Chapter 19

UNDERSEA MEDICINE

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INTRODUCTION

Humans have explored the sea for as long as recorded history. President Kennedy remarked:

> I really don't know why it is that all of us are so committed to the sea, except I think it's because in addition to the fact that the sea changes, and the light changes, and ships change, it's because we all came from the sea. And it is an interesting biological fact that all of us have, in our veins the exact same percentage of salt in our blood that exists in the ocean, and therefore, we have salt in our blood, in our sweat, in our tears. We are tied to the ocean. And when we go back to the sea—whether it is to sail or to watch it—we are going back from whence we came.[1]

Though humans have always felt a connection to the world's seas and oceans, these water bodies can be deadly. Surface water temperatures in most regions of the world can cause hypothermia and death for unprotected or overexposed individuals. Waves at sea create hazardous conditions for maneuvering personnel and supplies, and numerous forms of marine life can inflict severe or fatal injuries. There is no air, and in very few places is there any significant warmth. Humans have little physical aptitude for survival on or in the water, and under-the-surface survival depends completely on technology. Although advances in technology make underwater operations possible, they also expose other limits, such as the human body's vulnerability to depth pressure.

This chapter focuses on the occupational health aspects of undersea operations. Undersea medicine encompasses an understanding of the underwater environment, a familiarity with the ship and diving systems that allow survival in such an environment, a thorough knowledge of the duties and workplace hazards present in undersea settings, and an understanding of the physiological and medical issues unique to undersea operations. As a result of increased joint operations, the remote locations of many military operations, and the military's role in humanitarian and recovery operations that include underwater salvage and repair, it is essential that military physicians be familiar with undersea medicine.

This chapter reviews the physical properties of diving to foster an understanding of physiological consequences with respect to undersea medicine. Additionally, it examines environmental hazards that threaten the health or mission success of undersea operations and discusses unique aspects and considerations of the submarine environment. This chapter is neither a complete guide to the treatment of diving casualties nor a complete overview of diving medicine. Readers are directed to companion chapters in the Textbooks of Military Medicine series; the *US Navy Diving Manual*, Revision 6; and references such as Bennett and Elliott's *Physiology and Medicine of Diving*, or *Bove and Davis' Diving Medicine*.[2–4]

UNDERSEA OPERATIONS

Occupational health aspects of undersea operations are numerous and varied. The environment, the nature of the mission, the equipment, and the physiological conditions of personnel are all factors. Whereas commercial industries, such as those involved in oil and gas exploration, conduct diving and undersea operations, military undersea operations have unique constraints. Operating with stealth, under time limits, and in remote and possibly contaminated locations or under the threat of enemy fire are inherent conditions to military operations. The key to safety in these conditions is to understand and prepare for the environment and its dangers.

Onboard each US Navy submarine, including fast attack and ballistic submarines, selected crew are trained as divers and can conduct security swims of the submarine perimeter or perform limited ship management. Navy divers conduct thousands of dives annually to perform limited ship management. The Navy also has underwater construction teams; mobile diving and salvage units; explosive ordinance disposal units; and sea, air, and land units with divers. Figure 19-1 shows US Navy divers participating in a salvage operation to recover nine missing crewmen and personal items following the submarine USS *Greeneville*'s (SSN-772) collision with and subsequent sinking of the *Ehime Maru*. Figure 19-2 shows divers being lowered to the *Ehime Maru* wreck site.

While it may seem obvious that the majority of undersea operations are conducted by the Navy, all military branches have divers. The US Marine Corps trains combatant divers as members of elite reconnaissance units to reconnoiter and infiltrate coastal areas in advance of amphibious landings. In addition to Special Forces personnel who complete the combat diver qualification course, the US Army has four light and two heavy dive teams. Light dive teams are highly mobile and can perform both scuba (self-contained underwater breathing apparatus) and surface-supplied diving. Heavy dive teams also conduct scuba and surface-supplied diving but mainly in support of commanders controlling harbors, ports, and coastal areas.

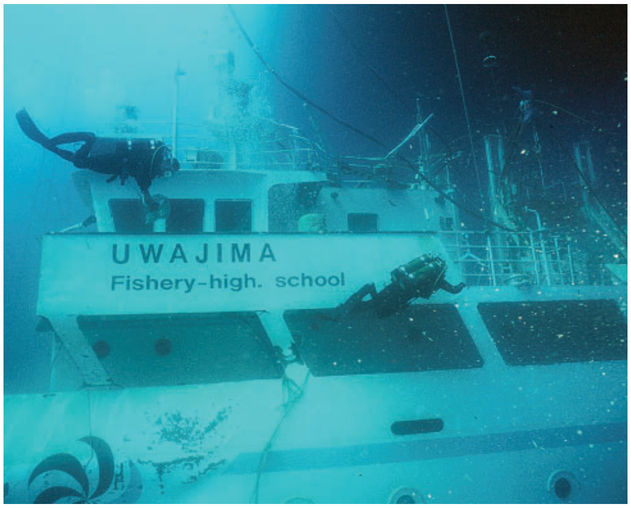

Figure 19-1. November 2001. US Navy divers swim along the *Ehime Maru* wreck site in Honolulu, Hawaii, to salvage personal effects and remains from the vessel off Honolulu International Airport's reef runway.
US Navy photo by Chief Petty Officer Andrew McKaskle.
Reproduced from: http://www.cpf.navy.mil/subsite/ehime-maru/images/011105shipsside-high.jpg.

Figure 19-2. Two divers from Mobile Diving and Salvage Unit One and a Japanese diver in MK 21 dive suits are lowered to the *Ehime Maru* wreck site.
US Navy photo by Chief Petty Officer Andrew McKaskle.
Reproduced from: http://www.cpf.navy.mil/subsite/ehime-maru/images/011105diveplatform-high.jpg.

Both light and heavy dive teams provide support for the Army Corps of Engineers. The US Air Force's special tactics elite ground combat force, comprised of combat controllers, pararescue, and combat weather personnel, are dive trained. Whether part of special tactics or in the conduct of their own occupational specialty, each service may be required to participate in dive operations.

ILLNESS OR INJURY KNOWN TO RESULT FROM DIVING

While diving is inherently dangerous, and the environment is deadly if equipment such as underwater breathing apparatus fails, there is very little documented evidence of occupational illness or injury from diving when correct safety and decompression procedures are followed. A number of small studies, case reports, and case series suggest there may be potential neurologic, pulmonary, and neuro-psychiatric changes associated with diving, mainly in those who have suffered decompression sickness (DCS).[5]

The only well-documented diving occupational injury or illness that occurs even when current safety procedures and decompression schedules are followed is dysbaric osteonecrosis. Dysbaric osteonecrosis is a condition in which necrotic lesions develop in the hip, shoulder, or long bones, and arise after an ischemic insult to the bone's vascular supply. Widely accepted as a rare but serious complication of deep diving, the exact mechanism by which it occurs remains elusive. It is more common in saturation diving and is prevalent across the world in caisson workers, but it can occur without extreme depth exposures.[6,7] Lesions that are juxta-articular effectively end a diver's career.[8] Dysbaric osteonecrosis rates are very low in military divers and almost nonexistent in the submarine force, most likely due to high fitness levels and attention to diving. A recent German study of military divers found they had the same rate of dysbaric osteonecrosis as matched nondivers.[9]

Many divers and medical experts feel diving results in hearing loss, while others feel any hearing loss seen in divers is a result of barotraumas such as squeezes, and late or forceful Valsalva maneuvers. The diving instruction courses at the Naval Diving and Salvage Training Center in Panama City, Florida, have long taught the most common injury to Navy divers is the middle ear squeeze. This fact is reiterated in several review articles,[10–12] and a recent study of over 700 experienced divers from the United States and Australia found 52% of divers had middle ear barotraumas, making it the most common dive-related injury.[13] A comparison of Navy divers and sea, air, and land team personnel's hearing thresholds to data from the Navy's hearing conservation program revealed sea, air, and land units were at significantly greater risk of hearing threshold loss greater than 40 dB for frequencies above 4000 Hz, meaning that sea, air, and land unit personnel are at a higher risk for hearing loss at this frequency versus Navy divers. For Navy divers, there was no increased risk compared to those in the hearing conservation program.[14] Although diver hearing loss is likely multi-factorial, the high incidence of ear barotraumas among divers places them at risk for hearing loss.

PHYSICAL PROPERTIES

Pressure

On land and at sea level, the pressure surrounding human bodies is that of the atmosphere, namely one atmosphere of pressure, or 1 atmosphere absolute (ata). Humans have evolved to breathe at 1 ata, and can only draw breath underwater via a snorkel to a depth of approximately 4 ft. To descend deeper than 4 ft requires compressed air. The military uses a variety of diving dress that delivers compressed air to the diver; however, delivering compressed air to the diver creates problems.

In the ocean, every 33 ft of depth adds the equivalent pressure of the entire atmosphere. Boyle's law states for a gas at a given temperature, $P_1V_1=P_2V_2$. For example, if a diver starts at sea level, where $P_1=1$ ata, and then dives to a depth of 33 ft, P_2 now equals 2 ata. Therefore, the new volume, V_2, will be half the volume of V_1. As a result, as the diver moves below the surface, air in the lungs, middle ear, and sinuses is compressed by the increasing pressure, creating a vacuum in these body spaces. Additional air is needed to fill the vacuum, and if none is available, the body's capillaries will rupture or leak, replacing the lost volume of air with blood. The essential mechanism behind dive-related barotraumas is compressed air within gas-filled, rigid, walled spaces of the body with a vascular supply. Dive-related barotraumas are called "squeezes." While the middle ear is the most common site for barotraumas, sinuses, teeth, and lungs (in breath-hold dives deep enough to compress the lung below reserve volume), as well as the artificial spaces between the dive mask and face, and wetsuit and skin, are also common squeeze locations.

When ascending, the reverse effect occurs. Divers have breathed a gas supply under pressure. If they were to hold their breath and ascend, Boyle's law dictates that on ascent, pressure falls and, conversely, volume increases. The pressurized air in the sinuses, teeth, middle ears, and lungs expands. Anything that prevents expanding gas from exiting will result in barotraumas of ascent, known as a "reverse squeeze." The most feared type of reverse squeeze is pulmonary overinflation syndrome. The alveolar membranes can rupture under a pressure differential of 70 mm Hg, or roughly 4 ft. Pressurized air expanding in divers holding their breath will rupture through the alveoli into the chest or surrounding vasculature, resulting in pneumothorax, mediastinal air, or arterial gas embolism. In operations involving explosives or underwater photography, individuals sometimes hold their breath as they concentrate to perform a delicate action. If the diver is near the surface when a wave passes, the result could be pulmonary overinflation syndrome.

Henry's law states the solubility of a gas in a liquid is directly proportional to the partial pressure of the gas over the liquid. Dalton's law of partial pressure states the partial pressure of a gas is equal to its percent concentration in a gas mixture, multiplied by the total pressure of the gas mixture. In diving, the partial pressure of gas increases as the pressure increases when diving deeper into the water. For example, at sea level, at 1 ata and 21% oxygen, the partial pressure of oxygen is 0.21 ata. At 33 ft underwater and 2 ata, oxygen remains at 21% (assuming the diver is breathing simple compressed air), but the partial pressure of oxygen now doubles to 0.42 ata. Following the characteristics of Henry's law, the amount of oxygen dissolved into the human body (where the main solvent is water) will also increase. The increased solubility of gasses, resulting in greater tissue concentration, is the direct cause of two major dive complications, gas toxicity and DCS.

Oxygen Toxicity

The exact mechanism by which oxygen causes toxicity is not completely understood, but symptoms are well described and are recalled utilizing the mnemonic VENTID-C. There is no order to the development of oxygen toxicity symptoms; convulsions may be the first and only sign.

- **V: Visual symptoms**. Tunnel vision, a decrease in the diver's peripheral vision, and other symptoms such as blurred vision may occur.

- **E: Ear symptoms**. Tinnitus, any sound perceived by the ears but not resulting from an external stimulus, may occur. The sound may resemble ringing bells, roaring, or a machinery-like pulsing.
- **N: Nausea or spasmodic vomiting**. These symptoms may be intermittent.
- **T: Twitching and tingling symptoms**. Any of the small facial muscles, lips, or muscles of the extremities may be affected. These are the most frequent and clearest symptoms.
- **I: Irritability**. Any change in the diver's mental status including confusion, agitation, and anxiety should be noted.
- **D: Dizziness**. Symptoms include clumsiness, incoordination, and unusual fatigue.
- **C: Convulsions**. It warrants repeating that the first sign of central nervous system oxygen toxicity may be a convulsion.

Nitrogen Narcosis

Nitrogen narcosis is another poorly understood phenomenon wherein nitrogen above a certain partial pressure exerts an anesthetic-like effect on brain neurons. Effects are generally seen near a depth of 100 feet of seawater (fsw) and worsen with increasing depth. Individuals vary in their susceptibility, and experienced divers are able to adapt somewhat to the effect. Narcosis is so potent that individuals have been known to become euphoric and irrational to the point of removing their dive gear, including the regulator and air supply. Because of the severe effect in deeper dives, the Navy limits diving to 150 ft if breathing compressed air. Signs and symptoms of nitrogen narcosis include loss of judgment or skill, a false feeling of well-being, lack of concern for job or safety, lack of common sense, inappropriate laughter, and tingling and vague numbness of the lips, gums, and legs.

Helium is commonly used in military mixed gas diving systems to replace some of the nitrogen gas mix because nitrogen narcosis limits the depth at which humans can safely breathe compressed air. However, helium presents a few problems of its own. It has a much higher thermal conductivity than nitrogen, which means it must be warmed at depths below 300 fsw or it will cause hypothermia. Helium also causes bronchorrhea, an excessive mucous discharge from the lung's air passages. Additionally, special communications equipment is needed to offset the effect helium has on the human voice. On extremely deep dives, especially saturation dives, helium can cause high pressure nervous syndrome. Its mechanism remains unknown, but the syndrome results in dysfunction of the central nervous system. Clinical manifestations include nausea, fine tremor, imbalance, incoordination and manual dexterity loss, decreased alertness, abdominal cramps, and occasionally diarrhea. In severe cases, divers may develop vertigo, extreme indifference to their surroundings, and marked confusion. High pressure nervous syndrome is first noted between 400 and 500 fsw, and the severity appears to depend on both depth and compression rate. Slow compression rates may allow divers to attain depth with little evidence of high pressure nervous syndrome; however, at depths greater than 100 fsw, high pressure nervous syndrome may be present regardless of compression rate.

Visibility

Visibility and color perception are often very poor underwater. The type and extent of particles in the water will determine visual accuracy. In general, objects appear larger and closer than they are until a distance of 2 to 3 m, at which point they appear farther away than they are. Color is generally lost in the order it appears in the visible spectrum, with red going first and blue remaining deepest. This description is only a generalization because the nature of solutes in the water may impact color absorption.

Sound

Sound travels nearly four times faster in water than in air. This speed surpasses the brain's ability to discriminate the arrival time of sound between the left and right ear, which is how the human ear normally triangulates or orients to sound. Also, sound is reflected on underwater objects and at the boundary of water layers with different densities or temperatures, which further affects hearing. Divers or surface swimmers with their heads in the water will have extreme difficulty judging the direction of sound; this is especially dangerous in the vicinity of motorized boats.

Temperature

Hypothermia

Water temperature needs to be approximately 33°C (91°F) to keep an unprotected, rested human body at a stable temperature. A wetsuit is required below 26.6°C (80°F), and temperatures below 18.3°C (65°F) will limit dive duration. Dry suits allow for greater dive duration at temperatures below 12.7°C (55°F), and a hot water suit is recommended for temperatures below 15.5°C (40°F) because vasoconstriction reduces the blood volume available for off-gassing.

Hyperthermia

Until the most recent change to the *US Navy Diving Manual*,[4] warm water diving was not addressed, and 31.1°C (88°F) was considered the water's upper temperature limit. However, standard diving procedures were modified after recent Middle East operations included dive missions in water warmer than 35°C (95°F). This was especially true for combat swimmers, who often swim on the surface, then dive to perform their missions, and then swim to the surface. The Navy Experimental Diving Unit (NEDU) found that Navy sea, air, and land units simulating such a mission with 1-hour transit, 2-hour dive, and 1-hour transit in 36.6°C (98°F) water and 32.2°C (90°F) air temperatures were unable to complete the dive. This 4-hour exercise scenario was based on profiles for combat swimmers developed by Naval Special Warfare Command and the Very Shallow Water Mine Countermeasures Detachment mission.[15]

Of special interest for special warfare and special operations missions is the fact that rebreather gas adds to the diver's thermal load; NEDU measured inhalation gas temperatures consistently -14.4°C (6°F) warmer than the ambient water temperature. Individual response in terms of heat stress symptoms was highly variable. Some individuals aborted dives due to classic heat stress symptoms, such as headache, nausea, dizziness, and cramping, whereas others showed no such symptoms even as their core temperatures reached 40°C (104°F). However, with daily acclimation, such a dive was possible within 3 days. A critical element to the acclimation process was that in-water exercises were conducted for at least 1 hour daily. The NEDU study revealed warm water dives once or twice a week are insufficient to develop and maintain warm water tolerance.[16]

The Navy developed guidelines for warm water diving based on data collected while observing heat-acclimated divers dressed in underwater demolition team swim trunks and t-shirts, who were well rested, calorically replete, well hydrated, and had no immediate heat exposure prior to starting exercise. Exercise rates for the divers replicated a moderate swimming effort. Conditions contributing to the thermal load, such as heavy work rates, significant pre- and post-dive activities, and various diver dress (dive skins, wetsuits, and dry suits), can reduce exposure limits appreciably. NEDU is developing refined guidelines for exposure limits based on diver dress. Until such further guidance, the provided limits serve as maximum exposure levels. The following operational guidelines and safety precautions were taken from the current *US Navy Diving Manual* and apply to warm water diving operations above 31.1°C (88°F).

- Weight losses up to 15 lb (or 6%–8% of body weight) due to fluid loss may occur, and mental and physical performance can be affected. Divers should hydrate fully (approximately 500 mL or 17 oz) 2 hours before diving.
- Fluid loading in excess of the recommended 500 mL may cause life-threatening pulmonary edema and should not be attempted.
- Rehydration with water or a glucose/electrolyte beverage should be done as soon as possible after diving. Approximately 500 mL should be replaced for each hour of diving.
- Exposure limits represent maximum cumulative exposure for a 12-hour period.
- Divers should be hydrated and calorically replete to baseline weight, rested, and kept in a cool environment for at least 12 hours before repeat exposure to warm water.

TABLE 19-1

WATER QUALITY AND PROTECTIVE GEAR RECOMMENDATIONS

Water Quality*	Protection Level†	Decontamination
Category 1	A	Yes
Category 2	A or B	Yes
Category 3	A, B, or C	No‡
Category 4	A, B, C, or D	No‡

*Categories:
1. Highest contamination. Grossly contaminated with concentrated chemical or microbiological contamination.
2. Moderate contamination. Increased levels of both chemical and microbiological contamination above what is normally expected.
3. Baseline contamination. Baseline contamination is defined as the water quality that is "normally" expected AND that has a demonstrated history of causing no acute effects on divers.
4. No contamination.

†Levels:
A. MK 21 dive helmet with double exhaust kit, vulcanized rubber dry suit with mating neck-dam, dry gloves attached to integral cuff rings on dry suit sleeves. Dial-a-breath in MK 21 is to be adjusted to slight free-flow mode while at maximum depth.
B. MK 20 full-face mask in positive pressure mode, vulcanized rubber dry suit with hood, dry gloves attached over cuff rings. The side-block assembly is to be used for an emergency gas supply.
C. Any diving helmet or full-face mask not used with a dry suit.
D. Any underwater breathing apparatus with a mouthpiece or T-bit.

‡Routine post-dive maintenance required.

CAUTION: Any breach of personal protective equipment used to conduct a dive in contaminated water should result in termination of the dive as soon as feasible to limit exposure to the hazards.

Reproduced from: Naval Sea Systems Command. *Guidance for Diving in Contaminated Waters.* Washington Navy Yard, DC: NAVSEA; 2008. NAVSEA Technical Manual SS521-AJ-PRO-010: 4-6.

Contaminated Diving

The Navy's *Guidance for Diving in Contaminated Waters*, published in 2008, drives the expectations for protection in water from various contaminants.[17] Dive dress is driven by the type of contamination source present. However, in most real-world scenarios, the exact contaminant may be unknown, and often a quantitative test for contamination levels may not exist or be readily available prior to the start of dive operations. A qualitative assessment of the water quality, based on criteria developed by the California Department of Transportation, is used to determine appropriate dive dress levels that will minimize ex-

TABLE 19-2

COMPARISON OF NAVY'S EXPOSURE GUIDELINES WITH THOSE RECOMMENDED BY THE SUBCOMMITTEE ON EMERGENCY AND CONTINUOUS EXPOSURE GUIDANCE LEVELS FOR SUBMARINE CONTAMINANTS

		US Navy Values*		
Chemical	**Exposure Level**	**Current**	**Proposed**	**NRC Recommended***
Acrolein	1-h EEGL	0.05	0.07	0.1
	24-h EEGL	0.01	0.03	0.1
	90-day CEGL	0.01	0.01	0.02
Carbon dioxide	1-h EEGL	40,000	30,000	25,000
	24-h EEGL	40,000	15,000	25,000
	90-day CEGL	5,000	7,000	8,000
Carbon monoxide	1-h EEGL	400	55	180
	24-h EEGL	50	20	45
	90-day CEGL	20	10	9
Formaldehyde	1-h EEGL	3	0.4	2
	24-h EEGL	1	0.1	1
	90-day CEGL	0.5	0.04	0.3
Hydrazine	1-h EEGL	--[†]	4	1
	24-h EEGL	--	0.3	1
	90-day CEGL	--	0.01	0.03
Methanol	1-h EEGL	200	200	600
	24-h EEGL	10	10	50
	90-day CEGL	10	7	10
Monoethanolamine	1-h EEGL	50	6	4
	24-h EEGL	3	3	4
	90-day CEGL	0.5	0.5	0.5
Nitric oxide[‡]	1-h EEGL	--	--	130
	24-h EEGL	--	--	50
	90-day CEGL	--	--	3
Nitrogen dioxide	1-h EEGL	1	3	10
	24-h EEGL	1	1	2
	90-day CEGL	0.5	0.5	0.7
Oxygen (min–max)	1-h EEGL	130–220 mm Hg	--	105 mm Hg (min)
	24-h EEGL	130–160 mm Hg	--	127 mm Hg (min)
	90-day CEGL	130–160 mm Hg	--	140 mm Hg (min)

*All values in parts per million (ppm) unless otherwise noted.

[†] There is no standard value available.

[‡] The Navy considers the guidance levels for nitrogen dioxide to be also protective of nitric oxide exposure.

Abbreviations: CEGL: continuous exposure guidance level; EEGL: emergency exposure guidance level; max: maximum; min: minimum; mm Hg: millimeters of mercury; NRC: National Research Council

Reproduced with permission from the National Research Council. *Emergency and Continuous Exposure Guidance Levels for Selected Submarine Contaminants: Volume 1*. Washington, DC: The National Academies Press; 2007: 6.

posure. The levels are patterned after Environmental Protection Agency guidelines for personal protective equipment, with level A offering the highest protection and level D the least. Table 19-1, taken from the Navy's *Guidance for Diving in Contaminated Waters*, addresses dive dress levels and water quality category descriptions. Table 19-2 compares the US Navy's exposure guidelines to those recommended by the National Research Committee.

Controlled human exposures to many sensory irritants typically use descriptors such as "mild" or "mild-to-moderate," and the database for sensory irritation thresholds can be highly variable. Research is needed to quantify the diverse methods and end points used in sensory irritation studies so data can be used in public health and occupational health risk assessment with greater confidence.

Certain scenarios can increase the potential exposure to chemical/biological contamination, and extra protective measures should be adopted. When possible, and especially if contamination is known to include volatile compounds, compressors for the diver's air supply should be positioned upwind of the contaminated area. If this is not feasible, bringing in compressed gas from an offsite location should be considered.

Divers working in sediment may be at greater risk because many contaminants are heavier than water and will accumulate and concentrate in the sediment. Efforts should be made to determine water quality using available resources. State and local health agencies often have water testing and reporting procedures in place that are accessible via the Internet. The National Center for Medical Intelligence (formerly known as the Armed Forces Medical Intelligence Center) available online at https://www.ncmi.detrick.army.mil can provide some local water quality information, and information requests can be made ahead of time to enable planning efforts. Additional international sources for water quality information can be found in the Navy's *Guidance for Diving in Contaminated Waters*.[17]

PROBLEMS WITH UNDERWATER BREATHING EQUIPMENT

Hypoxia

Hypoxia, a deficiency of oxygen supply in tissues, can occur during underwater diving when divers breathe mixtures of gases with insufficient oxygen content or when equipment malfunctions. Signs and symptoms of hypoxia are lack of concentration, lack of muscle control, inability to perform delicate or skill-requiring tasks, drowsiness, weakness, agitation, euphoria, and loss of consciousness.

Hypercapnia

Hypercapnia, an excess of carbon dioxide in tissues, can result in similar symptoms, such as confusion, inability to concentrate, drowsiness, loss of consciousness, and convulsions. Such effects become more severe as the amount of carbon dioxide accumulates in tissues. A diver breathing gas with as much as 10% carbon dioxide generally loses consciousness after a few minutes. Breathing 15% carbon dioxide for any length of time causes muscle spasms and rigidity. A diver who loses consciousness because of excess carbon dioxide in the breathing medium and does not aspirate water generally revives rapidly when given fresh air. The diver usually feels normal within 15 minutes, and the after effects rarely include symptoms more serious than headache, nausea, and dizziness.

Dyspnea

Dyspnea is difficult or labored breathing. Increased gas density and breathing apparatus resistance are the two main factors that impede breathing. Even in a dry hyperbaric chamber without a breathing apparatus, increased gas density may cause divers to experience dyspnea. Dyspnea usually becomes apparent at very heavy workloads and at depths below 120 fsw when a diver is breathing air. If breathing heliox, dyspnea usually becomes a problem at heavy workloads in the 850 to 1,000 fsw range. At great depths (1,600–1,800 fsw), dyspnea may even occur at rest.

UNDERWATER HAZARDS

Marine Life

Divers will likely encounter marine life during their undersea missions. While predatory marine species are frequently the focus of news and entertainment programs, attacks against operational divers are rare. Common dangerous species divers may encounter include sharks, barracuda, killer whales, and sea lions. Regardless of the species, treatment involves controlling bleeding and immediate transport to a higher level of care. Providers should control for shock, immunize for tetanus, and culture wounds prior to starting antibiotics.

Sound Navigation and Ranging

Sound pressure level, not distance, is the determining factor for establishing a permissible exposure limit to sonar (sound navigation and ranging). The probability of physiological damage markedly increases as sound pressures increase beyond 200 dB at any frequency. For this reason, diver exposure to sound pressures levels above 200 dB is prohibited unless they wear full wetsuits and hoods. Fully protected divers (in full wetsuits and hoods) must not be exposed to sound pressure levels in excess of 215 dB at any frequency for any reason. Diver exposure to low-frequency sonar (160–320 Hz) can result in vertigo, tingling, and vibratory sensations in the throat and abdomen. Low-frequency sonar is physically dangerous at higher power levels. Diver exposure to ultrasonic sonar (> 250 KHz) can result in tissue heating; however, the power dissipates rapidly with distance, and divers should be safe at a distance of more than 10 yd from the sonar's focused beam. Exposure sound pressure levels in Tables 1A-3 through 1A-6 of the *US Navy Diving Manual* can be used to calculate permissible exposure limits for various diver dress and sonar.

SUBMARINES

Submarine Types and Classes

Submarines are true marvels of engineering. The submarine is a self-contained, self-generating life-support system that enables the crew to safely live and work in an otherwise fatal environment at ocean depths. The US Navy submarine force is composed of approximately 5,000 officers and 55,000 enlisted personnel. Not all of these personnel are assigned to submarines. Some work onboard submarine tenders, at shore submarine repair facilities, and as submarine group or squadron staff. The submarine fleet consists of three major submarine types: attack, fleet ballistic missile, and guided missile.

Attack Submarines

The Navy has three classes of nuclear-powered attack submarines (designated SSN) in service: the SSN 688 Los Angeles class, the SSN 21 Seawolf class, and the SSN 774 Virginia class. The aging Los Angeles-class submarines (Figure 19-3), which are being refurbished and refueled or decommissioned, are crewed by 121 enlisted and 13 officers. They measure 360 ft in length and 33 ft in width, and some have bow and sail planes designed to allow operations under ice. The Seawolf class, crewed by 126 enlisted and 14 officers, was ordered toward the end of the Cold War as a planned replacement to the Los Angeles class. They are quieter, bigger (353 ft in length, 40 ft in width), and have greater offensive capability. They have twice the number of torpedo tubes as the Los Angeles class, can carry up to 50 Tomahawk cruise missiles, and were designed with Special Operations Forces (SOF) capability. Lastly, the Virginia class is smaller than the Seawolf at 377 ft in length 34 ft in width. Virginia-class submarines have four torpedo tubes, a vertical launching system (capable of firing Tomahawk cruise missiles), and SOF capability. It was the first submarine class specifically designed for both open-ocean, blue-water and littoral, brown-water operations. The crew complement is roughly the same as the other fast attack submarines, with 120 enlisted and 14 officers.[18]

Figure 19-3. The Los Angeles-class nuclear-powered attack submarine, USS *Dallas* (SSN-700), with dry deck shelter. Reproduced from US Navy news photo 040719-N-0780F-070.

Ballistic Missile Submarines

The nuclear powered ballistic missile submarine (SSBN) 726 Ohio class is the largest submarine ever constructed by the United States. The Ohio class was a cornerstone of strategic deterrence during the Cold War. The Ohio-class submarines carry half of the US nuclear warhead arsenal, are 560 ft in length and 42 ft in width, and are crewed by 140 enlisted and 15 officers. While all Ohio-class submarines have four torpedo tubes, their initial purpose was to carry nuclear ballistic missiles in their 24 vertical tubes. They originally carried the Trident I C4 missile, but subsequently were designed or retrofitted to use the improved Trident II D5 missile.[19]

Guided Missile Submarines

The Navy has 18 Ohio-class submarines, but following the Cold War, four were slated for conversion into guided missile submarines (SSGN). The first of four planned conversions took place with the USS *Ohio* (SSGN-726) in 2005, replacing most of the ballistic missile capability with a vertical launching system for guided missiles. Tubes 3 through 24 each have a multiple all-up round canister holding seven missiles. The multiple all-up round canisters of tubes 3 through 8 can be used to store SOF gear or other supplies. The remaining tubes were converted into lock-in/lock-out chambers for other payloads or SOF capability. With the SSGN conversion, the submarine has nearly the cruise missile capability of a surface battle group. The SSGN can carry and support a team of 66 SOF personnel for up to 90 days, whereas an SOF-capable SSN can carry only 15 (Figure 19-4). Dual dry deck shelters enhance the SSGN's SOF capability.[20]

With increased focus on special operations, the SSGN's larger support capability may prove especially helpful, not only in terms of the increased number of SOF personnel they can carry, but also by providing greater training capability while underway. A study of the aerobic performance of Navy sea, air, and land units subjected to a 33-day deployment aboard a fast attack submarine found a significant decrease in the sailors' running ability following deployment.[21] Given the physical demands of SOF missions, maintaining aerobic exercise capacity while on a submarine could be mission critical.

Figure 19-4. The guided missile submarine can support and launch up to 154 Tomahawk missiles, a significant increase in capacity compared to other platforms. The 22 missile tubes can also carry other payloads, such as unmanned underwater vehicles, unmanned aerial vehicles, and Special Forces equipment. This new platform can carry and support more than 66 Navy sea, air, and land unit personnel and insert them clandestinely into potential conflict areas.
Reproduced from US Navy news photo 030814-N-0000X-006.

The Submarine Environment

All submarines are nuclear powered and can distill water, make oxygen, and power a variety of devices to remove carbon dioxide and other toxic or dangerous gases and contaminants from the atmosphere. The amount of time a submarine remains submerged is driven by the amount of food it can carry, which is typically a 2-week supply of fresh food, including fruits and vegetables. After that, meals are comprised of dry, canned, or frozen ingredients. During the Cold War, an SSBN could remain submerged for months at a time. At present, most operations allow submarines to make port calls more frequently, thus replenishing perishable stock.

The submarine is designed for independent operation and is uniquely vulnerable to fire and flooding in comparison to surface ships. Fresh air is not available, and one cannot simply jump to safety. For this reason, every crew member must demonstrate expert knowledge on all submarine systems. In the event of an emergency, any crew member must act immediately and correctly to isolate and limit the problem. Successfully mastering this level of knowledge is indicated by the submariner qualification and the authorized wear of the submarine warfare device.

Although radiation is vilified in popular science fiction films and books and is viewed with distrust by the general public, there has been no evidence of risk associated with nuclear power aboard submarines. The submarine service operates what is arguably the safest nuclear power program in the world. The fear of cancer among crew members has not proved justified. Two separate studies examined the health of submariners, and both found those who served aboard submarines had no higher rates of cancer than the general public.[22,23]

Monitoring the Submarine Atmosphere

Central Atmosphere Monitoring System

The submarine atmosphere is monitored by the Central Atmosphere Monitoring System (CAMS). From the first successful nuclear powered submarine operations in 1955, it took the Navy 20 years to develop a reliable and accurate method to monitor the submarine atmosphere. Atmospheric monitoring was especially critical during the Cold War, when ballistic missile submarines remained submerged for extended periods of time as part of the nation's strategic deterrence capability. The first CAMS used mass spectrometry to monitor all vital gasses except carbon monoxide, which was monitored with infrared technology. The CAMS Mark I automatically and continuously provides air monitoring for vital gases, refrigerants, and aromatic hydrocarbons. CAMS Mark II is in use today on all submarines. The CAMS Mark II system can be programmed to monitor new contaminants or change the alarm levels based on new exposure limits.[24] In addition to CAMS Mark II, colorimetric manually operated Dräger-Tubes (Lübeck, Germany) are used to measure an additional 30 possible contaminants. When the submarine is submerged, the TGA200A trace gas analyzer (Campbell Scientific, Logan, UT), which includes a photoionization detector, is used to run daily tests for excess hydrocarbons. When battery charging operations are in progress, a thermistor monitors hydrogen levels in the battery compartment (ie, the submarine atmosphere).

2, 6-Di-tert-butyl-4-nitrophenol

In 1993, submariners reported a yellow film coating the interior surfaces of submarines, which upon contact resulted in a yellow skin discoloration. Subsequent investigations discovered the discoloration was from 2,6-di-tert-butyl-4-nitrophenol (DBNP) that was produced when oil mist from synthetic steam turbine lubricants and hydraulic fluids containing the antioxidant 2,6-di-tert-butylphenol (DBP) passed through the submarine's electrostatic precipitators, where the DBP nitrated to become DBNP. The cleaner the precipitator, the more effectively it nitrated DBP, and the longer the precipitator was used without cleaning, the less DBNP it produced. Although the DBP was released in machinery rooms, the nature of the submarine ventilation system, being a contained atmosphere, meant it was distributed throughout the ship. The Electric Boat Division of General Dynamics, which identified the yellow substance as DBNP, determined the 24-hour exposure concentrations to be in the range of less than 3.0 to 122 ppb in laboratory and submarine settings. Thus, the submarine crew could be exposed to these concentrations for 24 hours per day for up to 90 days during underway periods.

At the time, little literature was available on the toxicity of DBNP, but it is a known uncoupler of mitochondrial oxidative phosphorylation, so Navy researchers immediately investigated and found there was little risk from dermal absorption. However, this was not true for ingestion. Prior literature indicated the median lethal dose to be 500 mg/kg in a rat model. Researchers soon found this number was dependent on the delivery medium of carboxymethylcellulose. Using a delivery medium more typical of substances likely to enter the gastrointestinal tract (such as canola oil), researchers soon found the median lethal dose to be only 50 to 80 mg/kg. Toxic effects were noted in the liver, heart, kidney, and skeletal muscle. Radiolabeled DBNP was shown to cross the blood-brain barrier. Using the median lethal dose of rats at 80 mg/kg and a very large safety factor adjustment, one group of researchers recommended a reference dose of 27.3 to .273 ppb, which indicated the Electric Boat sampling fell within this range and could be a concern for chronic exposure.[25] It is unclear to what extent submarine crewmembers were exposed to DBNP, but Naval Sea Systems Command changed the specifications for TEP 2190 turbine oil (San Ramon, CA) so that current stocks contain 10 ppm or less of DBNP precursor DBP.[26,27] This example serves to illustrate the fragility of the submarine's atmosphere system. Today's submarines utilize a variety of products to maintain a healthy atmosphere for the crew, including oils that are safe for ingestion.

Atmosphere Management and Control

The Los Angeles-class submarines use an electrochemical oxygen generator to produce oxygen by the electrolysis of water. A direct current passes through a potassium hydroxide solution, electrolyzing water into hydrogen and oxygen. More recently, submarines have utilized their oxygen-generating plants to electrolyze water via a solid polymer electrolyte cell. This process has several advantages over the electrochemical oxygen generator in that it requires no free acids or caustic liquids; it can restart in 15 minutes rather than the 6 hours the electrochemical oxygen generator requires; it operates at lower pressure (600 psi vs 3000 psi); it involves less hydrogen (one-tenth) and produces oxygen free of hydrogen contamination; and a single oxygen generating plant can meet the oxygen needs of the entire crew.

Carbon dioxide (CO_2) is removed by either the nonregenerative lithium hydroxide (LiOH) canisters or the regenerative monoethanolamine scrubber. Each 31.5-lb canister of LiOH can remove approximately 28 lb of CO_2. Once total absorption is complete, the canister is jettisoned overboard. The regenerative system uses an aqueous solution of monoethanolamine (MEA), $NH_2CH_2CH_2OH$ to absorb CO_2 via a Lewis acid-base reaction. This reaction can be reversed by heat, allowing the MEA to be recycled. After absorbing 70% to 90% of the CO_2 in the airstream, the MEA is heated under pressure to drive off the CO_2, which is then cooled and discharged overboard. The only system drawback is that there is some MEA leakage into the atmosphere.[28]

The predominant system for air purification aboard submarines is the CO-H_2 (carbon monoxide-hydrogen) burner. Air is brought into the burner where the CO, H_2, and hydrocarbon are converted to CO_2 and water (H_2O) by reacting with a copper oxide/manganese dioxide (CuO/MnO_2) catalyst at 315°C (600°F). Combustion products are cooled and passed over lithium carbonate ($Li2CO_3$) to remove acidic gases. From there, the air passes over activated charcoal. Additional air purification systems include electrostatic precipitators that charge and precipitate particulate matter, especially in the galley, and vent fog precipitators, which charge and precipitate lube oil particulates in the engine room.

The Navy has detected over 50 potentially toxic atmospheric contaminants aboard submarines.[29] In 1985, the Navy asked the National Research Council to evaluate the submarine atmosphere, which resulted in its 1988 Committee on Toxicology (COT) report, *Submarine Air Quality: Monitoring the Air in Submarines and Health Effects in Divers of Breathing Submarine Air Under Hyperbaric Conditions*.[30] In the report, the COT recommended exposure guidance levels for six substances of interest to the Navy: ammonia, hydrogen chloride, lithium bromide, toluene, trichloroethylene, and lithium chromate. The COT found cigarette smoke accounted for much of the particulate matter, carbon monoxide, and hydrocarbons in the submarine atmosphere.[30]

The Navy Sea Systems 1992 Atmosphere Control Manual[31] lists 65 known contaminants identified in submarine atmospheres and establishes limits for certain toxic compounds. There are 90-day limits based on time-weighted averages for continuous exposure, 24-hour limits for urgent situations such as a release or spill, and 1-hour limits for emergency situations. Because of the risk of additional contaminants from products brought onboard, all items used onboard must be certified for submarine use. The Submarine Materials Review Board at the Navy and Marine Corps Public Health Center conducts such evaluations (eg, submarine atmosphere). To ensure there are no contaminants in the air that would put the crew at risk for toxic substances, each submarine undergoes routine inspections and atmospheric evaluation. The Navy continues to actively review potential contaminants and update exposure limits for submarines. There are currently 20 contaminants given top priority for review that include respirable particulates, formaldehyde, acrolein, ozone, monoethanolamine, oxides of nitrogen, methanol, carbon monoxide, carbon dioxide, oxygen, lead, ammonia, hydrazine, benzene, toluene, xylene, hydrogen, Freon 114, and Freon 12.[29]

In 2002, the Navy again approached the National Research Council to have the COT review proposed Navy exposure limits and make recommendations. The COT review resulted in the 2004 report *Emergency* *and Continuous Exposure Guidance Levels for Selected Submarine Contaminants*.[32] The committee found the Navy's proposed limits (see Table 19-2) conservative, with the exception of 1-hour CO_2, 90-day CO, 1-hour hydrazine, MEA, and 1-hour O_2 limits.[32] The Naval Submarine Medical Research Laboratory (NSMRL) and the US Naval Research Laboratory are actively updating atmospheric hazards through the Submarine Atmosphere Health Assessment Program.

Disabled Submarines

The grounding of the USS *Greeneville* near Saipan in August 2001; the death of a sailor aboard the USS *San Francisco* (SSN-711) following a high-speed collision with an underwater seamount south of Guam on January 8, 2005 (Figure 19-5); and the horrific loss of the Russian submarine *Kursk* are stark reminders of the possible dangers that accompany every submarine voyage.

The crew's quick damage control actions, preserved ballast tank function, and rapid assistance by nearby Navy and Coast Guard assets helped the USS *San Francisco* stay afloat. If not for the heroic efforts of the crew, the submarine easily could have been lost in the 6,000-ft-deep waters. In such a case, deep water would not cause a disabled submarine (DISSUB) scenario; in shallower waters, where the depth will not crush the submarine's hull, the likely outcome would be a DISSUB. As the sad events of the *Kursk* illustrated, a DISSUB is a race against time. The risks to survival include oxygen depletion, hypothermia, toxic gases from fires, pressure increase within the boat, and carbon dioxide buildup.

Figure 19-5. The Los Angeles-class nuclear powered fast-attack submarine, USS *San Francisco* (SSN-711), is pictured in dry dock undergoing damage assessment after a high-speed collision with an underwater seamount.
Reproduced from US Navy news photo 050127-N-4658L-030.

Oxygen Depletion and Toxic Gas

Oxygen depletion can be alleviated by venting air from compressed air banks or by having crew members breathe from the emergency air breathing (EAB) system, but this would result in internal submarine pressurization, creating a dangerous risk if the crew attempts escape (as discussed below). For this reason, the submarine has oxygen-generating chlorate candles, which can be used to replenish oxygen.

In recent studies, researchers have concluded that lower oxygen levels (16.5%) and higher carbon dioxide levels (2.5%) do not increase the risk of hypothermia.[33] A DISSUB exercise conducted pier side showed, surprisingly, that the temperature of the crew compartment increased from 21°C to 26.6°C (70°F to 80°F).[34] The study's limitations were that the submarine was not submerged and not all power was disconnected. Two European simulated DISSUB studies had opposite results. In a United Kingdom study, a 6-day experiment found that the air temperature dropped from 22°C to 4.4°C (72°F to 40°F).[35] In a Norwegian DISSUB study, the air temperature fell to 13.8°C (57°F).[36] In no study did subjects become hypothermic, suggesting if sailors can remain dry, hypothermia is unlikely a primary concern.

Toxic gas accumulation in a DISSUB scenario is a likely threat. As a result of fire, toxic gases such as ammonia, carbon monoxide, hydrogen chloride, hydrogen cyanide, hydrogen sulfide, nitrogen dioxide, and sulfur dioxide can accumulate. In the event these gases flood into the battery compartment and interact with battery sweat or leakage, chlorine gas could be released. Exposure to these gases, alone or in combination, can cause eye and respiratory tract irritation at low levels, and as levels increase, exposures can impair nervous and respiratory system functions and lead to death.

In 1998, the NSMRL recommended that exposure levels for toxic gas management include levels that would warrant escape from a submarine. The Naval Health Research Center addressed the problem and proposed the establishment of two exposure limits: Submarine Escape Action Level (SEAL) 1 and SEAL 2. SEAL 1 is the maximum toxic gas concentration a healthy submariner can be exposed to for 10 days without irreversible health effects. A submariner can be exposed to SEAL 2 for 24 hours without irreversible health effects. Although SEAL 1 or 2 exposure could cause health effects that limit response time, they should not prohibit personnel from donning protective gear or operating the EAB.

The chief of the US Navy Bureau of Medicine and Surgery then requested that the NRC independently evaluate the scientific validity of the Naval Health Research Center's proposed SEALs for the eight gases. The project was assigned to the Board on Environmental Studies and Toxicology COT, which formed a subcommittee on SEALs. In 2002, the subcommittee concluded the proposed SEALs were safe and conservative with the sole exception being chlorine gas, which the committee felt should be reduced by 50% for both SEAL 1 and 2. Table 19-3 is adapted from the NEDU report.[37]

The Naval Health Research Center's recommendation was to don the EAB system and commence escape during SEAL 2 unless rescue was imminent. During either SEAL 1 or 2 conditions, escape preparations must begin when 30% of the crew is using EAB, because the EAB system pressurizes the submarine.

Escape and Rescue

After initial damage control efforts to stop fire and flooding, the primary decision facing survivors is whether to attempt escape or await rescue. SEAL 2 limits are one consideration. The *Nuclear Powered Submarine Atmosphere Control Manual, Volume 1*[31] provides guidance for the DISSUB senior survivor to estimate survival time based on the number of survivors, material condition of the submarine, and available supplies. In addition, it provides guidance for safe escape measures. NSMRL recently developed software that assists the senior survivor in tracking parameters to guide decision-making. The software can be used on a battery-powered personal digital assistant (handheld personal computer) and was successfully tested in SUBEX (submarine exercise) 2003.[34]

The concept of unsafe escape conditions may seem illogical, but many DISSUB scenarios anticipate the submarine's internal atmosphere will become pressurized. Increasing atmospheric pressure in a DISSUB could result from flooding, ruptured compressed gas banks, air leaks, or prolonged EAB use. Pressurization to a depth as shallow as 23 ft for 24 hours would essentially turn the crew into divers. By breathing the submarine's pressurized air, nitrogen would dissolve into tissues, just as it does for scuba divers, and personnel would be at risk for DCS and arterial gas embolism when they surface. Researchers have determined DCS risk is less than 5% at an internal pressurization of 11 ft.[38] Survivors would also be at risk for oxygen toxicity (discussed previously), if the DISSUB were to be pressurized to 5 atmospheres (atm) or more (165 ft).

The US Navy's adoption of the British submarine escape immersion equipment (SEIE) suit has increased a crew's chance of surviving an escape. Figures 19-6, 19-7, and 19-8 show sailors dressed in SEIE suits in various training exercises. The US Navy's version, the MK 10 SEIE suit, provides considerably more protection because it contains a submarine escape and immersion suit, an inner thermal liner, and a gas-inflated single-seat life raft that can be deployed at the surface. The SEIE has been tested to water depths of 600 ft. The process of escape is slow but allows two crew members to escape together, with the cycle being repeated every 15 minutes. If the entire crew of approximately 140 survived, the escape process would take over 17 hours.

The Navy's default preference has been to await rescue because escape puts the crew at the mercy of the ocean environment, without access to medical care, including decompression chambers or life-support supplies. However, escape may be the only option depending on the submarine's condition and rescue response time. The Navy has two submarine rescue chambers and one submarine rescue diving and recompression system (SRDRS), based in San Diego, California. Both can be mobilized worldwide by air transport. The submarine rescue chamber can use any suitable vessel and is lowered to the DISSUB, at a maximum depth of 850 ft. However, it can only accommodate six submariners at a time and is limited by

TABLE 19-3

THE NAVY'S PROPOSED SUBMARINE ESCAPE ACTION LEVEL VALUES

	Navy's Proposed SEALs (ppm)	
Gas	**SEAL 1***	**SEAL 2***
Ammonia	75	125
Carbon monoxide[†]	75	85
Chlorine	1	2.5
Hydrogen chloride	20	35
Hydrogen cyanide	10	15
Hydrogen sulfide	15	30
Nitrogen dioxide	5	10
Sulfur dioxide	20	30

*The National Research Council subcommittee recommended that carbon monoxide be 125 and 150 ppm for SEAL 1 and SEAL 2, respectively.

[†] Except for carbon monoxide values, these values agree with the recommendations by the National Research Committee in 2002.

ppm: parts per million

SEAL: submarine escape action level

Adapted from: Lillo RS, Caldwell JM. *Development and Evaluation of a Hyperbaric Toxic Gas Monitor (SUBTOX) for Disabled Submarines*. Panama City, FL: Naval Sea Systems Command, Navy Experimental Diving Unit; 2013: 66. NEDU TR 13-04. 66.

Figure 19-6. Instrument mannequins dressed in MK 10 submarine escape immersion equipment suits inside an engine room logistics escape trunk await the start of General Dynamics' Electric Boat Division fully instrumented trunk test aboard the Virginia-class nuclear powered fast-attack submarine USS *Virginia* (SSN-774).
Reproduced from US Navy news photo 040821-N-2653P-001.

sea conditions. The SRDRS is the newest technology, replacing the deep submergence rescue vehicle Mystic class. The SRDRS allows personnel to be transferred under pressure, which eliminates the risk of DCS or arterial gas embolism during rescue. The submariners are transferred from the injured submarine to the remotely-operated pressurized rescue module and then to a suitable vessel (Figure 19-9). The SRDRS was successfully used to rescue three DISSUBs during Bold Monarch exercises in 2008. The SRDRS can perform to a depth of 2,000 ft, transfer 16 personnel at a time, and is designed to be deployable on station in 72 hours.[39]

The crew's goal is to survive a DISSUB scenario for 7 days until rescue. In most scenarios, a DISSUB would suffer a power loss. Since the CO_2 scrubbers would be inoperable, in the absence of toxic gases reaching SEAL 2 limits, CO_2 build-up is presumed to be the limiting factor to survival. Until recently, the only method to remove or scrub CO_2 from the submarine atmosphere was to spread LiOH powder in crew spaces to absorb exhaled CO_2. While an effective scrubber, LiOH is caustic, and is likely to cause skin or respiratory tract injury as it is spread or inadvertently disturbed. NSMRL researchers tested the Battelle curtain (Battelle, Columbus, OH) as an alternative CO_2 scrubbing method. Hanging the curtain allows a crew member to safely (even without personal protective equipment) pour LiOH into channels in the curtain, thus eliminating crew exposure. Battelle curtains were successfully tested during SUBEX 2003 and are now standard issue.[34]

The Working Schedule and Sleep

Submarine air is 0.3% to 0.5% CO_2, compared with 0.033% in ambient air at sea level. Recent findings of the Board of Environmental Studies and Toxicology suggest submariners become dependent on a

Figure 19-7. Gulf of Taranto, Italy, June 21, 2005. A sailor is rescued by a diver after escaping from the Italian submarine, *Primo Longobardo*, in the MK 10 submarine escape and immersion equipment suit, during the North Atlantic Treaty Organization submarine escape and rescue exercise Sorbet Royal 2005. Divers from various nations work together to rescue submariners during the exercise in the Mediterranean. Twenty-seven participating nations, including 14 North Atlantic Treaty Organization nations, test their capabilities and interoperability. Four submarines with up to 52 crewmembers aboard are placed on the bottom of the ocean, while rescue forces with rescue vehicles and systems work together to solve complex disaster rescue problems.
US Navy photo by Chief Journalist Dave Fliesen.
Reproduced from Navy.mil photo 050621-N-1464F-038.

Figure 19-8. A sailor assigned to the Los Angeles-class nuclear-powered attack submarine, USS *Key West* (SSN-722), receives training with the MK 10 submarine escape immersion equipment suit.
Reproduced from US Navy news photo 041012-N-0879R-007.

Figure 19-9. The pressurized rescue module is recovered from the water after performing a submarine rescue exercise with the Chilean submarine, CS *Simpson*, off the coast of San Diego, California, September 18, 2008.
US Navy photo by Communication Specialist 2nd Class Alexia M. Riveracorrea.
Reproduced from US Navy news photo 080918-N7029R-115.

physiologically higher CO_2 level for their respiratory drive after being underwater for several days. If the submarine is submerged for several days and then surfaces to ventilate the atmosphere, the crew will suffer interrupted breathing at night.[40] Such disturbances could lead to increased fatigue, poor work performance, and work-related hazards.

Adopted in the 1960s, the submarine working day is 18 hours, with the crew standing three watch sections, each 6 hours long, followed by 12 hours off watch divided between other shipboard duties and sleep. Rotating watch schedules, limited meal service, and group living quarters challenge sleep. The submarine work schedule conflicts with the natural circadian cycle (which is just over 24 hours), impacts alertness, and affects performance. Although the crew operates on an 18-hour day, research has shown internal biological rhythms remain set at just over 24 hours.[41] The conflict between internal biological rhythm and work schedule has been shown to impair cognitive performance.[42]

NSMRL conducted a submarine watch-standing study using an 18-hour day, a normal 24-hour day, and alternate 24-hour day watch cycles to examine crew performance measures. The first phase of the study took place in 2001 at the Air Force Research Laboratory sleep laboratory at Brooks City-Base, San Antonio, Texas. The alternate 24-hour schedule showed improved sleep and performance over the 18-hour submarine day and the traditional 24-hour maritime schedule.[43] However, the alternate 24-hour watch schedule placed duty periods on a 72-hour rotation, which resulted in off-duty periods of 12 and 24 hours. Unlike ashore, on a submarine there is nothing to do during long off-duty periods. During the second phase of the study, the alternate 24-hour watch schedule was tested onboard a submarine. Results showed only 15% of personnel preferred the 24-hour schedule to the standard 18-hour schedule.[44] Although a personal preference for the familiar may explain a portion of the study's results, more work is needed to develop a better submarine watch schedule.

SUMMARY

The undersea environment is a perilous place, yet every day humans successfully live and work on and in the world's oceans. Through careful engineering, the risks have been minimized; however, even with the best technologies and careful attention to safety, accidents and injuries happen. The military's operational requirements place personnel in situations where they face hypothermia, hyperthermia, and possibly contaminated waters. Aboard submarines, crews depend on the safe and effective operation of a host of machinery to maintain a healthy atmosphere. The specter of fire and flooding is a constant companion, and DCS remains a threat not only to every diver, but to any crew of a submerged submarine or DISSUB.

This chapter covered the occupational hazards associated with undersea operations. In recent years, NEDU has addressed the new challenge of warm water diving operations. NSMRL is working to make the submarine atmosphere safer through schedule modifications and atmosphere controls. The US Navy Bureau of Medicine and Surgery is updating medical knowledge and protocols for undersea operations and training. The Navy developed a better submarine rescue system, the SRDRS, in addition to the maintenance of the SRC. As the Navy continues to operate in the undersea environment, it will expand its capabilities and approach to risk mitigation through direct and specific medical knowledge, research, and applied physiology.

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