried out by a diver in the water. Events managers are minimizing the cost and time associated with diving by suggesting that non divers be used for surface support and the number of divers in the group reduced. Of course this puts added pressure of diving hours on the few divers available and introduces room for the topside support members, who are untrained in dive procedures, to make errors. Occasional emergency scenarios have shown the importance of having all team members with diving qualifications and all preferably trained ice divers.

Life lines: Most diving Events are scheduled for October – December and rarely last more than a few seasons. Consequently the diving staff are unfamiliar with their Antarctic habitat and more comfortable in temperate waters. Most new divers blanch at the idea of using a life line for every dive and are reluctant participants. However, they quickly become comfortable and there is a universal acceptance of life lines at the end of their project. When divers are on life lines the Dive Supervisor can recall them at any time. Also, they cannot move more than 50m from the hole. This results in mandatory compliance with the dive plan and reduces the risk of exceeding depth and time limits. As Antarctica New Zealand does not operate a recompression chamber, and our divers are on short stays on the ice, the life line remains our main tool for risk management and avoidance of decompression illness.

Equipment: For some organisations managing diving Events for the first time, funding for personal diving equipment is not considered high priority. Volunteer divers who are very keen

to gain polar diving experience in the field may even jeopardise their health by sharing dive suits and gloves of the incorrect size. Antarctica New Zealand does not supply or hire diving equipment and Event planners are reluctant to purchase good quality dry suits for a short duration programme.

Media divers: Most of the diving Events have had a scientific focus and some have been filmed and made into documentaries. Media divers can have unusual expectations and request considerable base resources. They also require much greater preparation time and need to be able to repeat shots. Event managers are often torn between compliance with media requests and the frustration of non-productive time that can extend field time into days. Media divers often request compromises in safety standards in order to enhance the “shot”. For safe oversight in these and other unforeseen situations the appointment of an even-handed but firm Diving Supervisor is extremely important.

Summary

Twenty two years of ice diving in Antarctica have seen a great improvement in equipment and procedures. Twenty three diving Events have been completed using 110 divers who have logged 1,296 dives. Equipment failures are rare. Most regulator shortcomings have been identified and gear failure is now minimized. The risk of low pressure inflation devices freezing open can never be eliminated but minimized with good training and on site care. We note all such incidents in the diving record. Diving injuries over the period have been minimal. So far only two minor injuries have been reported. Both involved burst ear drums and in each case the diver made a complete recovery. One diver elected to return to New Zealand immediately when he was fit to fly. Problems now are more likely to stem from the increased accessibility for scientists from a variety of government, university and private organisations to successfully propose an Antarctic Event and for a decrease in the ability to maintain control over diving safety of these disparate, one-off proposals and their media promotion.

**ANTARCTIC INLAND WATERS:
SCIENTIFIC DIVING IN THE PERENNIALY ICE-COVERED LAKES
OF THE MCMURDO DRY VALLEYS AND BUNGER HILLS**

Dale T. Andersen

Carl Sagan Center for the Study of Life in the Universe
515 N. Whisman Road
Mountain View, CALIFORNIA 94043 U.S.A.

Scientific diving in the ice-covered lakes of Antarctica presents a number of challenges to the researcher. Often located in remote areas and distant from main bases or camps, all personnel and gear must be transported to the site with severe limits on the weight and volume of gear. Perennial ice, up to 6 m thick, seals the lakes preventing easy access to the water column and benthic environments. The objectives of the research dives are to explore safely, document, sample and carry out experiments within these unique ecosystems. In addition, the lakes are environmentally sensitive and must be protected from changes to either the water column or benthos. Some lakes are highly stratified and disturbing the water column is of concern as is the introduction by divers of organisms from the sea or transport of microorganisms of differing species between lakes. The history, methods, techniques and safety considerations of underwater research in Antarctic lakes are discussed beginning in the late 1970s to the present. Training and equipment selection, techniques for creating dive holes through the ice and protocols for diving beneath the ice are addressed. Environmental considerations that impact the research and the diving are described.

Introduction

About four percent of the Antarctic continent is ice free. The McMurdo Dry Valleys of Southern Victoria Land and the Bunger Hills near the Shackleton Ice Shelf are the two largest such regions. In 1903, Robert Falcon Scott and two companions walked to the edge of what is now called the Taylor Glacier and discovered “the Dry Valley.” This was the first time a significantly ice-free area had been discovered in Antarctica. Lake Bonney was the first of the McMurdo Dry Valley lakes to be seen and other lakes in Taylor Valley were observed, named and noted by expedition members (particularly by Griffith Taylor) of the second Discovery expedition in 1911.

Modern studies and additional discoveries did not really begin until the International Geophysical Year in 1957. The various lakes of the McMurdo Dry Valleys were studied initially by drilling small (10-25-cm diameter) holes through the thick ice covers in order to access the

water columns. In 1977, Dr. George M. Simmons, Jr. visited the lakes as part of a research effort led by Simmons and Bruce Parker. Simmons asked a simple question for which, at that time, there was no answer: “what, if anything, lives in the benthic regions beneath the thick ice-covers?” To answer this question Simmons assembled, organized and trained a dive team that would, for the first time, make direct observations of the lake benthos. In November 1978, lakes Hoare (Fig. 1) and Fryxell in Taylor Valley were chosen to be the first lakes to be explored. The up to 6-m thick ice presented a formidable challenge: to the researchers of physically getting past the ice into the lake and to the divers who had to prepare and train for working in a completely new type of environment. These initial difficulties were overcome and our efforts led to the discovery of rich and luxuriant benthic microbial communities thriving beneath the thick ice covers of both of the lakes visited.



Figure 1. Lake Hoare, Taylor Valley, Antarctica.

Site Description

The perennially ice-covered lakes of the Dry Valleys of Antarctica are unique ecosystems relevant to the study of life in extreme environments on Earth and the prospects for life on other planets. Early studies of the lakes focused on basic limnology and the ecology of the benthic microbial mats and phytoplankton (Simmons *et al.*, 1993). In 1994, a Long Term Ecological Research (LTER) project was established as a means to investigate the physical, chemical and biological linkages of the lakes, streams, soils and glaciers located primarily in Taylor Valley. The LTER studies are guided by two main hypotheses: (1) the structure and function of the McMurdo Dry Valleys are differentially constrained by physical and biological factors, and (2)

their structure and function are modified by material transport. More recently a third hypothesis, one with a temporal component, has been added: (3) past climates in polar desert environments strongly overprint present ecosystem structure and function.

In 1991-1992, as a member of NASA's Joint Working Group for Space Medicine and Biology, Exobiology Implementation Team, we negotiated and organized with our Soviet counterparts a joint US-Soviet expedition to the Bunger Hills, Antarctica. The Bunger Hills is the second largest of the ice-free regions of Antarctica and hosts numerous lakes, some of which are perennially ice-covered as are the lakes in the McMurdo Dry Valleys. White Smoke Lake, a 90-m deep perennially ice-covered lake situated next to Apfels Glacier, was chosen as the main lake of study and site where the bulk of the diving was to take place. Several training/equipment evaluation dives were made in Lake Figurnoe near the main Russian "Oasis Station" prior to transportation of gear to the field camp set up at White Smoke.

The physical properties of perennially ice-covered lakes are determined to a large extent by the effects of a thick ice-cover which eliminates wind-generated currents, reduces light penetration and limits gas exchange with the atmosphere. The lakes have a persistent ice cover with a 4-6-m thickness overlying a layer of fresh water - although deeper layers in some lakes are saline. The ice thickness is determined by the energy lost from the lake by conduction through the thick ice cover, energy released in the lake by sunlight and, more importantly, by latent heat as water freezes to the bottom of the ice cover. McKay *et al.* (1985) developed a model of the lake ice cover by assuming that the ice cover was in steady state and were able to explain the thickness of the ice cover. In steady state the lake level and the ice thickness vary with season but remain constant on annual average.

Wharton *et al.* (1995), Andersen *et al.* (1995, 1998) and Doran *et al.* (1996) have described perennially ice-covered lakes in the Antarctic McMurdo Dry Valleys and Bunger Hills as analogs to lakes that may have existed on early Mars. These restricted environments contain thriving microbial communities growing in the absence of higher, multicellular organisms. Microbial mats are abundant throughout many of the McMurdo lakes and are composed primarily of cyanobacteria (*e.g.*, *Phormidium*, *Oscillatoria*, *Leptolyngbya* and *Lyngbya*) and pennate diatoms (Wharton *et al.*, 1983). These mats form in a variety of environments, depths and light regimes with species distribution and mat morphologies depending on particular environmental conditions (Simmons *et al.*, 1993) including the nature of perennial ice cover (Fig 2). Communities such as these are rare and provide a great deal of insight regarding metabolic strategies, community structure and the formation of the sedimentary record. The thick ice-covers have a profound effect on physical parameters that affect the biological communities. Temperature and light regimes, the retention and concentration of dissolved gases and sedimentation are all controlled by the presence of thick, perennial ice.

Science Description

Science investigations of the lake ecosystems are what drive the need for diving. There are numerous requirements that can only be addressed by a diver conducting *in situ* observations, measurements or sampling. Activities such as the collection of undisturbed sediment cores of the microbial mats, setting out colonization substrates in specific areas, taking measurements of

fluorescence yield within the benthic microbial mats made using a diver-operated, submersible PAM fluorometer, and *in situ* high-resolution O₂ and pH profiles are performed by divers using micromanipulators at the mat/sediment interface. These and other similar tasks require the human presence and are not capable of being made from the surface remotely.



Figure 2. Gas-saturated benthic microbial mats in Lake Hoare, Taylor Valley, Antarctica at a depth of 5 m. Lift-off is due to the added buoyancy of the bubbles trapped within the mat matrix.

Diver training and gear selection

In 1978, Simmons organized the first team of divers, all of whom were either undergraduate or graduate students in the biology department at Virginia Tech. The selection of individuals was based on their ability to contribute to the science by carrying out a variety of limnological tasks and ability to perform under water in a variety of difficult environments including lake, river or ocean, cold and dark, high or low current or high turbidity. While it was not practical to replicate the thick ice conditions, cold and isolation of the McMurdo Dry Valleys, we were able to train physically and prepare for what we expected and the unknowns that would be presented.

Training

Training included significant amounts of time dedicated to safety drills, team organization and specific tasks associated with underwater science. It was very important in those first few years that the group of divers operated as a coherent team with each person knowing his or her strengths and weaknesses. Our training was designed to prepare each of us for the demanding

environment of Antarctica and allowed Simmons to evaluate each individual in a wide variety of conditions which, in turn, provided him with insight into their level of ability.

Dive Gear

The first year of diving in the lakes custom fitted wetsuits (Dudas Dive Duds) were used. The suits were 3/8" Farmer Johns with neoprene skin on the inside, jackets with attached hoods and 3/4 length zippers. Thick neoprene booties and gauntlet mitts were used for foot and hand protection. At this time, double-hose Royal Aquamaster regulators were in use as the standard coldwater regulator. Fenzy vests were used for buoyancy control and steel twin 72-cubic foot dive cylinders as air supply. Standard weight belts were worn and a webbed harness was used for the attachment of a tether. Tethers were no longer than 50 m of 1/2 twisted nylon rope. A 5 cfm compressor was used on site to fill cylinders. During the first season of diving, we used standard face masks without communications. Attempts to use a hard rubber, US Divers full face mask with rudimentary communications supplied by lollipop mikes and earphones proved unsatisfactory and were not used after several dives.

After the first year of diving, we opted for drysuits (Poseidon Unisuits), Miller weight harnesses and KMB-10 full face masks with hardwire communications using US Divers cold water first stage regulators. The masks were used in scuba mode with twin steel 72 cu. ft. cylinders as air source. Wet mitts were still used for hand protection. Thermal garments at that time were limited to the issued cold weather gear from NSF such as several layers of cotton waffle weave Long Johns and a vest with synthetic insulation. Wool socks were worn as insulation for the feet. The addition of the drysuits and communications improved safety significantly, productivity and overall comfort of the divers before, during and after the dives.

In 1991, for dives in the Bunger Hills, we chose Diving Unlimited International (DUI) CF200 drysuits and Thinsulate undergarments, Exo-26 full face masks with hardwire communications, Poseidon Odin first stages with environmental caps, standard DUI weight belts, twin 80 cubic ft dive cylinders and 60 m tethers as our operational dive configuration. A 3.5 cfm Poseidon air compressor provided diving air and 400 cubic feet of aviator's oxygen and a demand mask was available as onsite emergency oxygen. Evacuation from the Bunger Hills at that time would have proved quite difficult because of its remoteness and lack of direct logistic support. Hence, all diving was conducted very conservatively, including profiles requiring no decompression or repetitive diving.

Regulator performance in general was quite good over the years if basic maintenance was performed. Of importance was to ensure that the regulators, particularly the full face masks, were warm and completely dry prior to diving. The Exo-26 masks were best dried by removing the diaphragm from the second stage in order to remove all water that had accumulated behind the diaphragm.

Recent years have seen the adoption of the KMB-18 full face mask with surface supplied air, a bailout bottle and hardwired communications as standard equipment for diving in the lakes. This new method provides additional safety to the diver by providing a large volume of available breathing gas and decreases the amount of gear required under water by eliminating the large cylinder(s) on the diver's back.

Dive Planning/Safety

Significant thought went towards safety planning in the event of a dive-related emergency. At that time the recompression chamber was not available in McMurdo and the nearest treatment facility was in Christchurch, New Zealand. A detailed dive plan was submitted to NSF which included this information as well as on site oxygen (minimum of 200-400 cubic ft) with a regulator and demand mask. All divers were trained in basic diver first aid and accident management procedures. All dives were conducted using the U.S. Navy no-decompression tables and depths were limited to 130 ft. with the "next greater depth and time" principle applied to all dives.

Divers were either tied in directly to the line using a bowline on a coil around the diver with a figure eight connected to the shoulder by a locking carabiner or by attaching the line in two places (waist d-ring and shoulder d-ring) with locking carabiners. Initially we used buddy pairs under water with each diver on a tether. This became somewhat unwieldy as lines tangled and typically there was only work that one diver could perform during a dive. We soon adopted the procedure of having one tethered diver under water with hardwire communications to the surface. While tether management included the use of line signals, safety protocols called for dive termination if voice communications failed or if regulators malfunctioned.

Without doubt, the most important skill for each diver to master was buoyancy control. This was paramount for safety and for being able to maneuver under water without disrupting the local environment which, in the lakes, is quite delicate and prone to disturbance. Being able to swim with a tether in tow, along with samples or other scientific apparatus in hand, without 'finning the bottom' was (and still is) essential to successful investigations in these lakes.

Making a dive hole

Perhaps the most daunting task that faced our group during the first year of diving at the Lakes was getting through the 6-m thick ice. In 1978, the drill normally used for boring dive holes in the sea ice was temporarily out of commission and Art DeVries was also in need of a new way to make holes through the ice. He developed the idea of using a copper coil and a steam cleaner to melt a hole through the ice. We worked with Art that first year to get the system together and used it to successfully melt the first holes in Lakes Hoare and Fryxell. Love *et al.* (1982) described methods for melting dive holes in thick ice. Eventually we simplified and improved upon the original system that was made up of a flat 1-m diameter copper coil, two 8-m long steam hoses, an Alkota steam cleaner and two 5 Kw generators. The system was filled with a water/glycol mix and once the burner was turned on it took the coil about 24 hours to get through 4 m of ice. A small submersible pump was placed on top of the coil in order to keep the water level just above the coil, which ensured that the bulk of the heat would be transferred to the ice, not to melted water. The coil was also tethered to the surface on four sides to help guide the coil through the ice, keeping it flat and level throughout the process.

A crevasse ladder was placed into the hole as it was melting into the ice to allow for sample collection or other observations and measurements made within the ice cover during the melting operation. The accumulation of sediment in the ice as the hole was being melted was also common, as some of the lakes have a significant load of sediment on and within the ice. The

sediment becomes a very good insulator and, once enough has accumulated, the coil had to be pulled up and the sediment removed before melting resumed. This method resulted in a very smooth, clean hole.

A recent change of approach now uses a long trombone shaped coil (about 15 cm in diameter) that has small coils wrapped around the 'trombone slide'. A small diameter drill is used to make several holes through the ice in the rough shape of the desired hole, and the long coil is then placed into a hole and is used to melt the ice between the various drill holes until the size and shape of hole is created. Both methods work well but the use of the flat coil does afford the scientist the opportunity to study the ice stratigraphy while making the hole.

Summary

Diving in the perennially ice-covered lakes of Antarctica presents a number of unique challenges including the remote nature of the sites, often only accessible via helicopter. This can place severe constraints on equipment weight and volume and evacuation in the event of emergencies. The lake environments are usually quite stable with very few conditions changing over time. However, they can be very dark, subject to turbidity and, because of the thick ice cover, require that scientific divers be adequately trained and prepared to carry out successful operations within these unique settings.

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SCIENTIFIC ICE AND COLD WATER DIVING IN FINLAND: TRAINING REQUIREMENTS, PRACTICES AND OBSERVATIONS

Juha Flinkman

Finnish Institute of Marine Research
P.O. Box 2 (Erik Palménin aukio 1)
FIN-00561 Helsinki, FINLAND

Background

Scientific diving has been conducted in Finland as long as scuba equipment has been available since the early 1950s. For a long period the requirements for scientific diver certification were the CMAS 2 or 3 star equivalent recreational qualifications. In the early 1990s the need arose to provide a professional standard and certification systems for scientific divers. This was achieved in 1994, when professional certifications were first issued to scientific divers. Finnish scientific divers participated in the ongoing development of European Scientific Diving Standards (ESDS). These standards were taken into consideration in a way that the Finnish national standards would meet or surpass the Advanced ESD standards. Also, inspired by the recorded experiences of development of U.S. scientific diver standards and the American Academy of Underwater Sciences, it was decided that it should be national scientific communities that set standards and supervise their own implementation of European standards. The Finnish Scientific Diving Supervisory Committee was founded in 2004.

As Finland is situated at fairly high latitudes (59° to 66°N), cold water and ice are unavoidable elements. All inland waters, and to a large extent the Baltic Sea, freezes annually for 3-5 months. In addition, strong thermal stratification in both larger inland water bodies and the Baltic Sea results in water temperatures of usually less than 3°C below the thermocline even during the summer. Hence, cold water and ice diving are integral parts of Finnish scientific diver training.

Training and Requirements for Cold Water and Ice Diving

All scientific diving training in Finland is based on drysuit diving. Hence, learning to dive in drysuits is not a specialty issue. However, the basic requirement for entering the ice diving module is the diving experience equivalency of a CMAS 2 star qualification, for example, the PADI AOW diver.

The ice- and cold-water training module (Leinikki, 2005) is designed for local (Nordic-Boreal) environments, inland waters and the Baltic Sea and hence lacks many of the specific features connected with polar (Arctic, Antarctic) environments. The training module consists of theory and practical components.

The theory portion is compiled into a manual and teaching materials are in the form of slide shows. The contents include:

Cold-water Diving	Ice diving	Entry hole
Safety lines and measures	Emergency: Lost diver	Pack ice diving: special safety precautions
Safety rules	Winter diving	Equipment for diving in water temperatures <+4°C
Ice	Pack ice	Diving under the ice (restricted surface)
Autumn ice	Spring ice	Strength of the ice
Moving on the ice	Equipment	Freeze-up and insulated first stages
How to avoid the freeze-up	Other diving equipment	Other equipment
Hole making	Transportation	Clothing
Dangerous places	If you fall through the ice	Helping someone fallen through the ice

The practical portion of the module is usually carried out on Baltic Sea ice during early spring, when sub-zero temperatures still prevail, and ice cover and thickness are at annual maxima. A location with access to pack ice is preferred as diving in pack ice is more demanding than on fast ice and requires specific techniques and skills. The practical part of the course contains a minimum of 10 ice dives. These exercises cover all the components of ice diving, including lost diver search and recovery drills.

Decompression and Mixed-Gas Diving in Cold Water

Because of the strong thermal stratification of the Baltic Sea, practically all diving to depths in excess of 20 meters consists of cold water dives. The summer thermocline can usually be found at 15-20 m depth, where the temperature very abruptly changes from 15-20°C to 3-4°C, or even colder. The water layer between thermocline and primary halocline (usually at 70m) is called “winter water” as its temperature remains the same throughout the year. In addition, except for June-September, even surface water temperature may be as low as 0°C. This, of course, must be taken into consideration when planning deeper dives that require decompression and/or use of mixed gases.

Cold effects on the diver need to be considered in all diving and especially so for decompression or mixed gas dives that by their nature tend to be longer. Thermal stress affects both bodily functions and mental capacity. When a diver gets cold the ability to perform tasks requiring agility, dexterity and delicate movements decreases. Also, being cold makes the diver increasingly prone to injury. In addition, reduction in body temperature affects both on- and off-gassing of inert gases. Gases other than air have different thermal conductivity capacities which further affect on- and off-gassing and accelerate cooling of the body’s core temperature. These need to be considered as well.

These topics are thoroughly discussed in classic works on diving medicine but not always brought together in a practical way for divers. Therefore, based on two decades of experience, we have tried to teach our scientific divers what the thermal factors are that restrict cold-water decompression diving.

Effects on cold on a diver are well known. Loss of dexterity and proneness to injury are evident but the effects on mental ability are more difficult to observe, at least to the diver himself. On a deeper dive, as decompression obligation increases, the necessity to solve

occurring problems at depth increases. As the dive gets more complicated, the importance of problem-solving ability is emphasized. The effect of cold on a diver is similar to nitrogen narcosis: the first ability to go is higher thinking, while super-learned, or instinctive, skills remain. Therefore, it is equally important to consider the problems associated with cold by providing adequate thermal protection and/or reducing dive time. It is also important to reduce the effect of inert gas narcosis by using appropriate gas mixtures.

Cold has a significant effect on the ability of tissues to on- and off-gas. Usually, the diver is warm prior to a dive. Most on-gassing occurs early to mid-dive when the diver gets the most exercise. Inert gases are rapidly absorbed in warm, well-circulated tissues, whereas towards the end of a dive, cooling takes place. Additionally, there is usually less exercise during the ascent. Cooling starts at the extremities, the hands and feet, where circulation slows down in cold tissues. This may result in a slower exchange of inert gases from the tissues and in the worst case may lead to localised bends. There are observations where a diver, being cold already from the onset of the dive, receives less loading of inert gases in the tissues. However, this is not a viable option, as the effect of cold reduces functionality of the diver to an extent where the whole dive becomes pointless.

Deep decompression dives benefit from the use of mixed gas. The aim is to reduce both inert gas narcosis and decompression requirements thus making the diver more efficient and making the dive more comfortable to the diver. The most commonly used mixed gas in scientific diving is nitrox, or oxygen-enriched air. Using enriched air nitrox (EANx) mixes means breathing a smaller percentage of inert gases thus reducing the nitrogen intake. However, the most important use of nitrox or pure oxygen is during decompression where it promotes accelerated exchange of the inert gases from tissues to the lungs. Also, this helps to offset the reduced amount of offgassing caused by cold effects.

In more advanced forms of mixed gas diving, the effects of nitrogen narcosis and the potential threat of oxygen toxicity can be reduced by replacing some of the nitrogen and oxygen with helium; this is called “tri-mix”. Helium is an inert gas but has a reduced narcotic effect. Helium is a small-molecule gas that is absorbed in tissues faster than nitrogen and hence needs slightly longer decompression times on bounce dives. However, surface interval times become shorter as helium exits the tissues faster than nitrogen.

The fact that helium is a very effective heat conductor has an impact on operational requirements, both in the suit and in the lungs. Helium conducts heat more effectively than air, making it “lethal” if used for suit inflation. This refrigeration effect can be avoided by using a separate cylinder containing air or argon for suit inflation. Argon insulates slightly better than air and, hence, adds to suit insulation capacity. Of importance is to thoroughly flood the drysuit with argon before the dive. However, argon is highly narcotic, hence a good neck seal is essential if using argon for suit inflation with a full-face mask.

Helium also accelerates cooling of the core through the lungs. As the breathing gas pressure is reduced, its temperature gets even cooler than ambient. Breathing gases in open-circuit scuba are very dry, which enhances cooling because of high evaporation, as the breathing gas gets moisturized by the lungs. When the excessive thermal conducting capacity is added into the

equation, breathing helium mixes in cold water at depth may cause a heat loss that approaches the human body's capacity to produce heat. Hence, saturation diver's heliox mixes are pre-heated. Scientific divers do not encounter such helium percentages or depths using scuba but the heat loss and cooling of the core must be considered when assessing the envelope for acceptable dive times in cold water.

Conclusion

When planning cold water decompression and/or mixed gas dives using scuba, the abovementioned points should be considered. Most importantly, adequate thermal insulation is a must and the possibility of accidental drysuit flooding, even a minor one, may not be overlooked. Additionally, cooling of the core must be considered as it affects the body's ability to maintain sufficient heat under the external cold stress significantly. This is especially important when breathing gases contain helium. As a rule of thumb in cold-water decompression diving, thermal management usually becomes the restricting factor before gas capacity presuming, of course, that the gear used is adequate.

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CANADIAN ARCTIC SCIENCE DIVING: A FISHERIES & OCEANS PERSPECTIVE

Jeremy W. Stewart

Fisheries & Oceans Canada Central & Arctic Region
501 University Crescent
Winnipeg, MANITOBA, R3T 2N6 CANADA

Introduction

Fisheries and Oceans Canada (DFO) is the federal department within the Government of Canada responsible for ensuring the sustainable development and safe use of its country's oceans and inland waters. DFO represents the majority of Canadian scientific diving operations in the Arctic and maintains one National Diving Safety Office and six Regional Diving Safety Offices in support of its research objectives. The Central & Arctic Region has coordinated Arctic diving operations on behalf of DFO since the early 1970s from the Freshwater Institute in Winnipeg, Manitoba (Townsend, 2007). The number of DFO employees who dive in the Arctic is project driven and will vary from one year to the next. Historically, departmental dive teams would deploy from permanent or semi-permanent camps; however, in 1995, DFO amalgamated with the Canadian Coast Guard (CCG) resulting in an increase in ship-based deployments. This paper will examine past, present and future DFO-led Canadian Arctic science diving projects, as well as review regulatory requirements and safety procedures, ice diver training and competency, equipment standardization and operational considerations for Arctic diving operations from a DFO perspective.

Canadian Arctic Science Diving Projects

On October 2, 1997, the Canadian Coast Guard Ship (CCGS) DES GROSSEILLIERS began over-wintering in the Beaufort Sea where it served as a floating laboratory for an international team of scientists in a year-long quest to understand thermodynamic interactions among atmosphere, sea ice, oceans and snow cover as part of the Surface Heat Budget of the Arctic Ocean/Joint Ocean Ice Studies (SHEBA/JOIS). During the joint Canada – United States research expedition, departmental dive teams provided bubble-free operations that largely aided ice algae studies and science outreach programs. At the time, SHEBA/JOIS represented the largest Arctic project ever funded by the National Science Foundation (NSF), and the most comprehensive study ever carried out in Arctic waters (Welch, 1998).

The Joint Western Arctic Climate Study (JWACS) is an ongoing collaborative effort between DFO and the Japan Marine Science and Technology Center (JAMSTEC) to study ocean ice processes and climate change in the western Arctic Ocean (Fig. 1). In 2002, the United States also participated through the National Oceanic and Atmospheric Administration's (NOAA) Ocean Exploration Program from the CCGS LOUIS. S. ST. LAURENT. The largest icebreaker

in the Canadian fleet facilitated a survey that covered an extensive area of the mainly uncharted Canada Basin, where divers supported fish observations and zooplankton collections (Gradinger and Bluhm, 2004), video surveys of sea ice topography and the National Geographic Magazine story *Breaking the Ice* (Holland and Nicklen, 2004).



Figure 1. A biologist sips from a melt-pond as divers deploy from the CCGS Louis S. St. Laurent during the Joint Western Arctic Climate Study (JWACS) in 2002.

Funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Canada Foundation for Innovation (CFI), the Canadian Arctic Shelf Exchange Study (CASES; Fig. 2) is a multi-year international research project led by Canadian universities and federal departments to understand the biogeochemical and ecological consequences of sea ice variability and change on the McKenzie Shelf (University of Laval, 2007). As part of the initiative, the CCGS AMUNDSEN was transformed into a state-of-the-art research icebreaker that features an internal moon pool, acoustic well, bottom-mapping multi-beam system and several dry and wet laboratories. The main component of the project occurred in 2003/04 when the ship over-wintered in Franklin Bay and divers performed water and zooplankton collections, light measurements through sea ice (Ehn *et al.*, in press), under-ice coring and photo and video surveys of the complex modifications to the icebreaker.

DFO-led dive teams will once again deploy from the CCGS AMUNDSEN in 2008 on behalf of the Circumpolar Flaw Lead (CFL) System Study. With 200 scientists from 14 countries, CFL is positioned to be the largest International Polar Year (IPY) research program in Canada, and among the largest in the world. Divers will support a wide-range of science activities in the flaw lead system, and the making of an IMAX documentary film.



Figure 2. A DFO diver positions an ultra-sensitive light meter beneath 2-metres of sea ice in support of the Canadian Arctic Shelf Exchange Study (CASES).

Regulatory Requirements and Safety Procedures

The Canadian Occupational Safety and Health (COSH) Regulation Part XVIII, Diving Operations, came into effect on September 15, 1998. Pursuant to the Canada Labour Code Part II, it prescribes legal requirements for diving operations in the federal jurisdiction of Canada and aims to prevent diving-related accidents and injuries among employees who dive, as well as non-employees who dive with employees. This important piece of federal diving legislation distinguishes between no-decompression diving operations that are undertaken for scientific or archaeological purposes and commercial diving applications.

The Departmental Diving Safety Procedures (DDSP) identifies the administrative and operational requirements that are necessary to ensure that DFO employees who dive comply with the Canada Labour Code Part II and the COSH Regulation Part XVIII Diving Operations. The DDSP assigns roles and responsibilities for its operation and maintenance, as well as establishes protocols for medical standards, training, competency and approval to dive requirements, diving equipment preventative maintenance and inventory control, record keeping and diving operations. The DDSP also defines procedures specific to under-ice diving in Arctic environments, including training and competency requirements, equipment standardization and operational considerations.

The CCG Fleet Safety Manual was developed to meet the objectives of the International Management Code for the Safe Operations of Ships and for Pollution Prevention (ISM Code). Section 7.D.16, Diving Operations, describes the protocols that must be adhered to whenever diving operations are deployed from, or in support of, CCG vessels (Fig.3). DFO Central & Arctic Region Diving Safety Office is responsible for reviewing and approving all Arctic science diving plans from CCG vessels, in cooperation with Commanding Officers, prior to the commencement of diving operations.

<u>CCG FSM Diving Operations Checklist</u>	
CCG Vessel _____ Diving Operations Checklist	
Date of Operation: _____	
Designated Officer selected	Name: _____
	Signature: _____
Diving Supervisor	Name: _____
	Signature: _____
Divers certification and logbooks reviewed.	
CO/Designated Officer aboard.	
Collision Regs - Warning devices deployed (shapes, buoys, flags, lights).	
Vessel Traffic advised (Traffic Control / Security Call).	
Engine room notified - diving notices posted in E/R.	
Engine room systems secured & logged in E/R log.	
Diving plan and contingency plans reviewed.	
General announcement made.	
Commencement of diving operations logged.	
Completion of diving operations logged.	

Figure 3. Canadian Coast Guard (CCG) Fleet Safety Manual Diving Operations Checklist must be completed prior to the commencement of diving operations from CCG vessels.

Ice Diver Training and Competency

DFO has developed a comprehensive training program to prepare its employees and partners for ice diving operations in Arctic environments. In order to qualify for this training course, several prerequisites must be met. Those who wish to participate are carefully screened to ensure that they possess the appropriate medical clearance to dive, as well as the diver and emergency response training and experience needed to successfully complete the course objectives. Participants must demonstrate advanced diving and drysuit diving techniques and provide valid certifications in first aid and cardiopulmonary resuscitation and emergency oxygen

administration. The course includes a combination of classroom instruction and 10 under ice training dives that cover the following topics:

- Cold stress physiology;
- Characteristics of ice;
- Site preparation and safe use of associated tools;
- Equipment and lifeline configurations;
- Line-pull signals;
- Regulator use and free-flow procedures;
- Emergency procedures; and,
- Tender duties.

In addition to the aforementioned training requirements, employees who dive under ice in Arctic environments must be declared competent to perform these types of dives on an annual basis to maintain their departmental approval-to-dive status. This is accomplished through a check-out dive under ice or verification of previous ice diving experience that is considered adequate to ensure safe and effective Arctic diving operations.

Equipment Standardization

Drysuits and buoyancy control devices (BCD) are among the required equipment components for DFO Arctic diving operations. Makes and models are largely determined by personal preference; however, weight-integrated BCDs with quick-release mechanisms are encouraged to reduce or prevent back injuries that can be caused by repeated weight belt use. BCDs equipped with D-rings are not usually designed for tether attachment, so a harness must be worn underneath. Chest harnesses are used and constructed of stiff material webbing with parachute nylon stitching for maximum strength and durability. The X-back design avoids unnecessary neck strain, and a built-in stainless steel D-ring located at the abdomen connects the diver to a lifeline with a locking carabineer.

The main scuba system is made up of a 63 or an 80-cubic-foot aluminum scuba cylinder equipped with a single-hose regulator and submersible pressure gauge (a dive computer and underwater compass is worn side by side on the diver's wrist or forearm). A pony bottle bracket is used to securely mount a completely independent air supply to the main scuba system. A 13-cubic-foot aluminum pony bottle that includes its own single-hose-regulator and a compact pony gauge provides the redundancy needed for diving safely under ice. The US Diver/Aqua Lung Arctic SEAS and Conshelf Supreme XIV first stages, and US Diver/Aqua Lung Arctic second stage have proven to be extremely reliable under the most inhospitable conditions. The first stage regulators are environmentally sealed and calibrated as per the manufacturer's recommendations for coldwater use.

It is also important to note that DFO is in the process of phasing out and replacing non-coated lead diving weights with rubber-sealed weights. This will eliminate the potential for lead exposure by divers and reduce the environmental impacts on aquatic ecosystems.

Operational Considerations

A dive team consisting of at least two divers, with a minimum of one tender for each diver, is present at every dive site. A diver's tender is responsible for devoting his or her entire time and attention to the work of a diver and to the surface environmental conditions for the duration of the under-ice dive. One member of the dive team is designated as the Diver-in-Charge and this person is in command of the dive site and the diving operation, including the health and safety of the dive team members. A wildlife observer equipped with a firearm provides the surveillance and protection necessary in areas where polar bear encounters are likely to occur.

A lifeline is always used to tether a diver during under-ice dives. 150 to 250 feet of nylon braid rope is made available to the diver and the rope itself is conspicuously marked at 10 feet and 50-foot increments to allow the diver's tender to easily determine the distance between the diver and the surface. If the dive plan requires a standby diver to be deployed only in the event of an emergency, the standby diver's line is 33% greater than the length of the primary diver's line to assist in a search and in locating a lost diver or a diver in distress. In every situation, the lifeline is attached to the diver's harness with a locking carabiner and anchored into the surface of the ice with ice screws or secured to some other stationary and secure object.

In addition to the operational considerations for diving under ice, specific safety procedures are introduced when diving from ships. If diving operations are conducted in areas of marine traffic, the appropriate warning devices, such as flags, buoys, lights and reflecting material are displayed to define the restricted access limits of the dive site. The Commanding Officer or the Designated Officer, in consultation with the Chief Engineer and the Diver-in-Charge, ensure the ship's devices that could represent a hazard to the dive team members are properly secured and logged. A general announcement is made to inform the ship's personnel that diving operations are beginning and a similar notice is posted in the engine room. The CCG Diving Operations Checklist was designed to facilitate the process of diving from CCG vessels and is completed and signed by the Designated Officer and the Diver-in-Charge prior to the commencement of diving operations. During the course of a dive, communications are established between the dive site and bridge by handheld radio.

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ICE AMPHIPODS IN DRIFTING SEA ICE AROUND SVALBARD: QUANTITATIVE COLLECTIONS BY SCUBA DIVERS

Haakon Hop

Olga Pavlova

Norwegian Polar Institute
N-9296 Tromsø, NORWAY

Ice amphipods in drifting Arctic sea ice generally comprise four species: Gammarus wilkitzkii, Apherusa glacialis, Onisimus nanseni and O. glacialis. They utilize food resources under sea ice and represent an important link from lower to higher trophic levels in Arctic marine food chains. The abundance/biomass of ice amphipods below drifting sea ice around Svalbard has been determined from quantitative samples collected by scuba divers using electrical suction pumps. The trajectories and concentrations of ice occurring at different ice stations were determined from satellite data and the distribution of ice amphipods was interpreted based on both ice concentration and the origin of the sea ice. Their estimated biomass transport into Fram Strait and the Barents Sea has been estimated to be about 3.55×10^6 t wet weight (4.2×10^5 t C) yr^{-1} and 1.5×10^5 t ww (1.8×10^4 t C) yr^{-1} , respectively. Thus, the carbon import into the Barents Sea is only 4 % of that channeled through Fram Strait. This annual loss represents a large drain on the core population of ice amphipods in the Arctic Ocean. Reduction in ice thickness and extent caused by climatic warming will decrease this southward biomass transport substantially. If multi-year sea ice disappears from the Arctic Ocean, it is unlikely that the population of ice fauna will be sustained and a scenario of open water in the Arctic Ocean during summer, possibly occurring as early as 2040-50, would become detrimental to all ice-associated organisms.

Introduction

Sea ice represents a habitat for sympagic or ice-associated organisms (Horner *et al.*, 1992). Four amphipod species are known as autochthonous ice macrofauna in the Arctic: *Gammarus wilkitzkii*, *Apherusa glacialis*, *Onisimus nanseni* and *O. glacialis* (Poltermann, 1998; Lønne and Gulliksen, 1991a, c; Hop *et al.*, 2000), although *Gammaracanthus loricatus* may also be present in low numbers. *Gammarus wilkitzkii* is the largest ice amphipod, reaching 4 cm at age 6; maximum age being 6 for females and 7 for males (Beuchel and Lønne, 2002). These sympagic species use all food resources available under the sea ice (Poltermann 2001; Werner and Auel, 2005) but are also an important food for other ice-associated organisms such as the polar cod (*Boreogadus saida*), sea birds and seals (Bradstreet and Cross, 1982; Lønne and Gabrielsen, 1992). Ice amphipods, thus, represent an important link from lower to higher trophic levels in Arctic marine food chains. Polar cod is part of the ice fauna since the juveniles (ages 1, 2) are

associated with drifting sea ice (Lønne and Gulliksen, 1989; Gradinger and Bluhm, 2004). Cod feed primarily on planktonic copepods and amphipods, but also on ice amphipods (Bain and Sekerak, 1978; Craig *et al.*, 1982; Lønne and Gulliksen, 1989), and is a key species in Arctic marine pelagic food webs (Welch *et al.*, 1992). The structure of the sympagic food web has been further determined by stable isotopes of carbon and nitrogen, to determine carbon sources and trophic levels (Hop *et al.*, 2006; Søreide *et al.*, 2006).

Methods

Arctic marine research performed by the Norwegian Polar Institute (NPI) in the Marginal Ice Zone (MIZ) and in fjords in Svalbard often involves scuba diving to collect organisms or install sampling equipment. In drifting sea ice, the diving operations generally involve two divers, line tenders and polar bear guard. Since NPI has only one qualified diver (Haakon Hop, S-Diver), other scientific divers are hired for the Arctic expeditions. For diving in sub-zero water, with temperatures down to -1.9°C , the divers use neoprene Poseidon Unisuits, Poseidon Odin regulators and Cressisub full-face masks with communication to the line tender. Yellow hard-hats with cabled lights are used generally, particularly for diving under ice or in murky conditions (*e.g.*, plankton blooms and turbid waters of inner glacial fjords).

Ice amphipods have been sampled quantitatively during the projects *PRO MARE* (1983-1988) (Lønne and Gulliksen, 1991a, b, c), *ICE-BAR* (1995-1996) (Hop *et al.*, 2000), and recently (2003-2005) during six research cruises in the *On Thin Ice* and *CABANERA* projects to the Marginal Ice Zone north and east of Svalbard (Hop and Pavlova, unpubl.). The recent sampling campaign has included 185 quantitative samples, which were collected from different mesoscale structures, flat areas (105) and ridges (80), below Arctic sea ice. All quantitative sampling has been carried out by scuba divers by means of 50 x 50-cm floating frames placed below sea ice, and the inside of the frame was sampled by electrical suction pumps (Lønne, 1988). Samples were taken from a set area (2.5 m²) on a single mesoscale structure by placing these frames 10 times (= one replicate sample) from the starting point where ice amphipods occurred. When vacuuming animals from inside the frame, the diver did not exhale to avoid disturbance and loss of organisms by air bubbles. After vacuuming one frame, it was moved about a meter forward to an undisturbed area where the procedure was repeated. Replicates (3-5) were taken by a single diver to avoid repeated sampling of the same area. The maximum diving range under the ice was 40 m from the edge, which implied that a half circle with this radius (2500 m²) was generally available to the diver.

Results and Discussion

Hop *et al.* (2000) and Lønne and Gulliksen (1991 a, b), have shown that the largest ice amphipod, *G. wilkitzkii*, is the most abundant amphipod in multi-year ice (MYI) and with the highest biomass (> 90%), whereas *A. glacialis* is abundant, but may contribute little to the total biomass (< 4%). The two *Onisimus* species generally contribute < 2% of the biomass. Both abundance and biomass of ice amphipods have been found to decrease along a latitudinal gradient from north to south across the MIZ in the Barents Sea (Hop *et al.*, 2000), although this gradient was likely coincident with a declining ice concentration in the same direction. Their distribution was also related to the under-ice topography with regard to mesoscale structures (*i.e.*,

edge, flat area, dome and ridges on MYI; Hop *et al.*, 2000). The amphipod biomass was much higher under ridges (4 g/m^2) than under flat areas (1 g/m^2) or on edges and in domes (0.4 g/m^2), mainly because the large *G. wilkitzkii* is most abundant ($> 100 \text{ ind./m}^2$) under ridges (Hop *et al.*, 2000). The small *A. glacialis* is associated predominantly with edges (45 ind./m^2) but may also be somewhat abundant under flat areas and dome shaped areas (6 ind./m^2). The *Onisimus* species are present in low numbers at all structures and their biomass generally contributes $< 1\%$ on any one structure. Basically, the results showed that abundance and biomass were higher on ridges than on flat areas, although both also varied with ice conditions and the progression of the melt season. The ice history is important for the abundance of ice amphipods, particularly *Gammarus wilkitzkii*, which is predominately associated with MYI, and will colonize first-year ice (FYI) from their original source points (Arndt and Lønne, 2002). Early in the season the FYI has not been much colonized whereas the highest values were in early summer. At the end of the season the values were also high but so was the variability since some ice stations were in a state of advanced melting and the ice amphipods had thus started to melt out of their brine channels.

The source population of ice amphipods is likely contained in the Beaufort Gyre in the Arctic Ocean whereas parts of the population are lost annually in the exits of the transpolar ice drift. About 10% of the sea ice mass in the Arctic Basin exits the Fram Strait annually and melts in the Greenland Sea (Aagaard and Carmack, 1989; Kwok *et al.*, 2004). The trajectories for ice occurring at the different ice stations were simulated based on the daily and monthly mean ice motion vectors computed from Advanced Very High Resolution Radiometer (AVHRR), Scanning Multichannel Microwave Radiometer (SMMR), Special Sensor Microwave/Imager (SSM/I), and International Arctic Buoy Programme (IABP) buoy data (<http://nsidc.org/data/nsidc-0116.html>). Concentrations at these stations can be determined from daily and monthly mean sea ice concentration derived from the SMMR and SSM/I (<http://nsidc.org/data/docs/daac/nsidc0051.html>) and the abundance/biomass distribution of ice amphipods in Svalbard waters are interpreted based on both ice concentration and the origin of the sea ice present. The analysis of potential trajectories showed that sea ice from the Kara Sea has a strong influence on the Barents Sea and eastern coastal zone of Svalbard. The ice formed in the Laptev Sea primarily reached the Fram Strait and northern coastal zone of Svalbard (Hop and Pavlova, unpubl.).

The ice-associated biomass transport of amphipods into Fram Strait was determined based on biomass values of 0.5 and 5 g/m^2 for FYI and MYI, respectively, and a mean annual ice flux of about $866,000 \text{ km}^2/\text{yr}$ (Kwok *et al.*, 2004; Hop *et al.*, 2006). The annual biomass transport was estimated to be about $3.55 \times 10^6 \text{ t}$ wet weight or about $4.2 \times 10^5 \text{ t C/yr}$, based upon 29.5% dry/wet weight for ice amphipods and 40% carbon/dry weight factor. The biomass transport into the Barents Sea depends mainly on the total ice aerial flux through the two openings, Svalbard - Franz Josef Land and Franz Josef Land-Novaja Zemlja, as well as the relative composition of FYI and MYI. The spreading centers for ice amphipods are in MYI, which typically only constitutes a few percent of the ice-covered area in the Barents Sea. The total annual mean ice flux in both Franz Josef Land-Svalbard channel (40%) and Franz Josef Land-Novaja Zemlja channels (60%), based on a 5-year running average for the period of 1966-2000 (ISMO model results, Pavlov *et al.*, 2004), indicates $130\text{-}230 \times 10^3 \text{ km}^2$ ice annually. Using $0.5\text{-}1 \text{ g/m}^2$ as a unit estimate for amphipod biomass in FYI and MYI in the Barents Sea, this implies a total annual biomass transport of about $1.5 \times 10^5 \text{ t}$ of ice fauna wet weight, or $1.8 \times 10^4 \text{ t C/yr}$, into

the Barents Sea (Wassmann *et al.*, 2006). The carbon import of ice amphipods into the Barents Sea is then only about 4 % of that channeled through Fram Strait.

Ice algal production may constitute up to 20 to 25% of the total primary production in Arctic waters (Hegseth, 1992; Legendre *et al.*, 1992). The ice-associated biomass transport of ice algae and microorganisms is probably also substantial, although the ice algae are less abundant in the predominately MYI of Fram Strait than in the predominately FYI of the Barents Sea. The biomass transport of ice macrofauna in Fram Strait is likely double that of ice flora, meiofauna and microorganisms combined, based on their biomass values from the literature (Gradinger *et al.*, 1999). In the Barents Sea, the biomass input of ice macrofauna is much less significant. Assuming that the harvestable primary production is 50% of the total primary production, ice amphipod carbon import to the northern Barents Sea comprises only 0.14% annually (Wassmann *et al.*, 2006). It represents 0.86% of the harvestable ice-associated production. In addition, polar cod is also transported with the sea ice into the Barents Sea, but this biomass constitutes substantially less than the ice amphipods (probably < 5%). When the polar cod are released to the water masses they become part of the pelagic food web.

Consequences of predicted sea ice reductions

The annual loss of ice fauna through Fram Strait represents a large drain on the core population of ice amphipods in the Arctic Ocean. Ice amphipods cannot be maintained in the open water masses and eventually sink to the bottom as they run out of energy. Their potential recolonization of ice during the next season is likely not possible because of the depth of Fram Strait, but it may be possible in shallow waters of the Barents Sea (Poltermann, 1998). Reduction in ice thickness and extent in the Arctic Ocean caused by climatic warming, will likely decrease this southward biomass transport substantially. A continuous loss of MYI because of climate warming will likely dramatically reduce this important food source, because most of the biomass, represented by *G. wilkitzkii*, is associated with this ice habitat. If the multi-year sea ice disappears more or less completely from the Arctic Ocean, the population of ice fauna can most likely not be sustained, and a scenario of open water in the Arctic Ocean during summer would become detrimental to all ice-associated organisms. The latest models predict that an ice-free Arctic Ocean may be seen as early as in 2040-50.

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4. Scientific Diving Session Discussion.

O. Oftedal: What limits clam growth?

H. Hop: Temperature is of course the driving factor. Precipitation had a good correlation. Food source is predictable and it comes in pulses associated with the spring plankton bloom so food availability is probably not the critical factor.

M. Lang: Is your Atlantic water mass data from the oceanographic buoy accessible in real-time?

H. Hop: No. Several mooring buoys are anchored in the bay, but we have to download the data. They are working on cabling a mooring buoy. The key issue for moorings is to keep shrimp trawlers out of the fjord. We have now managed to get a protection zone in part of the fjord.

J. Flinkman: I seem to remember a Polish paper showing recent increased temperature effects causing increased glacier melt water which affects the crustacean zooplankton populations.

H. Hop: The enhanced freshwater runoff from the glaciers impacts the confluence zone between freshwater and seawater in the fjord. Because of the transport mechanism the surfactants vector into the inner part of the fjord and meet the freshwater coming from the glacier. The copepods experience an osmotic shock resulting in mass mortality. The seabirds feed here at the surface. The Polish data estimated 15% of the standing surfactant community is killed off each year. Increased runoff makes this value larger but the effect is still there on a yearly basis.

J. Flinkman: The little auks are able to find the big copepods whereas the fancy multinets won't capture them. This is actually a common phenomenon. A zooplankton haul before and after a trawl do not capture the large copepods in the Baltic but the stomachs of the herring are evidence that they do know how to find them.

M. Lang: This is a similar situation in the Antarctic with the Adelie penguins' ability to find *Euphausia*.

H. Hop: Little auks can also find specific stages of copepod species.

M. Lang: How are the buddy lines attached?

M. Sayer: With carabiners that are snapped to the d-ring on the bc. The buddy lines are 3-m lengths.

B. Stinton: It appears that the brass block on the side of the AGA mask is a counterweight to offset the manifold on the other side?

M. Sayer: Right, and you can also attach lights to it. Both weights counteract the positive buoyancy of the mask.

J. Flinkman: The piece on top of the regulator with the push/talk comms need to have the screws securely fastened to prevent the regulator from coming off.

B. Stinton: What is the volume of your pony bottle?

M. Sayer: Three liters at 210 bar (232 maximum).

J. Flinkman: 300-bar systems are technically difficult especially in cold water. 300 bars of air in the pony bottle is not 300 times the volume of the cylinder. There is almost less than 90 % of that volume in the cylinder and you get a further drop out of pressure in the cold water. In order to get 300 bar you almost have to fill the cylinder to its testing pressure.

D. Long: Your manifold system allows for a redundant air supply but one of your stated problems was the freezing of that single regulator. What is your experience with having that single regulator freeze?

- M. Sayer: The bailout is actually a free-flow mode, a hole in the side of the mask, bypassing the regulator.
- J. Flinkman: In one of your pictures the divers sitting on the side of the entry hole seem to have octopuses.
- M. Sayer: The replacement masks were shipped before we modified the faceplates. In this situation a single-hose bailout and half-mask in the BC pocket were used on a temporary basis.
- H. Hop: What is your experience with the buddy line system between divers? The line tender has to drag two divers out who are on the same tending line. I told the Germans I dived with that I wanted my own buddy line because if something happened to me I wanted to be dragged out of the water as fast as possible and not via another diver.
- M. Lang: Besides, if the other diver has a problem such as a suit blow-up, he will drag you to the surface. Such an ascent is difficult to stop and may result in two diver embolisms.
- H. Hop: I would cut the buddy line of course.
- M. Lang: Sure, besides extracting my knife with cold hands let me also find my spare mask in my BC pocket while we are ascending at speed.
- M. Sayer: We have also used two individual lifelines. Voice communications allow you to monitor how a situation is developing between divers and diver to topside.
- H. Hop: We use two lines from a single hole and agree which direction each diver will swim to avoid entanglement of lines.
- J. Clarke: Can you comment on the first-stage regulator on the bailout bottle?
- M. Sayer: That is an environmentally-capped Poseidon first stage.
- D. Long: What has been your actual experience with single regulator freezing in the AGAs?
- M. Sayer: When the AGAs were first deployed in Antarctica during the winter there were 4-5 freezeups before the drying out procedure of the diaphragm cartridge was instituted. We have had no freezeups since then by drying and storing the masks in the bag.
- D. Andersen: What is your average visibility?
- M. Sayer: Pea-soup plankton bloom in the summer (7 m) and 30 m in the winter.
- R. Palozzi: Do you do night dives in Antarctica?
- M. Sayer: I am not aware of any BAS night diving even though it is dark in the winter.
- S. Mercer: I am intrigued by the washing out of the diaphragm cartridge because you need to have a drying area. If you are out on the ice all day for multiple dives or locations what do you do?
- M. Sayer: During the winter we do less than 2 dives per day because of the operational constraints of available light. During the summer we can do up to seven dives per day (2 at a time) so it's a rolling system where the equipment always comes back to the dive store in between dives.
- M. Lang: Martin, you mentioned that the tables were used based on an agreement between the dive supervisor and the divers on what the dive plan will be.
- M. Sayer: The operational procedure is that the dive supervisor will give the divers the maximum depth and time for a particular point in a dive (either first stop or total dive).
- M. Lang: That is the justification for using tables, right?
- M. Sayer: This is for the purpose of planning the dives.
- M. Lang: My question then is why doesn't the dive supervisor push for putting a dive computer on the diver? Post-dive they can then see whether the diver adhered to the agreed-upon dive plan which puts the supervisor in a better legal position.

Session 4: *Scientific Diving Discussion*

- M. Sayer: We do wear dive computers as depth-time and ascent rate monitors, but not for monitoring decompression status.
- H. Hop: Have you done qualitative sampling while diving?
- L. Quetin: With the krill larvae we can do a good job. Trying to do it photographically is tricky but we have also worked with video transects.
- J. Clarke: Where do the contaminated water dives take place in Antarctica?
- R. Robbins: Winter Quarters Bay is where the ship docks next to McMurdo station. It is a very contaminated area with PCBs and other contaminants in the sediments. It used to be the dump with a landfill. There is not much water or sediment transport out of Winter Quarters Bay. Another area we dive for operational and science reasons is at the sewer outfall. In those areas we use Viking rubber suits with a Superlite yoke and helmet connected to the suit.
- E. Glauser: With the Aladin Pro you can use a Memomouse to extend the dive recording capability so you don't need a PC.
- R. Robbins: We send a Memomouse out with divers at remote sites for dive logging which records 200 hours. We also use the SensusPro recorders but they give no information on decompression status.
- C. McDonald: Do you require a secondary dive hole?
- S. Mercer: No, we do not.
- J. Clarke: What are the bacterial or microbial species?
- D. Andersen: The Antarctic lakes are dominated by cyanobacteria (blue-green algae). In the water column is phytoplankton and in the microbial mats are heterotrophic bacteria. In the chemocline areas are sulfide oxidizers. In Lake Hoare there is a very strong chemocline. Because of oxygen values of 50 mg/l when we hit the anaerobic zone there is a nebular cloud of bacteria.
- H. Hop: Are there higher life forms in the lakes?
- D. Andersen: Gastrotrichs, rotifers, nematodes and some protozoans.
- B. Stinton: How do the microbial mats spread?
- D. Andersen: After the mats lift off they float to the undersurface of the ice. Ice is always accreting from the bottom so the mats freeze in and the net movement of the ice is upward. It takes about ten years to stabilize and get scattered. As soon as they are in touch with water, the mats can grow again.
- O. Oftedal: You mentioned that a community existed and got trapped in an ice layer, is this in the thaw zone?
- D. Andersen: During the height of the summer, that sediment layer in the ice is isothermal (zero degrees). There is much liquid water moving in and out. That sediment layer will break out a channel almost like a lake inside of the ice. You end up with a sediment layer and a base that is supported by multiple columns of ice. They line the surface of the sediment lens that runs through the ice. This is a much simpler, scattered microbial community than exists on the bottom.

- L. Quetin: Do you have any instances of plugged holes?
- J. Flinkman: We have had a few smaller floes come into the hole but these are easily removed with poles.
- B. Stinton: Have you considered a 30-m instead of a 20-m tether for the standby divers?
- J. Flinkman: The standby diver tether is 50 m.
- B. Stinton: You mentioned a long decompression problem vis-à-vis a flooded suit. Lew Nuckols of the Naval Academy had developed a shelter (a surface-supplied hot water tent). If the diver had a totally flooded suit he could move from cold water to a much warmer environment. Because of the buoyancy of warm water you could not easily exit this “bell,” which served as a warm-water bubble. The water was heated from an outboard motor.
- J. Flinkman: In the Baltic we restrict our bottom times so that we do not incur a decompression obligation of more than 30 mins. You could complete the decompression and even though very cold breathe oxygen on the surface and evacuate to the nearest chamber.
- O. Oftedal: Are the assumptions in your trophic level graph well supported?
- H. Hop: There is an enrichment between trophic levels. The Canadians established a nitrogen step value of 3.8 to move to the next level based on polar bears eating ringed seals. They extrapolated that value to the entire food chain but we found out this did not work and the step value was too high. We worked with stable isotopes and determined the trophic level step from primary producers (algae) to primary grazers (zooplankton) to be 3.4.

THE COMPARATIVE INCIDENCE OF DECOMPRESSION ILLNESS IN ANTARCTIC SCIENTIFIC DIVERS

Martin D.J. Sayer

NERC Facility for Scientific Diving
Dunstaffnage Marine Laboratory
Oban, Argyll, SCOTLAND PA37 1QA, UNITED KINGDOM

Michael A. Lang

Smithsonian Institution
Office of the Under Secretary for Science
PO Box 37012, MRC 009
Washington, DC 20013-7012, U.S.A.

Steve Mercer

National Institute for Water and Atmospheric Research
Private Bag 14901
301 Evans Bay Parade, Hataitai
Wellington 6021 NEW ZEALAND

Introduction

Divers who dive in cold water are often considered to be more at risk from decompression illness (DCI) than those who dive in warmer water (Mekjavic *et al.*, 2004; Mueller, 2007). Three national Antarctic scientific diving programmes have maintained activity records from under or around ice since 1985; they are Antarctica New Zealand (ANZ), the U.S. Antarctic Program (USAP) and the British Antarctic Survey (BAS). In general, the diving reported here was undertaken in water of temperatures at or below 0°C; the incident statistics that have been collated provide observed rates of decompression illness (DCI) that are comparable with the same type of diving (scientific) undertaken in warmer waters. The incident rates are also compared with published examples from other types of diving, locations and/or diving sectors.

Data collation

Information about Antarctic diving activities has been routinely collected by the national Antarctic scientific diving programmes of New Zealand, the US and the UK since 1985. The datasets are not all complete but, when combined, give a total of nearly 18,000 person dives under or around ice completed by over 600 divers (Table 1). The different diving programmes collated different kinds of data; for example, the USAP collated dive times and depths (over 6,111 hours logged underwater at an average depth of 73 fsw and average duration of 34 minutes), the BAS profiled their diving by depth ranges (33.7% of dives shallower than 9 msw, 31.5% between 10 and 19 msw, 16.9% in the 20-29 msw depth range, and 17.8% of the dives

were in 30 msw or deeper). Much of this data is not shown; the only consistent data collected were person dives, numbers of divers and incident rates. Again, with the incident rates, different data were collated and so only data relating to DCS (nominally split between the traditional type 1 (DCS1) and type 2 (DCS2) forms) and barotraumas were collated consistently between the three programmes.

Table 1. The numbers of Antarctic ice dives, divers and DCI rates for some years from 1985 to the present for Antarctica New Zealand (ANZ), the US Antarctic Program (USAP) and the British Antarctic Survey (BAS).

	ANZ	USAP	BAS	Total
first reporting year	1985	1989	1991	
years of data	22	18	16	
dives	1296	10859	5492	17647
divers	110	296	212	618
DCS1	0	2	3	5
DCS2	0	0	0	0
AGE	0	0	0	0
Barotrauma	2	0	3	5
DCS 1000 dives ⁻¹	0.00	0.18	0.55	0.28

Table 1 details the information collated commonly between the three programmes. Out of the total of nearly 18,000 person dives there were 5 cases of mild barotraumas and 5 cases of mild DCS. There were no serious diving incidents (DCS2 or arterial gas embolism, AGE). This produced DCS incident rates of 0.00, 0.18 and 0.55 cases per 1,000 person dives in the ANZ, USAP and BAS diving programmes, respectively. Collectively, the incidence of DCS was 0.28 cases per 1000 person dives.

Comparative rates of DCS/DCI

A review of published DCS/DCI rates is summarized in Table 2. Any comparative review of this type is always complicated through the inconsistent use of terminology relating to decompression sickness and/or illness (DCS/DCI). In addition, it is not always clear whether the reports are based on person dives or on dives alone irrespective of the number of divers performing those dives. That notwithstanding, the published DCS/DCI incident rates range from 0.00 to 9.55 per 1000 dives (Table 2). However, those rates include many different forms of diving that are not entirely relevant to scientific diving. When the previously-published rates for scientific diving are examined, they range from 0.00 to 0.06 DCS/DCI cases per 1,000 person dives; in the Antarctic, the rate for scientific diving is much greater (0.28).

Table 2. A summary of a review of published DCI /DCS* rates per 1000 dives with additional rates from the present study. Rates in parentheses have been calculated based on a single incidence of DCI/DCS.

Type of diving	DCI/DCS incidence per 1000 “dives” **	Reference
US Navy: deep air diving (150 fsw)	9.55	Hunter <i>et al.</i> (1978)
US Navy: 4 th quartile of no-stop time (USN57)	1.28	Flynn <i>et al.</i> (1998)
Multi-day decompression diving	1.12	Sayer <i>et al.</i> (2007)
Commercial (oil platform) scuba 100-165 fsw	1.03	Luby (1999)
Commercial (oil platform) all diving 165 fsw+	(0.76)	Luby (1999)
UK multi-dive multi-day wreck diving	0.25-0.49	Trevett <i>et al.</i> (2001)
Tropical multi-dive multi-day	0.29-0.33	Davis & Walker (2003)
US Navy shallow no-stop air diving	0.29	Flynn <i>et al.</i> (1998)
US Navy: 1st quartile of no-stop time (USN57)	0.22	Flynn <i>et al.</i> (1998)
Overseas US military community	0.14	Arness (1997)
Commercial (oil platform) all diving 30-99 fsw	0.14	Luby (1999)
West Canada amateur scuba	0.10	Ladd <i>et al.</i> (2002)
Caribbean amateur scuba	0.09	Gilliam (1992)
UK recreational / amateur divers	0.07	Wilmshurst <i>et al.</i> (1994)
UK scientific diving	(0.06)	Sayer & Barrington (2005)
Japan recreational scuba	0.05	Nakayama <i>et al.</i> (2003)
US scientific diving	0.05	Lang (2005)
International scientific diving	0.04	Sayer (2005)
Australian scientific diving	0.00	Carter <i>et al.</i> (2005)
Antarctic scientific diving	0.28	This study

* Some studies are specifically DCS; some are specifically DCI; some do not make the distinction

** Dive is assumed to be a “person dive” but not all studies make this clear.

Conclusions

Although scientific diving in the Antarctic has a comparatively low rate of DCS/DCI cases compared with all types and forms of diving, the rates are much higher than those previously reported for scientific diving *per se*. An obvious explanation for this is the general acceptance that cold water diving carries a proportionately higher risk of contracting DCS/DCI (*e.g.*, Mekjavic *et al.*, 2004; Mueller, 2007). In particular, peripheral vasoconstriction following prolonged immersion in cold water is known to contribute to the likelihood of causing cutaneous decompression sickness (Mekjavic *et al.*, 2004). In fact, all three of the DCS1 cases reported by BAS in Table 1 were cases of cutaneous DCS. However, it is also likely that because of the remoteness of the diving operations in Antarctica that there is probably an increased inclination

to perform precautionary treatments sometimes in association with over eager diagnoses. Other factors, such as low atmospheric pressure, may also contribute and so there has been a developing tendency in the Antarctic scientific diving programmes to adopt more conservative dive profiles and/or decompression tables.

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U.S. COAST GUARD CUTTER HEALY DIVING MISHAP

Michael A. Lang
Smithsonian Institution
Office of the Under Secretary for Science
PO Box 37012, MRC 009
Washington, DC 20013-7012 U.S.A.

Overview

On 17 August 2006, three Coast Guard divers from USCG Cutter HEALY attempted to conduct two 20-minute cold water familiarization dives at 20 fsw during an ice liberty stop in the Arctic ice approx. 490 nautical miles north of Barrow, Alaska. After one of the divers exited the water due to equipment malfunction, the other two divers continued the dive in 29-F waters. The divers quickly descended to depths far exceeding their planned 20-foot depth (187 fsw and 220 fsw). Once it became evident that too much tending line had paid out to support a 20-foot dive depth, the divers were brought to the water surface. The divers were recovered with no vital signs and were pronounced dead after extensive resuscitative efforts failed.

Diver experience

Of the three divers embarked in CGC HEALY on 17 August 2006, only two were up-to-date with the currency requirements set forth in the Coast Guard Diving Manual that requires four dives every six months.

LT Hill

Prior to the dive on 17 August 2006, Jessica Hill had conducted approximately 24 dives during 19 dive days. Seven of the 24 dives were conducted in the Arctic Ocean during the summer of 2005; however, those dives were conducted with surface-supplied air as opposed to dives with SCUBA. This was LT Hill's first cold water SCUBA dive. The last dive LT Hill participated in prior to the one on 17 August 2006 was on 10 April 2006. With this dive profile, LT Hill was a diver with limited military dive experience. While LT Hill had initially qualified as a Basic Diving Officer after attending the Navy Diving and Salvage Training Center (NDSTC), LT Hill's currency qualification had lapsed on 15 May 2006. CGC HEALY's previous Commanding Officer signed a diving requalification letter for LT Hill on 28 April 2006. However, two of the four dives used to substantiate this requalification were recreational dives and were not conducted in accordance with standards articulated in the Coast Guard Diving Manual. These recreational dives were not authorized to count for periodicity purposes and as such the requalification letter signed on 28 April 2006 was not valid. Therefore, LT Hill was not qualified for diving duty on 17 August 2006.

BM2 Duque

Boatswain's Mate 2 Steven Duque reported aboard for his first tour afloat on 25 May 2005. He later went to dive school and the NDSTC qualified BM2 Duque as a SCUBA diver on 1 March 2006. Since receiving his training, BM2 Duque had only conducted two dives in one dive day on 10 April 2006. With this dive profile, BM2 Duque was a diver with limited military dive experience. BM2 Duque had never conducted a cold water dive.

Diver 3

The Navy Diving and Salvage Training Center qualified Diver 3 as a SCUBA diver on 8 July 2005. Since receiving training, Diver 3 had only one dive day consisting of four dives on 20 October 2005. Diver 3 reported aboard for Diver 3's first tour afloat on 18 July 2006. With this dive profile, Diver 3 was a diver with limited military dive experience. Diver 3 had never conducted a cold water dive.

Findings

In the administrative investigation into the Aug. 17, 2006, accident, Coast Guard Commandant Adm. Thad Allen found the deaths of divers Lt. Jessica Hill and Boatswain's Mate 2nd Class Steven Duque preventable. Among the problems that were discovered during the investigation:

1. The Command

- Inadequate review of the dive plan.
- Lack of familiarization of Coast Guard and Navy diving manuals.
- Lack of oversight of the ship's crew during liberty, including the amount of alcohol consumed by crew members.
- Inappropriate use of alcohol by the command cadre during an operation.

2. The Participants

- Improperly manned operation; at least four trained divers were required.
- Limited diving experience among all three scheduled participants.
- Lead diver not qualified for military diving duty.
- Improper briefing of dive tenders.
- Unqualified dive tenders.
- Deviation from dive plan when one diver was forced to exit the water.
- Continuance of dive plan following the loss of manual dexterity, from cold, by one of the divers.
- Unqualified personnel conducting equipment checks.
- Inappropriate use of alcohol by dive tenders.
- Unauthorized "polar bear plunges" and other recreational activities by other crew members near the dive site.

3. Dive Manual Violations

- No manual present at dive site.

Lang: USCG HEALY mishap

- No verification that ship equipment and machinery was properly secured and positioned to prevent interference with dive operation.
- No dive log maintained.
- No redundant scuba systems used.
- Extra weight loaded into zippered pockets, instead of being added with an easily removable weight belt.
- Improper anchoring of the dive tending lines.
- Lack of medical and emergency evacuation plans, proper treatment equipment or dive medical officer on board Healy.
- Lack of a viable preventive maintenance system for dive equipment as well as lack of records dating back to 2002.
- Improper storage of gear.
- No safety survey conducted of Healy dive program since its commissioning in 1999.

4. Equipment

- Neither BM2 Duque nor LT Hill had a low-pressure hose attached to their Buoyancy Compensator Devices (BCD) so the BCDs could not be inflated. Their variable volume drysuits were properly rigged to their air supplies so the suits could be inflated as necessary.
- Both BM2 Duque and LT Hill donned split fins that are designed for high speed and provide only minimal thrust. Split fins are not considered appropriate for heavy diving and lack the power necessary to overcome the drag of a drysuit. Instead, they are better suited for light diving and snorkeling.
- None of the divers wore weight belts as required by the Navy Diving Manual. A standard diving weight belt is designed to facilitate the ability to jettison weight in emergency conditions.
- Instead, both LT Hill and BM2 Duque used the weight pockets integrated into the design of their buoyancy compensator devices. Additionally, they filled their BCD equipment pockets, which are secured by heavy zippers and are not easily opened, and would make an emergency jettison difficult, if not impossible.
- The divers initially entered the water with over 40 pounds, but returned to the side following surface checks to add more weight. BM2 Duque specifically commented that he was floating too much. Each diver eventually departed the surface with over 60 pounds of weight (including lead shot and steel tank).

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5. General Discussion Session.

A. SNORKELING WITH KILLER WHALES: Yasmin Hunt.

My background is in marine tourism working with whales, sharks and marine fish. My family is based in Western Australia where Ningaloo Reef runs 260 km along the coastline. From working there I came to Norway to snorkel with the killer whales four years ago. The Norwegian killer whales follow the migration of the herring. Our snorkeling activity with these whales in northern Norway is from November to January. The herring schools then move to southern Norway to spawn and then head out to the middle of the North Sea to feed on plankton. In October they return to the fjords of northern Norway. There are no documented fatalities by killer whales and we are lucky to be able to swim with them here. The killer whales use a carousel feeding technique on the herring by bunching them up high in the water column against the surface. The tight packing of the herring consumes the oxygen in the water and they become lethargic. The killer whales then stun some fish with a tail slap and eat them one by one.

B. Stinton: What is the size of a herring school?

Y. Hunt: That's hard to say. During the day the herring sink into the depths to hide and at night they come to the surface. The Norwegian herring population is estimated at 7 million tons and is one of the healthiest in the world now.

M. Sayer: After the leopard seal attack at Rothera there is now no diving when leopard seals or orcas are in the vicinity.

M. Lang: Different populations of orcas feed on different prey. A herring-feeding specialist pod might not warrant the same concern as a sea-lion feeding pod.

Y. Hunt: In most countries it is illegal to swim with killer whales so you cannot get in the water with them to experiment. In New Zealand a colleague with research permit snorkels with orcas regularly who feed on sharks and sea lions. Off Alaska they feed on salmon and in Patagonia on seals. In Mexico the orcas hunt gray whales and sea lions.

D. Long: In British Columbia there are two populations of killer whales: the resident pods that feed on salmon and the transient pods that feed on seals. These groups do not mingle. Divers in BC have no problem swimming with the resident pods but exist the water when transient pods approach. Killer whale dorsal fins and markings allow for identification of pods and individuals.

Y. Hunt: Laws are quite restrictive regarding marine mammal protection so most people will not have the opportunity to swim with orcas. The best approach to view the whales in the water is from the surface. Free-diving down or scuba diving only pushes the orcas deeper and further away. When we put the snorkelers in the water we do not give them any fins at all and tell them to stay as still as possible at the surface. This is when the killer whales are more curious and come in for a look providing for a great encounter in the water.

B. USCG HEALY MISHAP comments

M. Lang: The USCG divers' low pressure hoses were not connected to their buoyancy compensator power inflators and thus there was no way to inflate the BCs other than orally which, with an AGA mask, is nearly impossible.

J. Clarke: The weighting issue was replicated at NEDU and the diver sank like a rock. If you extrapolate the depth another thirty feet down the diver is gone.

- M. Lang: In the course of the safety investigative panel’s work we were shown a video clip of a USN diver of same height, weight and equipment configuration as one of the USCG divers. Notwithstanding the decreased buoyancy offered in a fresh water pool it was clear that it was with difficulty that he swam up from the bottom of the test tank. The split fin issue was also interesting. Similar to a car engine that is rated for horsepower and torque split fins, compared to full-blade dive fins of similar stiffness, have minimal torque. This means that during the course of a gentle dive you do not need to kick hard but swimming against a current or trying to lift a heavy object from the bottom becomes difficult. The other important contributing factor was the remarkable inexperience of the divers in cold water scuba diving.
- S. Deweese: There are huge cultural differences between the military and scientific diving communities. These inexperienced divers trusted their Diving Officer.
- W. Lynch: How long were they down before being pulled back up?
- M. Lang: It was a short duration and there was no air in one cylinder and very little in the other.

C. IPDW DIVE COMPUTER USE

IPDW participants were fitted with UWATEC Aladin One dive computers (provided courtesy of UWATEC). Table 1 summarizes the dive data for dives conducted during IPDW, March 15-21, 2007.

Table 1. IPDW dive data summary for 21 divers using Aladin One computers.

Diver	DC ID	Dives	BT min	Max D fsw	Max BT min
AD	29	6	203	90	46
DS	40	2	42	48	26
FJ	42	5	189	68	47
FB	36	5	152	59	39
GE	37	6	201	59	41
HH	41	7	236	67	45
HY	33	5	141	90	33
LM	32	7	202	58	34
LD	34	4	139	50	44
LW	43	6	169	75	43
MC	45	2	74	40	44
MS	23	5	127	77	30
OE	31	7	194	58	36
OO	25	5	96	58	27
OR	26	3	101	62	40
PR	44	6	152	70	29
PL	22	7	193	69	38
QL	24	4	98	46	28
RK	39	7	188	58	36
SM	46	4	82	59	27
SB	30	3	87	44	31
		106	3066		764
			51 hr	62 fsw	:36

It is interesting to note that none of the dive computers at any time experienced battery shortage (minimum battery status during the dive is recorded in the computer's logbook). All Aladin Ones were fitted with new batteries at the UWATEC factory and checked to ensure that 6 battery indicator segments were displayed. Full strength indication is displayed by 4, 5 and 6 segments. The Aladin One warns the diver that it is time to change batteries when 3 or 2 segments are displayed. When 1 segment is displayed the computer does not function any longer as a dive computer. The battery status is checked by the dive computer every 30 minutes during the dive and if the temperature changes by more than 7 degrees. Some computers dropped to 5 segments during the Svalbard dives while some others dropped to 4 segments. One dive, only 2 minutes long, showed 6 segments as a minimum during that dive but 5 segments both for the previous and successive dives. This means that the battery was able to recover to 6 segments when kept warm for a bit but that the strain of the dive, *i.e.*, the internal resistance caused by the extreme cold, was sufficient for the computer to notice a drop in performance of the battery. Battery monitoring is important because a battery strong enough to perform 50 or more dives in tropical waters (reaching the approximate reserve at 4 segments) might not be able to provide the energy needed at -2°C and can thus cause the computer to fail during the dive. Online monitoring of battery status is critical for these extreme conditions. No dive computer problems were reported by the 21 divers.

D. SCIENTIFIC ICE DIVER TRAINING/CERTIFICATION

The following programs list the requirements for their national scientific ice diver training and certification requirements:

British Antarctic Survey

- CMAS 3* equivalency
 - o Recreational route: PADI Divemaster;
 - o HSE route: HSE scuba (Part IV);
- HSE diving at work medical;
- Pre-ice: National Facility for Scientific Diving: min. 1 week competency assessment in:
 - o Dry suits;
 - o Buoyancy control;
 - o FFM (AGA);
 - o Voice communications (through water and hardwire);
 - o Line tending;
 - o Recompression chamber operations (operator and tender);
- On-ice: competency assessment through checkout dives with FDO (Field Diving Officer);
- All dive equipment provided at Rothera, except for dry suit (neoprene); and,
- HSE First Aid at work and oxygen administration and AED.

Antarctica New Zealand

- Department of Labour certificate of competence in underwater diving; rescue diver plus specialties in night, deep, navigation, search and recovery;
- AS2299 medical clearance to dive (validity for 12 month);
- 100 logged dives;
- Pre-ice: ice diving orientation (4 days);

- On-ice: competency check-out with the Event Diving Supervisor; and,
- Workplace first aid certification (< 6 months of deployment).

U.S. Antarctic Program

- Certified open water scuba diver for 1 year;
- 50 logged dives;
- 15 drysuit dives;
- 10 drysuit dives within past 12 months;
- Current USAP deployment medical;
- In McMurdo: check-out dive with Scientific Diving Coordinator;
- Regulators and dive computers supplied in McMurdo; and,
- Current Diving First Aid training (within one 1 year).

Finland

- CMAS2* and dry suit diving equivalency;
- Ice and cold water diving module (part of scientific diver training – 1 week);
- Advanced European Scientific Diver (Finnish Scientific Diver Supervisory Committee);
- Diving Medical for Professional Divers (<12 months); and,
- Special First Aid Course for divers (renewable every 3 years).

Norway

- CMAS3* or PADI Divemaster;
- Norwegian Labor Inspection Authorities Certificate S (CMAS 3* plus 40 logged dives);
- Commercial diver medical (valid for 2 years);
- Dry suit experience; and,
- Checkout dive by Dive Leader.

Germany

- Scientific diver training program at 6 institutions: University of Rostock, University of Kiel, Biological Institute of Helgoland (AWI), Oldenburg, Technical University of Munich, University of Konstanz;
- Prerequisite: prove necessity of scientific work under water and Occupational Medical Standard for Diving (G31) certification;
- Scientific diver training (240 hours): European Scientific Diver (includes 70 open water dives, 20 with scientific purpose, 10 dives between 15-24 m, 5 dives >25m);
- Advanced European Scientific Diver (100 dives, 10 dives 20-29 m, 10 > 29 m, 20 under severe conditions), 20 dives as Dive Leader;
- Certified by Commission on Scientific Diving in Germany: (www.forschungstauchen-deutschland.de);
- GUV-R2112 max depth 50 m, 3 person dive team; and,
- Tethers, FFM, drysuit use.

Australia

- Australian Antarctic Division scientific divers are commercially trained to Australian Standards (AS2815.1 for SCUBA, and AS2815.2 for SSBA);
- Commercial diving medical (AS2299.1);

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- Must have extensive scientific diving experience in all types of diving;
- Current first aid qualifications;
- DCIEM tables used with dive computers for profile recording only;
- Compulsory rest day after 6 continuous dive days; and,
- Two members of dive team are trained as chamber operators and DMTs.

COMMENTARY: Dick Long, Diving Unlimited International

I would like to thank Michael for putting this workshop together. I have enjoyed it and like talking and listening to smart people. It's not often that I get quality time with a group like this without many distractions. Over the years I have been very lucky to have been in the right place at the right time and to have participated in a number of major diving projects. I was there when NAUI was formed, was involved in SEALAB 2 and 3, and commercial offshore oilfield diving from the beginning.

What you are working on here is also at the forefront of diving activity. Why does DUI support something of this nature? It is not a very profitable exercise because there is not a huge market out there for diving under ice in the Arctic Ocean. But from our standpoint you are in a very unique position within the diving industry. You are recognized as an authority because you are primarily scientists and all the rest of us are primarily divers. You develop information, quantify that information, report it out and back it up with science. Almost no one else does that with the exception of the US Navy. You are disciplined for the most part and have a far greater influence than you might expect. You are my replacement, that's why I am here.

How are you going to lead science diving forward? You are addressing issues here that are not addressed by anybody else. Change is going to happen. Information we have now will be replaced by better information and equipment in the future. Luck is what happens when preparedness meets opportunity. Oil embargoes, 9/11 and Katrina have changed all of our lives resulting in national resources being reallocated. Global warming also affects our lives and is occurring. We don't know yet what our government and public reaction will be to that. If the decision is to apply a treatment they will be looking to scientists for answers.

Several comments have concerned "drag." There is actually very little drag on the diver in the water especially at the speeds you are swimming. What you are experiencing is the difference between swimming in a wetsuit versus a drysuit. Donning wetsuit trousers brings them all the way up into the crotch resulting in easy movement of the legs. Donning a drysuit includes underwear and the outer shell of the drysuit. There is more resistance on your legs when you are kicking yourself through the water.

Rarely do we come up with some great innovation that greatly improves our working time under water. Most of what we do under water is through the use of our hands. The blue zipseal dry gloves are 50% thicker than the orange gloves. If you dive in an abrasive environment use the blue ones. Puncture of the glove is a different issue than abrasion and both gloves can be penetrated similarly. When you use heavier gloves with more liner layers it becomes harder to bend your fingers and you slow down the only tool you have. Michael believes wearing one liner under the glove and elevating the hand every few minutes while wiggling the fingers allows

warm air from the body to enter the glove. Some divers have arthritis, low blood circulation to the hands or non-freezing cold injuries. There is great variability among individual divers. Women often have long slender fingers and a lower surface to mass ratio than men. The amount of insulation will therefore vary between individuals and you should have a variety of insulation to choose from. Wool gloves with a thinsulate liner can also be used for additional insulation.

There are some divers who swear that argon works but there is also much misinformation about it. No one has actually quantified the increase in insulation that argon or carbon dioxide provide which would be a good project to pursue in the polar diving business. There is much diving material on www.DUI-online.com which you are free to use as a source of technical information.

Compared to where we were in 1991 in La Jolla during the first polar diving workshop discussions you have come a long way. We no longer appear to have some of the problems we had before that I thought we might still have. Freezing regulators was a big issue at that point in time. Learning to train divers how to use drysuits is no longer an issue today. Some of the same rules still apply such as pre- and postdive regulator care and sufficient diving experience with drysuits prior to going into under-ice conditions. Diving is 5% knowledge and 95% practice. A diver who has owned a drysuit for five years but only used it once does not qualify him to dive with it. There is nothing that replaces the value of work-up dives.

There is no question that the safety record that scientific diving has is anything short of spectacular. If it was not you would not be able to be in business today. Certainly you are vulnerable because there are people who will be critical of what happens here today. If you kill someone under water you will make headlines versus a traffic death that goes barely noticed. Therefore you must be conservative in the kinds of diving you take on. There is a tradeoff, however, in that you can't do nearly as much as you would like to.

From the papers and discussions it appears that there are still difficulties with the competencies of some of the divers coming into the programs. You still have very little money and are begging and borrowing anything you can. I saw some suits here and in the some of the pictures that Michael needs to have at the Smithsonian (on the wall, not in his dive locker). Your dives are currently restricted to no-decompression limits which restrict what you can do. This probably will not continue. As you formulate your polar diving recommendations here keep not only the short-term but also long-term conditions in mind for the challenges that will arise. Hand warmth remains the number one issue that you face. Up until thirty minutes into the dive you are probably OK. You would like to dive for an hour or perhaps two but your hands will not last that long other than serving as an ineffective club. We have experimented with electrically heated gloves at least three times before and have spent time with our gloved hands in a bucket of ice water with good results. At the end of the day, however, we have to look at what you pay for these gloves, what kind of performance you get out of them and how long they will last before they need to be repaired or replaced. None of what has been tried has measured up to our needs or performance criteria.

This group represents an international group with different national regulations. Perhaps through this group some of these rules may be changed with enough information. Make sure that

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recommendations do not prevent you from taking advantage of new technology that will come available as options. Develop of variety of tools that a Diving Officer can choose from and do not restrict access to that information or procedures.

I am going to leave this workshop and work on face protection, regulator isolation and tricks of the trade. Thank you.

6. Conclusion Session.

- M. Lang: As we organize our workshop recommendations we take this opportunity for workshop participants to offer any prioritized take-home messages they would like to emphasize based on the discussions of data presented.
- B. Stinton: Concentrate on the items that limit your diving right now such as the hands and put your resources and thoughts into that. Potentially establish a web bulletin board to share operational procedures that do or do not work. Managing pre- and post-dive hand protection especially for standby divers and tenders is important to consider.
- J. Clarke: I feel gratified that what NEDU is finding and publishing is in line with what you are experiencing in the field with regard to regulators. The primary concern is that we should not replace equipment that works with the latest greatest black box without independent lab and field testing under polar conditions. The same issue exists for power inflators for drysuits and BC inflators.
- E. Glauser: Use of an isolation valve (free-flow control device) on the regulator second stage (left) in conjunction with a first-stage overpressure relief valve (right) should be further evaluated. See for example Apeks products at <http://www.apeks.co.uk>



- P. Mueller: For polar diving the functionality of the diver is the primary goal and we want to keep the diver warm all the time. We have some evidence however that indicates that heavy lifting and external heat application immediately post-dive should be avoided.
- M. Sayer: The tether issue needs to be addressed specifically when it should be used and under which environmental conditions. Divers working independently using surface-supplied diving should have voice communication to the surface through a full-face mask and an independent air supply.
- L. Quetin: Tenders are responsible for monitoring changing ice conditions.
- H. Hop: Ensuring a rapid exit is warranted if ice starts shifting. Also, diving with marine mammals requires special procedures.
- R. Robbins: It is important that we continue to evaluate regulators for our polar diving use.
- S. Mercer: The influence of non-diving risk managers with respect to a recompression chamber location and availability is of continuous concern as is having sufficient oxygen available on site.
- D. Andersen: Buoyancy control is still the number one safety and science skill that polar science divers must master comfortably.
- R. Palozzi: It is better to finish your dive before you finish your gas.
- B. Stinton: The difference between cave and under ice diving is that you traverse a certain distance while cave diving that you must backtrack to the exit hole.

- R. Robbins: Divers really need to have experience with the drysuit system they are going to use before they arrive on the ice.
- O. Oftedal: An in-water competency test or polar check-out dive was repeatedly mentioned as an essential element for determining competency.
- M. Lang: Thermal protection, Equipment, Operations and Training appear to be the major categories under which these recommendations could be organized.

International Polar Diving Workshop
March 15-21, 2007

Michael A. Lang and Martin D.J. Sayer, Co-Chairs

CONSENSUS RECOMMENDATIONS

Polar diving experience has shown that buoyancy control is the primary differentiating skill affecting safety and science.

THERMAL PROTECTION

1. Pre- and post-dive thermal and hand protection must be carefully managed.
2. Adequate thermal protection must be provided to tender(s) and standby diver(s).
3. The effect of cold on DCS risk is not fully understood. However, the diver should be kept warm throughout the dive and external heat application and heavy lifting should be avoided during the immediate post-dive period.

EQUIPMENT

4. It is important that continued data be collected on the performance of regulators, buoyancy compensators and drysuits in polar conditions and be accessible to scientific diving programs.
5. Regulator model revisions require field experience or independent lab testing validation prior to adoption for polar diving use because it cannot be assumed they will perform as well as earlier successful models.
6. Owing to the tendency for scuba apparatus to free-flow under polar conditions a minimum of two independent regulator systems is recommended for diving in overhead environments; divers must be proficient in switch-over procedures.
7. A second-stage isolation valve used in conjunction with a first-stage overpressure relief valve should be further considered as a method to independently and rapidly manage regulator free-flow.
8. To minimize the possibility of regulator free-flow proper pre- and post-dive care should be followed. Proven methods include ensuring that regulators are kept warm and dry prior to diving and minimizing regulator breathing prior to immersion. The purge valve should not be activated prior to immersion, upon entry or during the dive.

OPERATIONS

9. A drysuit must be used with a buoyancy compensator for polar diving in general. It is recognized that conditions may exist in which the diver would be more at risk with the buoyancy compensator than without one. In such cases a buoyancy compensator will not be required.
10. A tethered diver, who is deployed to work independently, must be equipped with full face mask, voice communications to the surface and redundant air supply.

11. During pack ice diving operations tenders must constantly monitor changing ice conditions to ensure rapid diver exit.
12. A recompression chamber should be within a traveling distance that is concomitant with the risks associated with any particular diving operation. Where no recompression chamber is available then the risk must be managed in a way that reduces the potential for decompression illness significantly. Sufficient oxygen must be on site as an emergency diving first aid treatment.
13. Generally, divers under ice should be tethered by life lines. It is recognized that conditions may exist where high visibility and lack of currents obviate the need for tethers.
14. Appropriate measures for safeguarding all personnel from predatory mammals (*e.g.*, polar bear, leopard seal and walrus) must be considered and implemented.
15. Diving under ice requires additional gas management considerations.

TRAINING

16. Divers in polar regions should be proficient in the use of drysuits, thermal insulation strategies and weighting and should be highly experienced with the particular system and equipment they will use.
17. When lifelines are used divers and tenders must be trained and proficient in their use.
18. A polar check-out dive is essential to determine competency.

7. International Polar Diving Workshop Participants

Lang	Michael A.	Co-Chair	langm@si.edu	USA
Sayer	Martin D.J.	Co-Chair	martin.sayer@sams.ac.uk	UK
Stinton	Bob	Speaker	bstinton@dui-online.com	USA
Clarke	John R.	Speaker	John.R.Clarke@navy.mil	USA
Angelini	Sergio	Contributor	sergio.angelini@uwatec.ch	Switzerland
Mueller	Peter H.J.	Speaker	pete@ejuhm.de	Germany
Hop	Haakon	Speaker	haakon@npolar.no	Norway
Quetin	Langdon B.	Speaker	langdon@icess.ucsb.edu	USA
Robbins	Rob	Speaker	rob.robbins@usap.gov	USA
Mercer	Steve	Speaker	s.mercer@niwa.co.nz	New Zealand
Andersen	Dale T.	Speaker	dandersen@carlsagancenter.org	USA
Flinkman	Juha	Speaker	juha.flinkman@fimr.fi	Finland
Stewart	Jeremy W.	Contributor	StewartJW@DFO-MPO.GC.CA	Canada
Long	Dick	Speaker	rlong@cox.net	USA
Brown	Hugh	Participant	hbro@sams.ac.uk	UK
Brubakk	Alf O.	Participant	alf.o.brubakk@medisin.ntnu.no	Norway
Deweese	Shawn	Participant	shawn.deweese@navy.mil	USA
Forbes	Bobby	Participant	bobby.forbes@uk-sdsc.com	UK
Glauser	Emmanuel	Participant	eglauser@uwatec.ch	Switzerland
Hunt	Yasmin	Participant	yazzy25wahoo@yahoo.com.au	Australia
Lynch	Warren	Participant	lynchw@si.edu	USA
McDonald	Christian	Participant	cmcdonald@ucsd.edu	USA
Ochoa	Edgardo	Participant	ochoae@si.edu	Panama
Oftedal	Olav T.	Participant	oftedalo@si.edu	USA
Olsson	Ragni	Participant	ragni@npolar.no	Norway
Palozzi	Roberto	Participant	bobpalozzi@libero.it	Italy
Penland	Laurie	Participant	penlandl@si.edu	USA
Richardson	Karen	Participant	karen.richardson@mac.com	Australia
Thurston	Simon	Participant	srth@sams.ac.uk	UK