Review article

Scientific diving in Antarctica: history and current practice

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Antarctica, diving, scientific diving, hypothermia (see thermal problems), equipment, logistics, safety, review article

Abstract
(Pollock NW. Scientific diving in Antarctica: history and current practice. *Diving and Hyperbaric Medicine*. 2007; 37: 204-11.)
Diving has served as an important research tool in Antarctic science for the past 50 years. Equipment, techniques and oversight have developed to make it a mainstream function in many polar programmes. The safety record is encouraging, particularly given the unforgiving nature of the environment.

Introduction

Diving has long been an important tool in underwater science. This is true even under the extreme conditions of the Antarctic. The first recorded event was a surface-supplied dive conducted in April 1902 during a 1901–03 German expedition.[1] The US Underwater Demolition Team (UDT) tested their cold-water wetsuits at the surface and completed at least one dive in the Antarctic in February 1947 during Operation Highjump.[1–3] The first Australian dive was conducted by Phillip Law in March 1956 at Mawson Station (67°62'S 62°87'E).[4] Antarctic peninsular research diving was reported by Americans participating in an Argentinean cruise in 1958 (exploring as far south as Paradise Harbour, 64°51'S 62°54'W);[5,6] the British in 1962 (Signy Station, 60°43'S 45°36'W);[7,8] the French in 1962 (Morbihan Gulf, 49°25'S 70°8'E);[9] the Russians in 1965 and 1968;[10,11] the Japanese in 1968 (Syowa Station, 69°00'S 39°35'E);[12,13] and New Zealanders in 1970.[14]

Protective suits

Protective suits were the first priority. Early practice employed a range of equipment, some as used in more temperate waters and some modified for polar conditions. Both wetsuits and drysuits were used in early dives. The reality of wetsuits was most graphically captured by Norton: "*Endurance increased as diving suits improved, notably the introduction of the zipperless two or three piece suit of unlined 10 mm neoprene. However, dressing consumed half the world's talc production and undressing was like skinning a reluctant rabbit.*"[7]

The potential for the greater thermal protection with drysuits was acknowledged in early cold-water trials.[15] Drysuits of this era, however, were very different to modern suits. Without valves, the internal airspace was compressed with increasing depth ('suit squeeze'), reducing the thermal protection, producing large changes in buoyancy, and often increasing the likelihood of leakage. These concerns, and those of added bulk and restricted mobility, led many early dive teams to prefer wetsuits.[5,6] Others wore wetsuits under drysuits to maximize in-water times.[16]

The modern polar diver is unlikely to use a wetsuit for any operation or as an undergarment. Suit and undergarment technology have evolved to bring the –1.9°C water temperature found along the continental Antarctic to within a reasonable tolerance range. A variety of configurations are available to provide levels of (relative) comfort (see Figure 9, photospread). The most sensitive issue for diver performance is hand temperature. Unfortunately, dexterity and thermal comfort are competing priorities. Practically, the choice will vary with the length of the intended dive and task requirements.

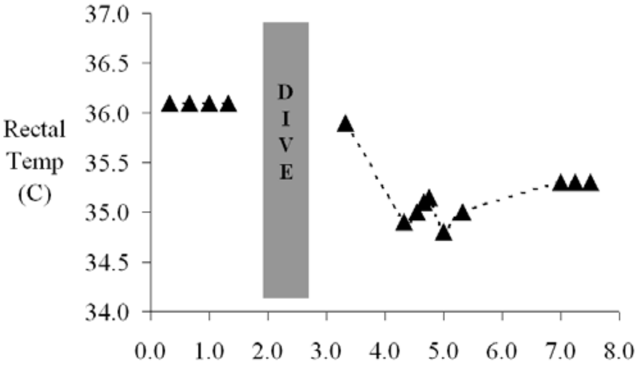
Thermal stress

The challenges for thermal protection in polar diving are the high thermal capacity (i.e., the product of specific heat and thermal conductivity) of water and practical limits to the bulk of thermal-protection equipment that can be worn whilst maintaining adequate mobility. The demands on protective suits can be put in perspective by considering the influence of cold-water immersion on unprotected persons. A research group in Canada immersed 21 lightly clothed subjects to the lower neck in water of 0°C stirred at 0.2 $m.s^{-1}$. The subjects remained in the water on average for just over 30 minutes. The core temperature in these unprotected subjects fell at a rate of –6.4 ± 0.7°C for males and –5.6 ± 0.7°C for females. The ability to self-rescue was lost in a matter of minutes.[17] The cold-water diver faces the additional challenge of having the head fully immersed, a major centre of heat loss.

Limited data exist on the core temperature response of polar divers, but those available suggest it has a fairly modest impact.[18–20] The 35°C threshold for hypothermia is likely rarely reached. The response of a diver to an unusually extreme polar dive (19 November 1993) is offered as an example. The diver donned a drysuit ensemble (full cover polypropylene underwear, fleece jumpsuit, heavy-weight Thinsulate™ jumpsuit and a Diving Unlimited International CF200 crushed neoprene drysuit) in a heated hut and then travelled approximately eight kilometres by snow machine in less than 20 minutes to reach an uncovered dive hole (78°S latitude). The air temperature at the site was –6°C with variable wind around 8 km.h^{-1}. Upon entering the water the diver realised that there was a leak near the bottom of the front entry zipper, allowing water to enter the suit (noticeable immediately upon immersion). The diver opted to continue the dive to survey the underside of an iceberg. The team proceeded to a depth of 36 metres' sea water (msw) to begin the survey, then moved progressively shallower. The seawater temperature was a uniform –1.9°C. Water continued to infiltrate the suit, soaking the undergarments up to the top of the chest anteriorly and the upper lumbar region posteriorly. The diver chose to abort the dive when he realised that he was having difficulty mentally computing manual camera settings. The total underwater time was 43 minutes. The diver then drove the snow machine back to the heated hut to change.

Coincidentally, the diver had a rectal probe in place to track his core temperature over the course of the day. Readings were taken until the drysuit was sealed prior to travel to the outside hole and immediately upon opening the suit after return to the building two hours later (Figure 1; Pollock N, unpublished data). The diver had a stable pre-dive rectal temperature of 36.1°C. A temperature of 35.8°C was measured when the suit was first opened in the hut post-dive. Measured rectal temperature fell after the diver changed clothing, to a low of 34.8°C, only recovering to 35.3°C within the next two-and-one-half hours while the diver remained in a heated building. This example highlights the limitations of rectal temperature in reflecting whole-body thermal stress. It can be insensitive to thermal cooling that may ultimately be important. In this case, removing the suit and undergarments and drying/warming the skin likely combined a rapid attenuation of shivering thermogenesis, increased convective cooling via changes in peripheral blood flow, and possibly increased conductive heat loss along tissue thermal gradients.[21,22] The impact of these events, primarily through heat redistribution within the body, was evident as rectal temperature 'afterdrop' only long after the end of the exposure period.

Figure 1
Extreme core temperature response to a 43-minute outside dive (with drysuit leak) in –1.9°C seawater; maximum depth 36 msw; air temp –6°C; wind at 8 km.h^{-1}



While secondary to immersion stress, there are also physiological considerations of hyperbaric exposure on thermal stress. Respiratory heat loss increases under hyperbaric conditions as gas density and heat capacity increase. Generally this becomes a significant avenue for heat loss only at depths greater than 200 m, particularly when breathing helium-oxygen gas mixtures,[23,24] but the combination of cold polar water and the cooling of expanding gas is not trivial. A field study of regulator performance reported mean first stage housing temperatures of –3.8±0.6°C during typical Antarctic dives.[25] The actual gas temperature was likely lower than this as the housing temperature (measured within a partial thickness hole drilled in from the outside) was simultaneously being warmed by the surrounding water.

Finally, there is also some evidence for a narcosis-induced reduction of heat production during cold-water immersion.[26–28] Further work is required to determine what practical influence this may have on the polar diver. Both respiratory heat loss and narcosis-related impairment will become more important if operational depth increases as it has for scientific diving in more temperate regions.

Breathing apparatus

While surface-supplied and closed-circuit devices were used in the earliest operations,[1,4,6] open-circuit scuba diving with double-hose regulators became the predominant choice for Antarctic diving beyond the late 1950s.[12,16,29,30] The advent of single-hose regulators prompted a series of comparison trials under polar field conditions.[31] The double-hose regulators were substantially more reliable for cold-water use than any single-hose regulator at that time and were confirmed as the standard for polar operations. While single-hose regulators evolved, a largely unchanged style of double-hose regulator served the polar diving community for almost two decades. Eventually, the reliability of these units suffered, largely due to an increasingly limited supply of parts. The failure rate observed in the US Antarctic programme reached a peak in 1990, when individual regulators had a failure rate as high as 40%.[32] Regulator failure is usually expressed as a progressive free flow instead of an abrupt loss of air supply. Breathing can become difficult and gas loss severe, but the diver should have a redundant regulator to switch to while swimming toward an escape hole. The possibility of failure kept dives short, since the risk increased over time for some regulators, and close to a point of egress. A study of regulator performance started in 1989 indicated superior reliability of several single-hose regulators,[33] including Poseidon models already adopted by the British and New Zealand programmes.

Continued testing within the US programme led to the selection of the Sherwood Maximus™ as the new standard because of its combination of reliability and ease of servicing. The model demonstrated a 1.7% failure rate in 1,341 dives conducted over a four-year period, an order of magnitude lower than the 17.4% failure rate of the double-hose US Divers Royal Aquamaster™ in its final two years of service.[25,34]

Of historical interest is the fact that unmanned testing conducted by the US Navy concluded that the Sherwood Maximus™ could not be recommended for cold-water use.[35] Some confusion arose in that the Maximus regulators tested by the Navy did not include a heat retention plate provided by the manufacturer in some of the regulators field tested in the US Antarctic programme.[25,36] The heat retention plate was associated with a non-significant reduction in the failure rate observed with polar use.[25] The Sherwood Maximus™, with heat retention plate, remains the standard regulator for the US Antarctic programme, with a cumulative failure rate of 0.3%.[37] This experience reinforces the importance of field testing in addition to bench trials. Cautious field testing is even more important before accepting performance claims of new devices with no independent testing history. Memory of the performance of the Royal Aquamaster™ regulator in its final years should also drive additional effort to test new regulators to find a replacement for the Sherwood Maximus™ before similar ageing problems occur.

Polar diving programmes

While many countries likely conduct at least some diving in conjunction with Antarctic research programmes, the literature record is highly variable.

UNITED STATES

The United States maintains the greatest physical presence in the Antarctic. The largest Antarctic facility is McMurdo Station on Ross Island (77°51'S 166°40'E), established in 1957 and now supporting in excess of 1,000 persons in summer and around 250 persons in winter. Formalised diving procedures were established at McMurdo sometime prior to 1960.[30] The first reported under-ice dive was made in November 1961, with a total of 35 dives completed over the following year.[16] Ten more under-ice dives conducted in 1963 were reviewed by Ray and Lavallee.[29] Given the dominance of fast ice in the vicinity of McMurdo Station, the majority of dives were under-ice once the ability to conduct these operations was established. The ice thickness at the entry point can range from 1.5–5.8 m.

Formal records of US Antarctic programme diving activity between 1960 and 1978 were not preserved. The only available means to estimate McMurdo diving activity between 1978 and the 1988/89 season is the service log of cylinder fills maintained with the main station air compressor.[38] Totals from 1978/79 to 1993/94 are listed in Table 1 (Mastro JG, personal communication, 1994). These totals undoubtedly underestimate total dives, particularly those conducted during the non-winter periods, since they do not include fills made with a portable compressor available for remote field operations. The difference between fill records and dive log totals for the 1989/90 and 1990/91 seasons provides an indication of the potential magnitude of this problem. The addition of a cascade storage system to the McMurdo air station in 1990 (allowing cylinders to be filled without starting the compressor) might have further confounded the picture but, fortunately, dive records were captured by that time.

Table 1
Air compressor records from McMurdo Station

Season	Compressor fill record total	Logged dive total
1978/79	106	
1979/80	51	
1980/81	177	
Winter 1981	162	
1981/82	347	
Winter 1982	110	
1982/83	157	
1983/84	143	
1984/85	908	
Winter 1985	106	
1985/86	252	
Winter 1986	29	
1986/87	83	
1987/88	132	
1988/89	226	
1989/90	394	526
1990/91	481	658
1991/92	313	288
1992/93	444	435

Bearing in mind the shortcomings, a total of 2,989 fills were recorded between the 1978/79 and 1988/89 seasons. Annual fill totals ranged from 51 to 908. (Note: winter fills were arbitrarily added to the following summer season for these calculations). The median number of fills recorded annually was 177 (mean ± standard deviation 272 ± 248).[38]

Centralised record-keeping of diving activity within the US Antarctic programme was initiated in the 1989/90 field season. A total of 3,113 person-dives were completed between 1989/90 and 1994/95; 519 ± 183 (288–795) annually. Underwater time varied dramatically, up to 76 minutes.[38] The annual number of dives was more stable from 1996 through 2006, averaging around 800 and peaking in

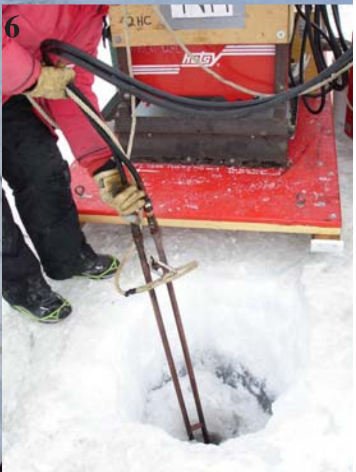


Figure 2. Cape Bernacchi dive hole
Figure 3. Hole melter assembly beginning hole melting process
Figure 4. Hydraulic drill assembly (1.2 m diameter drill) towed in vicinity of McMurdo Station
Figure 5. Hole melter partially inserted into ice
Figure 6. In-hole heating trombone used to start the melting
Figure 7. Keeping warm whilst hole melting
Figure 8. *Leptonychotes weddellii* hauling out of dive hole
Figure 9. Diver beside an ice wall

2002 at 1,200.[37] A total of 10,859 dives were logged in the programme from 1989 through 2006. The average dive had a depth of 22 msw and a duration of 34 minutes.[39]

The 1994/95 season was the first from which reliable records of diving activity are available for the US peninsular Palmer Station on Anvers Island (64°46'S 64°05'W). A total of 79 dives were completed by 11 divers. The mean underwater time was 23 minutes and the mean number of dives was 7.2 per diver per season (Mastro JG, personal communication, 1996). A practical description of pack-ice diving practices employed in the peninsula was recently reported.[40] All diving activity in the US Antarctic programme is currently managed and monitored under a health and safety initiative administered by the National Science Foundation.[37]

UNITED KINGDOM

The British Antarctic Survey (BAS) has maintained a record of its diving activity since 1962. A brief review was published in 1995.[8] The total number of dives conducted per year exceeded 100 in 1969, 200 in 1972, 300 in 1984, and 600 in 1993. Approximately two-thirds of these were open-water dives. The number of under-ice dives peaked at more than 200 in 1987. A total of 1,254 dives were conducted at the peninsular Signy Station, South Orkney Islands, in 1993 and 1994. Almost 87% were open-water dives. The mean dive duration was just over 18 minutes, with a maximum underwater time of 78 minutes. The mean depth was 12.7 msw, with a maximum depth of 45 msw.[8] Another 112 dives conducted from an oceanographic vessel were also described.[41] The majority of BAS diving is now conducted at the peninsular Rothera Station on Adelaide Island (67°34'S 68°08'W). The range of work conducted was recently reviewed.[42] A total of 5,492 dives were logged in the BAS programme from 1989 through 2006.[39]

AUSTRALIA

Diving in the Australian programme was primarily limited to the austral summer prior to 1982. A year-round programme was initiated in 1982 at the continental Davis Station (68°35'S 77°58'E).[19] No data are available on dive tallies. A summer diving programme was established at the continental Casey Station (66°16'S 110°31'E) in 1999. Both scuba and surface-supply modes were supported. A total of 1,099 dives conducted over a five-year period were reviewed in 2004. The mean underwater time was reported to be 40 minutes with 92% of the dives shallower than 20 msw (Watzl RF, personal communication, 2005).

NEW ZEALAND

Diving from Scott Base (77°38'S 166°24'E), 3 km from McMurdo Station, began in 1985.[43] The ongoing activity is modest, varying from year to year, often taking advantage of holes prepared for dive teams in the US programme. A total of 1,296 dives were logged in the New Zealand (NZ) programme from 1985 through 2006.[39,43]

Procedures

Antarctic research diving is almost universally restricted to no-decompression diving, although the allowable decompression models vary. The British, NZ and Australian programmes require adherence to the Canadian DCIEM dive tables while the US programme requires the US Navy tables or an ‘approved’ dive computer. The majority of programmes require tended line tethers for all under-ice diving. The exception is the US programme, which employs tended lines under some conditions (low visibility, current, etc.) but generally allows free-swimming operations with holes marked by downlines festooned with flags, multiple compact strobe lights and a 400 L bail-out bottle with regulator. Dive depth is limited to 30 msw within the Australian, NZ, and Norwegian programmes. The US programme maintains a 40 msw limit with approval possible for deeper dives if required. Maximum dive duration is 40 minutes for the NZ programme, 60 minutes for the Australian programme, and not specified in the US programme.

Dive hole construction

Pack-ice diving common in the Antarctic peninsula may include access into fairly open water from small boats or from holes cut into stable pack-ice floes.[40] Access in the fast-ice environment of the continental Antarctic may be through tide cracks or through holes opened in the solid ice. Tide cracks may be wide enough to allow free access but may also be prone to sudden changes in conformation. Fast-ice holes are typically preferred, frequently covered by surface shelters for protection from ambient weather conditions. Ice holes can be opened by progressively cutting/drilling and removing manageable sections of ice from the surface to create a hole of the desired size. The holes flood when the full thickness of the ice is finally breached, typically filling to within 25 cm of the ice surface (Figure 2). This approach is time intensive, described by an early dive team as requiring 32 man-hours to clear a 2.3 m wide hole through 4 m thick ice.[29] A hydraulic drill (Figure 4), currently capable of opening 1.3 m diameter holes in a few minutes has replaced manual labour in the vicinity of McMurdo Station.[37,44]

Sealed glycol melters offer an option for opening holes at remote sites,[45] but still with significant effort (Figures 3 and 5–7). Transporting the necessary equipment is no mean feat in areas with rough surface ice, particularly when multiple holes are required. The melting process is also time-consuming. The equipment must be closely monitored to ensure that the melting is progressing in a useful direction. Sideways slippage of the heat transfer assembly may stop progress if the resultant pool is large enough to absorb sufficient heat energy. Too rapid a vertical advancement may place enough of the assembly under the lower reach of the ice to similarly stop widening progress. The maximum vertical penetration is also dependent on the length of the hose and heat transfer assembly. Additional length increases the volume of glycol required and the collateral heat loss in the early stage of operation, when the supply lines remain in the air. Melting a dive hole through 5.0–5.8 m of ice can take between 24 and 36 hours.

Explosives remain a necessary option in some locations.[37,44] They allow the construction of holes of almost any practical size through 6 m or more of ice with six to eight man-hours of labour, primarily spent moving pulverized ice and checking for clear passage between blasts.

Diving safety

Hyperbaric chambers are available at McMurdo (US), Rothera (UK) and Casey (Australia) stations. Diving anywhere outside the immediate vicinity of a hyperbaric chamber may result in significant delay to treatment since surface transport options are typically limited and air travel is restricted to visual meteorological conditions. A pilot effort to test a 2.6 hour in-water recompression protocol confirmed that thermal stress issues rendered the option untenable.[46,47] Dive groups will typically carry emergency oxygen, frequently for open-circuit delivery but in some cases with closed-circuit devices, which can dramatically extend supply time.[43,48] Fortunately, despite potentially-augmented risk factors of cold stress, obligatory physical labour, and prevailing low atmospheric pressure, decompression sickness is a fairly rare event in Antarctic research diving. A recent report describes incident rates of 0, 0.18 and 0.55 cases per 1,000 person-dives for the New Zealand, US, and BAS programmes, respectively. This represents an overall rate of 0.28, or five cases in 17,647 dives. There were no reported cases of arterial gas embolism.[39]

Two fatalities related to scientific diving in the Antarctic have been documented. A male research diver in the US programme died in November 1987 when buoyancy problems developed during an effort to transport a piece of experimental apparatus weighing approximately 18 kg from the surface to the bottom under fast ice in a field camp at Explorers Cove, New Harbor (77^{O}34'S 16^{O}35'E), 80 km west of McMurdo.[49,50] A female researcher in the British programme died in July 2003 following an unprovoked attack by a leopard seal (*Hydrurga leptonyx*) while she was snorkelling with a partner on a research site adjacent to Rothera Station.[51]

Conclusions

Diving has served as an important research tool in Antarctic science for the past 50 years. Equipment, techniques and oversight have developed to make it a mainstream function in many polar programmes. The safety record is encouraging, particularly given the unforgiving nature of the environment.

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