SPUMS ANNUAL SCIENTIFIC MEETING 1998

A SHORT HISTORY OF SUBMARINE ESCAPE: THE DEVELOPMENT OF AN EXTREME AIR DIVE

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Key Words

Accident, bell diving, decompression illness, emergency ascent, history, hyperbaric facilities, rescue, surface decompression, transport, treatment.

Introduction

"One of our submarines is missing..." This announcement is rarely heard but, when it is, even those who have no links with the sea may feel some inner foreboding. For many the depths of the sea remain unseen and full of mystery and so the prospect of men who may be entombed for days, while fate slowly determines the conclusion, becomes high drama.

Fortunately it is not the public's perception with which we are concerned here though, as in many other safety issues, it does need to be acknowledged that the political response to adverse media publicity can be a useful spur to the funding of relevant research and development. In relation to submarine rescue and escape, much research has had practical application, some has been important academically and quite a bit is relevant to diving.

The problem

Submarines have been a significant factor in naval warfare for more than two hundred years but, for our purposes, the 150-year or so history of the submarine can be simplified:

- depths have extended from several inches to those of the worldwide oceans.
- power sources have developed from muscles to nuclear fuel.
- submerged duration has progressed from minutes to months.

Those with a realistic chance of emerging alive from a submarine trapped at depth are likely to be still at atmospheric pressure (or maybe just a little more), and there are only two ways out. One is by direct transfer at the same environmental pressure into a rescue bell or another submarine. The other route is to emerge from the submarine into the sea outside, to be exposed to the full pressure of that depth and then to float up to the surface. The first is "Submarine Rescue", and the second "Submarine Escape".

Submarine Rescue avoids exposure to the extremes of raised environmental pressure and the consequent physiological problems. Rescue may be associated with some decompression risk if the internal pressure has built up within the stricken boat but, because the survivors make their transfer at close to atmospheric pressure, there are few physiological lessons relevant to diving.

Submarine Escape, in contrast, means that the survivors have to get out of the boat by emerging into the sea where they are exposed to the full environmental pressure of that depth. The extreme physiological consequences of this provide analogies with diving which are worthy of review.

With each procedure there is the common problem that there is only a limited time that the survivors can remain safely waiting in a submerged submarine compartment. The oxygen is being consumed, carbon dioxide is accumulating and, with leaks and flooding, the internal pressure may be rising. In some boats the period of waiting could be days but in other operational circumstances escape may be urgent.

There is also another factor which determines how long survivors need to wait for rescue and that is the enforced delay waiting for arrival of a rescue vessel. So, while Submarine Rescue may be the preferred method, it is not always practical. This is why Submarine Escape will remain an important option: it does not depend on the arrival of a rescue vessel and escape can begin immediately.

The first submarine escape

Of course there may have been some successful escapes from sunken boats previously but the escape of the crew of Wilhelm Bauer's submarine on 1st February 1851 was the first to be witnessed and well reported. The story illustrates very well the basic challenges that all submarine survivors must overcome if they wish, like Bauer, to escape from a watery tomb.

Wilhelm Bauer, who had been a corporal in the Bavarian Artillery, designed an all-iron submarine *Brandtaucher* which was used against the Danish blockade of Kiel Harbour.[1] Propulsion was by a propeller powered by his two crewmen who also had to control the angle of the boat underwater by means of hauling a heavy ballast weight back and forth along the bilges. The hull had four square windows for observation and to provide illumination. It was a prototype pressed into premature service by its investors and the following translation is adapted from Bauer's own written account.[2]

Operated by Bauer and his two assistants, Witt and Thomsen, the submarine lost its horizontal stability at 9 a.m., after some 14 minutes running out to sea and shortly after flooding the flotation compartments. The tilt of the stern's more rapid descent caused the horizontally-adjustable ballast to shift further towards the back, and the increasing pressure crushed the starboard side of the hull fracturing a propulsion drive wheel. The boat, now leaking water through several seams, came to rest stern lowermost at around 16 metres.

The three men were trapped in a disabled and leaking submarine and seemed doomed to certain death. Bauer's frightened companions tried to plug the leaks and pump out the water but Bauer realised that the rising water level could be their salvation. He realised that when the trapped air became compressed to ambient pressure, it would be possible to open the hatch, escape outside and float to the surface. He then had to convince his two crewmen to stop plugging the leaks because this would only delay their escape and cause them to use up valuable oxygen. Instead he urged them to rest and conserve their energy.

Some four or more hours later, when the three men were in the cold and near-dark of the compressed air remaining trapped in the uppermost bow, they heard chains and grappling hooks against the hull and Bauer became concerned that a salvage attempt might obstruct their escape. The water level was rising more slowly now and so they unscrewed an iron bar from the pump and used it to try and pry open the hatch. A frightening stream of cold water was their reward. The most powerful man of the three used his back against the hatch, it suddenly flew open and the escaping air swept him out into the sea. Instantly Bauer grabbed his other companion who was desperately trying to hold on, pulled him by the hair, and they were both swept out of the hatch by the remaining air stream.

They were rescued by the astonished crews of the salvage boats and, though cold and exhausted, there were no reports of any symptoms that might imply decompression illness.

Four years later Bauer built a successful 12-man submarine in St Petersburg and it completed more than 300 dives. Bauer built an escape lock into this boat as a result of his previous experience[3] and it has been suggested that it was also a lock out for hard-hat divers.

Escape breathing apparatus

There are many claims for the first true submarine, most were later than Bauer, but these rivalries concern us less than the origins of breathing apparatus for the escaper. The reasons for such apparatus are not always defined but appear to have been a concern that the escaper would be affected by build-up of carbon dioxide during ascent, would be unable to control inspiration and might drown.

The first oxygen-regenerating device used in the UK was the Davis submarine escape apparatus (DSEA) designed by Robert Davis in 1903. It was based on the Fleuss apparatus of 1878,[4] but the oxygen cylinders of those days were too large for the hatches. To avoid this problem the Hall-Rees apparatus (Figure 1) was designed to use sodium peroxide for both oxygen generation and carbon dioxide elimination, but because the process was slow to get going, the escaper had first to be enclosed in the air retained by a type of open diving dress with a helmet.[4,5] A potential problem was that, if it became wet, the sodium peroxide would burst into flames, but it was the first individual escape apparatus to be brought into service and lasted through to the end of the First World War. As one submarine commander is said to have remarked *"it might offer a sporting chance"*. A more compact oxygen apparatus was designed by Dräger in 1911 and, with modifications, was used by the German Navy for some 35 years. The DSEA was later adapted for use by the Royal Navy (RN) (Submarine Escape Breathing Apparatus) with, at Haldane's suggestion,[6] an apron to be extended by the escaper in order to slow down the rate of ascent (Figure 2).

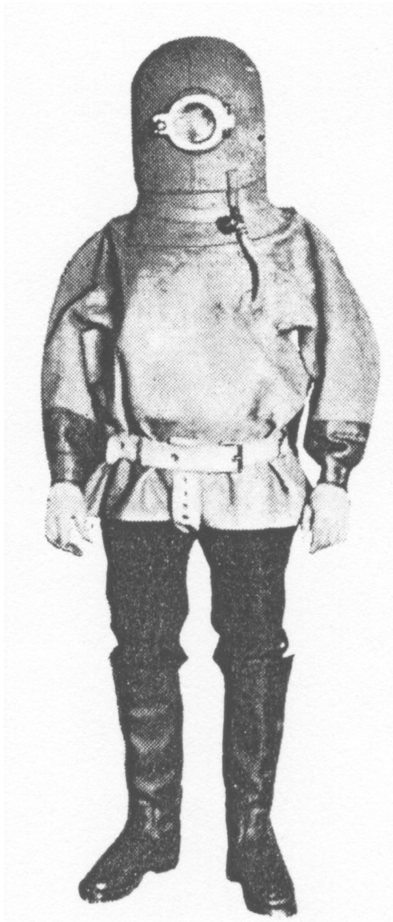

Figure 1. The Hall-Rees submarine escape breathing apparatus with built-in sodium peroxide oxygen generation [Fig 507 from Ref 4].

Figure 2. Davis submarine escape apparatus (DSEA) with vane extended to slow the rate of ascent. [Fig 252 from Ref4].

Perhaps unimpressed by these early developments, Lt Kenneth Whiting made a “free escape” in 1909 from the torpedo tube of a US Navy submarine at 26 feet (8 m),[7] a brave demonstration of a method that, somehow, has never caught on.

A very readable account of this whole period, with many stories of survival from sunken submarines up to those of *HMS Truculent* in 1950, has been written by Shelford.[5]

In 1917 HM Submarine *K-13* sank in Gareloch but was located immediately enabling the bow to be hauled to the surface and 46 men saved directly into air at atmospheric pressure; a fortunate outcome and maybe the first true Submarine Rescue (Figure 3). In 1918 there was a successful escape with Dräger oxygen “lungs” by the crew of the German *U-57* which had been mined off Dover.

These relative successes were overshadowed in 1927 when the US submarine *S-4* was rammed off Provincetown and sank in 100 feet (30 m). The rescue vessel could not get there for 16 hours. Although some survivors were still alive, gales and other problems meant that a hose to blow fresh air into the survivors’ compartment was delayed another 20 hours, too late to save life.

The beginnings of planned Submarine Rescue

In response to this tragedy, an old seaplane hanger was removed from the US submarine *S-1* in 1928 and Momsen halved it to make prototype rescue bells which later, redesigned, became the McCann bell.[5]

In 1930 this rescue bell was tested to 1,000 feet (304 m) by the USN but it was recognised by the RN that, to be of practical use, accurate and early location of the disabled submarine is essential and, from a UK point of view, to maintain a world-wide network of rescue bells would be impossible.

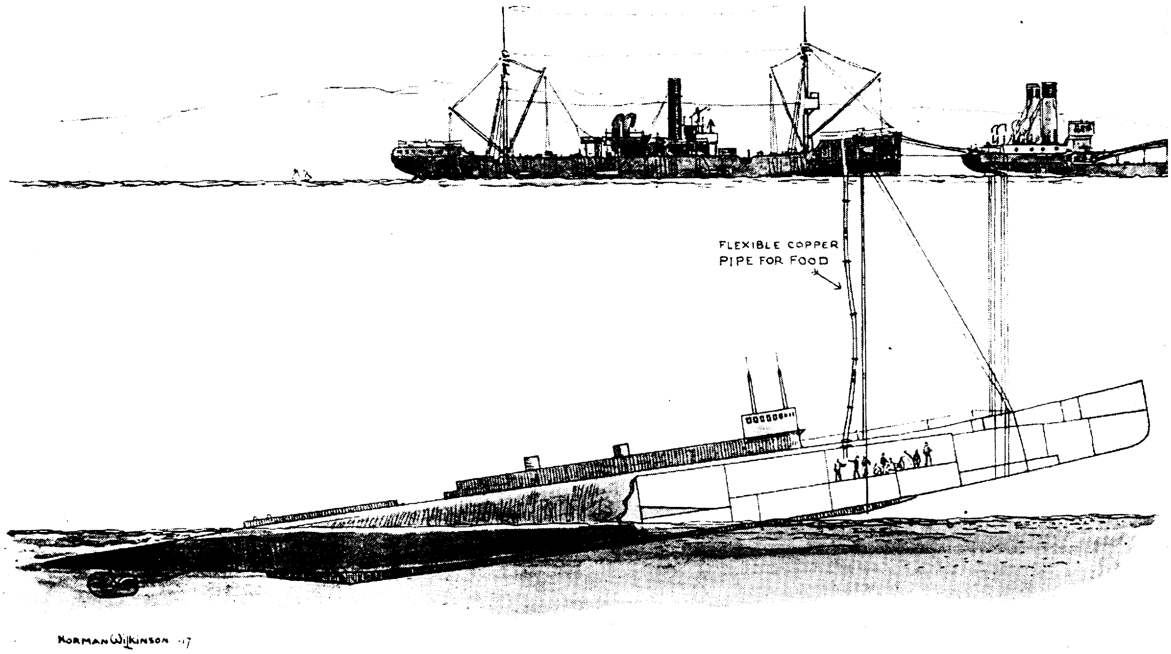

Figure 3. K 13, the first submarine rescue operation. [Fig 393 from Ref4].

Development of individual escapes

In 1930 individual escape without outside aid through either a submarine hatch or torpedo tube was reviewed.[8] Based on demonstrated ascent times from 40 feet (12 m) of 11 seconds without swimming and 8 seconds with swimming, a limit of 50 feet (15 m) had been decided for individual escape. For deeper escapes an individual escape apparatus with twin hoses and a carbon dioxide scrubber, "the lung", was introduced by Momsen and others.[5] An oxygen supply is illustrated in the paper and was used to charge the lung before use. Simulated escapes were made through the water from 60 feet (18 m) and in the wet pot of the Experimental Diving Unit (EDU) from 250 feet (76 m) but with decompression stops. After some open sea tests from a bell, escapes down to 206 feet (63 m) were made from the salvaged submarine *S-4* submerged at sea. Compartment escapes were made from 100 feet (30 m) and from a special escape lock at greater depths. Ascent was made up a buoy line and the escaper timed any necessary stops by counting 16 breaths as one minute. Subsequently a simulated ascent was made in the EDU chamber from 357 feet (108 m) but the details are not given. These trials were conducted at the time when the US Navy Submarine Escape Training Tank, 18 ft (5.5 m) diameter and 100 feet (30 m) depth, was being built.

Only a year later there was a fatality after a 15 foot (4.5 m) training ascent using the Momsen Lung when the subject, in a manner later to be found typical of such incidents, fell back in the water on reaching the ladder.[9] The first experimental studies of pulmonary barotrauma followed.[10]

In 1931 the submarine HMS POSEIDON sank off Hong Kong in 125 feet (39 m) and, for the first time, the oxygen-regeneration breathing equipment was used.[6] An account of the escape by one of the survivors, Holt, tells that two of the eight in the forward torpedo compartment died during the flooding-up phase which lasted some 3 hours, one with no breathing apparatus and one whose apparatus became depleted. Six survivors escaped from the compartment but one was killed by a head injury sustained on emerging through the hatch. They developed decompression sickness from what had been their one and only exposure to raised environmental pressure. Perhaps the most relevant observation for divers is that 3 were examined again 12 years later and all three had juxta-articular necrosis of a shoulder and/or hip after this one exposure.[12]

The use of the "Momsen lung" for compartment escapes with ascent at 50 feet (15 m) per minute was reviewed in 1936 because of concerns about the risk of decompression sickness if the survivor was exposed to a prolonged period of preparation at pressure before escape.[13] During trials in the wet pot at EDU, subjects breathed compressed air at a depth of 100, 150, 167, 185 or 200 feet (30, 45, 51, 56 or 61 m) for predetermined exposure times. Exposure time was defined as half compression time plus time at maximum depth, but the rate of compression is not stated. The subject then submerged and breathed from the lung for two minutes and then was decompressed still submerged. In some the "lung" was charged with oxygen and in others with air. *Four series were conducted at 100 feet with a total of 1,231 exposures. The first case of caisson disease occurred following an exposure of 37 minutes breathing oxygen, but .. breathing air ... not until 43 minutes.* Similar results from other depths led to a conclusion that, breathing air for the ascent, safe exposure times were

100 ft (30 m) for 37 min
150 ft (45 m) for 18 min
200 ft (61 m) for 13 min.

The year 1939 was a tragic year for submarine accidents with nearly 300 fatalities. In February *SM I-63* of the Imperial Japanese Navy sank after a collision and 83 died. Then, in May, the US submarine *Squalus* dived with an air-induction valve open (though marked "secured") and sank in 243 feet (74 m) off Portsmouth, New Hampshire. Twenty-six of the crew died but, after a wait of nearly 24 hours for the rescue vessel, 33 were saved in the next 15 hours in 4 trips of a McCann bell. The account of the first open-sea use of heliox diving for the salvage of the *Squalus* is a separate story.

Nine days later, *HMS THETIS* sank on her initial trials off Liverpool in 150 feet (46 m) of water with her stern showing but only 4 survived, 99 died. In his review,[6] Donald concluded that the lethal effects of compressed foul air were not appreciated at the time. Then, only two weeks later, the French Navy who had just ordered but not yet received a McCann rescue bell, lost their submarine *Phenix* in 300 feet (91 m) and 71 men died.

War experience suggested that the majority of successful escapees had not used breathing apparatus and this was confirmed in 1946 by the reviews of an Admiralty Committee. In the meanwhile the US Navy abandoned the "oxygen lung" and adopted free escape for submariners with training in the 30 m tank at New London.

The dangers of deliberate flooding prior to compartment escape were recognised. Any decision to delay the flooding process, perhaps misguidedly because it symbolises abandoning one's ship, leads to an accumulation of carbon dioxide and toxic fumes. Compression of only a low percentage of carbon dioxide can lead to the toxic and potentially lethal effects of its increased partial pressure. Relief by breathing from DSEA, an oxygen "lung", can lead to an oxygen convulsion exacerbated by the vasodilatation from prior carbon dioxide. Also, if there are leaks in the escape compartment which are high up, maybe into another compartment, the precious air lock could be lost before equalisation occurs.

Nitrogen narcosis during deeper escapes and decompression sickness afterwards were other hazards.

Animal work using goats became intense and demonstrated a safe path to be followed by human volunteers.[6] They showed that, after 3 to 5 minutes at depth, escapes would be possible from 250 feet (76 m) and suggested that faster and deeper cycles would be possible. Compression and ascent were at 2 feet (0.6 m) per second. The use of 60/40 nitrox led to bends which showed that, contrary to expectations, the oxygen content could not be ignored in decompression calculations but, in any case, the carriage of nitrox solely for escape would not be feasible in operational submarines. Human subjects were used during rapid compression to 300 feet (91 m) to study the effects of narcosis, but found no significant disturbances and concluded only that escape tasks should be kept as simple as possible.[15]

Evidence from human escapes about the desire to breath during a long ascent was ambiguous: some had no problem, some had an urgent desire to inhale and others became unconscious during the ascent without it seems inhaling a significant amount of water. Paton had shown in 1947 that the desire to breathe in is more easily resisted during ascent because of the diminishing partial pressure of carbon dioxide during ascent.[16] At the Royal Naval Physiological Laboratory (RNPL), Wright calculated that there would be no significant accumulation of carbon dioxide in lungs or body during an ascent with exhalation at 4 ft (1.2 m) per second from 300 ft (91 m).[17] There was still some concern that escapees might drown during an ascent of more than one minute and, immersed in water in a chamber, some volunteers felt a great need to breathe during ascents from 150, 200 and 300 feet (45, 61 and 91 m). Characteristically, Wright then tested deeper (330 feet, 100 m) and slower (2 feet, 0.6 m per second) ascents on himself. Time at the bottom was 60 sec at 300 feet (91 m) and 30 sec at 330 ft (100 m) and no decompression injuries occurred. Around 1950 a positive buoyancy stole attached to an immersion suit was introduced in the Royal Navy. With a positive buoyancy of 10 lbs (4.51 kg) the ascent rate for every escaper was increased to around 4 feet (1.2 m) per second.

In 1950 the sinking of the submarine *HMS TRUCULENT* highlighted the dangers of compartment escape from shallow depths and, in particular, with the subsequent loss of some 40 persons on the surface after their escape, the dangers of immersion hypothermia.

Buoyant ascent training by the Royal Navy began in 1953 in the new escape tank (SETT) at the submarine base, *HMS DOLPHIN*. The US Navy performed simulated escapes at New London with rapid compression from as deep as 450 feet (136 m) and in 1960 two open sea escapes from 300 feet (91 m).[18] Compression time was 25 seconds, 7 seconds were spent at maximum depth and ascent was at 5 feet (1.7 m) per second.

In 1962 escape trials (Upshot 1)[19] from 240 ft (73 m) were made from *HMS TIPTOE*. Compression in 30 seconds was not linear, with time at depth of 27-49 seconds, and ascent was at 6 feet (1.8 m) per second using the buoyancy stole and streamlined by the hood of the immersion suit. In spite of a bottom time, in diving terms, of a minute or more, most of the inert gas uptake would be during ascent. A greater compression rate was considered necessary and the Hood Inflation System (HIS.) was devised.[20] After more goat trials[21] to 500 feet (152 m), human trials were conducted with a linear compression in 20 seconds to the maximum depth and ascent after 20 seconds at maximum depth. One case of neurological decompression illness occurred after a 30 second exposure so this was abandoned. To compress a chamber on air at those rates to exactly 500 feet and then to maintain a precise decompression required great skill. On one occasion, with enormous banks of high pressure compressed air available, the senior escaper was once accidentally compressed to 300 feet (91 m) in around 2 or 3 seconds. He was decompressed immediately and, quite unfazed, lit a cigarette to help pass the obligatory "bend watch". Smoke came out of both ears. His only complaint, after this barotrauma, was that on getting home some three hours later, the drums had sealed and he could not show this new trick to his children. A small story but one that characterises the many willing submariners who volunteered to be subjects for this work.

In 1965 the escape trials (Upshot IV)[22, 23] were conducted from *HMS ORPHEUS* at a keel depth of 500 feet (152 m) off Malta. The single escaper entered the escape tower wearing an immersion suit with an integral stole providing 150 lb (68 kg) positive buoyancy. By holding a hose into a compressed air supply in the tower, which was regulated to provide compressed air at 1 psi (6.8 kPa) over ambient, the escaper's buoyancy stole was inflated and, with an overflow from that into his hood set at 0.5 psi (3.4 kPa), he always had a respirable space around his head during the subsequent phases of flooding and then rapid compression.

With a vent open into the boat, incoming sea water was allowed to flood the tower to a height related to the depth of the submarine, the escaper remaining at the submarine's atmospheric pressure during this time. When the sea water reached its predetermined height, the water would begin to cascade down the vent which was the signal for those within the boat to close it (Figure 4). The last man out would simply cap the vent from within the tower. Then, with only a small air space in the tower around the head of the escaper the sea water, continuing to flood in, would compress it rapidly. In fact the compression to depth took around 15 seconds and a triple spring nose clip helped to clear the ears. There was one ruptured drum from the 87 escapes. The partial pressure of oxygen in the compressed air reached 3.4 bar.

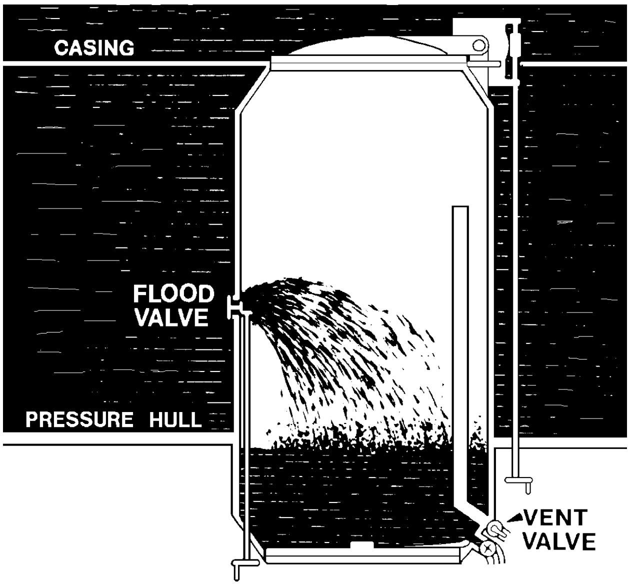

Figure 4. Single-man escape tower, for use by escaper with Hood Inflation System, shown when flooding up and venting into the submarine, with no change in pressure in the escape tower, before the phase of rapid pressurisation of the remaining air lock. [from Ref 23]

On equalisation, the spring-loaded hatch flew open so that, with a bottom time at 500 feet (152 m) of some 4 seconds and no time to wave to those watching through the periscope, the escaper was accelerating towards the surface achieving a terminal velocity through the water of around 8 feet (2.4 m) per second which is an ascent rate of nearly 500 feet (150 m) per minute. A compressed air dive to 500 feet, a bottom time of some 20 seconds and a decompression of around one minute. Exhilarating was the commonest comment. The water was clear and those who made more than one escape learned to control their direction through the water and to modify their speed of ascent. Within the latent period before the onset of oxygen toxicity and nitrogen narcosis, the whole dive was just too quick. As the medical officer at the receiving end I had some anxieties about the potential consequences and treatment of a decompression barotrauma with deep onset, but there were no decompression symptoms.[24]

After more goat trials to 950 feet (288 m) and some human trials to 620 feet (189 m) in the laboratory, on compressed air and with no narcosis, approval was given for more trials (Upshot V) at sea. In 1970 from *HMS OSIRIS* at 182 m (600 ft) manned escapes were made with 20 to 30 seconds compression time, 3 seconds at maximum depth and ascent at 8.5 feet (2.6 m) per second. One subject, after a 500 ft (152 m) escape, had an episode of impairment of vision and balance both of which responded to recompression. Research has continued since then, trying to push the envelope a bit further but, with one or two other episodes of possible decompression illness during validation exercises down to 180 m (590 ft) in 1987,[25] it seemed wiser to stop. The volunteers and the ethical committee could relax, wise in the knowledge that all should be able to escape from a disabled submarine at the depths tested and that, should a deeper escape be needed, the probability is that significant proportion will arrive at the surface safely.

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Acknowledgments

I wish to thank Phillippe Rousseau of France, Joseph Bauer of the USA and Ulrich van Laak of Germany for their invaluable help in sourcing much of the early documentation and illustrations and, while there are many submariners, known and unknown, who deserve recognition for their dedication at depth to submarine escape, I would like to acknowledge two such selfless volunteers in research, Matty Todd[22] and the late Cam Wright,[17] for their inspiration and help in the preparation of my earlier papers.[23,24]

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THE HISTORY OF AUSTRALIAN SUBMARINE ESCAPE AND RESCUE OPERATIONS

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Key Words

Accident, bell diving, decompression illness, emergency ascent, history, hyperbaric facilities, rescue, surface decompression, transport, treatment.

Abstract

The Royal Australian Navy has developed and implemented a sophisticated submarine escape and rescue organisation. It includes not only the material hardware but a framework for review, accountability and progress. This paper outlines the development of the system looking historically at the events which initiated its formation.

Background

Australian submarine operations date back to WW1. The AE1 was commissioned in 1913 and was lost with all hands on approximately 14 Sep 1914 off New Britain. The submarine failed to return from patrol and the cause of its loss remains unknown. No trace of the AE1 has been found.

The AE2 was commissioned in June 1913 and was lost as a result of enemy action in the Sea of Marmora on 30 April 1915. The AE2 was the first allied warship to penetrate the Dardanelles and saw 5 days of action in these waters before being sunk by enemy fire. The entire crew survived. Rumours that the AE2 has been found off Turkey are yet to be confirmed.

During the period 1915-1922 Australia had a series of J boats, originally built for the Royal Navy (RN), but these do not appear to have seen much action. From 1918-1939 the Oxley and Otway were commissioned by the Royal Australian Navy (RAN), but again little action was seen by these boats.

It was not until the 1960s that the RAN purchased the Oberon Class of submarines from the RN and we became an active submarine nation. With this purchase came the corporate knowledge of the RN with respect to submarine escape matters: the single escape tower (SET), the built in breathing systems (BIBS) and submarine escape immersion equipment (SEIE). The RAN relied entirely on the RN for expertise in submarine escape, rescue and air purification systems.

During the 1980s there appears to have been a decrease in the flow of information coming from RN and policy changes were often “found” by accident with no information available as to how these decisions were made.

The 1990s saw the introduction of the Collins Class Submarines and, along with the requirement to build a unique submarine, came the requirement to develop and maintain in-house expertise in submarine escape, rescue and air purification matters. This resulted in the establishment of a department with a full time focus on submarine escape, rescue and air purification as they pertain to Australian submarines.

Why Maintain a SUBSUNK Organisation?

There are a number of reasons why the Australian government has directed the RAN to maintain a submarine