Commercial Diving Operations in Construction

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Abstract: This paper classifies diving modes available for civil construction: (1) scuba; (2) surface-supplied air with no decompression; (3) surface-supplied air with decompression; (4) surface-supplied gas; and (5) saturation. It then discusses the characteristics of each mode, moving from the most limited, scuba, to the most unlimited, saturation. It also provides some details of diving work services.

INTRODUCTION

Commercial diving operations use life-support equipment to place workers in hostile environments. The major factors relevant to operation choices are depth, duration of the task, nature of the task, and costs. This report classifies diving equipment as

- Scuba
- Surface-supplied air, no decompression
- Surface-supplied air, with decompression
- Surface-supplied gas
- Saturation diving

Scuba is an acronymn for self-contained, underwater breathing apparatus. It has become a common means for recreational trips into underwater areas. Its use in commercial operations is more limited than that of the other four classifications. Marine researchers sometimes use scuba for excursions from their saturation habitats, but commercial diving services never use scuba for saturation excursions.

The three ''surface-supplied'' modes and commercial saturation diving use umbilicals to supply divers. Because the diver typically wears a full-head helmet, umbilical-supplied diving is often called ''hard hat'' diving. Full-face masks, sometimes called band masks, appear in surface-supplied and saturation diving, but even these may be called ''hard hats.''

Commercial diving currently uses three major breathing mediums. Compressed air is the least expensive and most common. Nitrox is a breathing medium where the dive operations alter the percentages of nitrogen and oxygen from normal air to either enriched oxygen or lower percentages of oxygen. Although nitrox is not pervasively used in commercial construction diving, it is popular among advanced marine biology researchers and some interest is appearing for its use in commercial diving. The third common breathing mixture is heliox, an artificial mixture of helium and oxygen.

Other gas mixes include trimixes of helium-nitrogen-oxygen and mixtures that include hydrogen. Saturation diving uses these to limit the effects of high pressure nervous syndrome (HPNS), which is a physiological effect of very deep diving [deeper than 180 m (600 ft)] (HPNS is described later in this article). While combating HPNS with hydrogen gas, French researchers have reported that their hydrogen techniques increase divers' efficiency and improve breathing comfort (Gardette et al. 1997).

There are other underwater intervention methods, including one-atmosphere suits, manned submersibles, and robotic vehicles. A one-atmosphere man-shaped suit, sometimes called a ''hard suit,'' encases the worker and maintains a normal atmospheric pressure inside. Sophisticated joints allow the worker to move his or her arms, and manipulators on the ends of the hard suit arms replace human hands. The one-atmosphere suits are like small, single-person submersibles with arms and sometimes legs. Full submersibles can carry >1 occupant but lose some accessibility and maneuverability. Work from a submersible proceeds by using robotic arms or, if the task is inspection and conditions amenable to vision, simple viewport and camera observations. Growing sophistication in controls and robotics has allowed submersible operators to remain on the surface while they work through remotely operated vehicles (ROVs), which carry a variety of tools. When coupled with a camera, various sensors, robotic arms, and construction components specifically designed for them, ROVs are rapidly becoming the work systems of choice in very deep waters. This article, however, concentrates on ambient pressure (the human presence). The human sense of touch, dexterity of a human hand, and versatility of the whole human body still affords an irreplaceable advantage to a human presence in underwater work.

SCUBA

Scuba supplies a free-swimming diver with a complete breathing system. Its main features are a high-pressure bottle and demand regulator. Scuba is inexpensive to purchase, easy to mobilize, and has low operational costs. Its portability is the source of all of its advantages and cause of its disadvantages.

Conventional scuba uses compressed air. The physics of the equipment results in decreasing duration with increasing depth. A typical single scuba bottle contains about 2 standard m^3 (75 standard ft^3) of air. Moderate diver effort results in a respiratory volume breathing rate of about 0.03 ambient (or actual) m^3/min (1 ambient ft^3/min). The ambient pressure versus standard pressure is important. As pressure increases, the same rate of respiratory activity draws more air out of the scuba bottle. This varying of gas consumption with depth is a consequence of ideal gas laws. If the reader is unfamiliar with this aspect, any elementary text on sport diving will cover the subject. The principle is Boyle's law. It also is covered in Zinkowski (1971), Shilling et al. (1976), *Commercial* (1990), Nuckols et al. (1996), and U.S. Navy (USN) (1996). As a consequence of Boyle's law, moderate breathing rates for the same 2-m^3 bottle will last about 75 min on the surface, 40 min at 30 ft, and 20 min at 100 ft. The result is that scuba is useful only for short and shallow dives.

Scuba also isolates the worker; he or she has no contact with anyone not in the water. Even contact with others in the water is tenuous. Without actual physical contact, scuba divers are completely lost in the murky waters that are common to commercial operations. Therefore, if the work is hazardous, or strenuous, the worker's safety becomes unacceptably compromised.

Through-water communication devices are available for in-

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stallation in scuba full-face masks. These devices are not very reliable and have not received widespread acceptance in the harsh world of commercial diving. The lack of communication makes scuba useless in large operations that require cooperation with other crafts.

Scuba limits a diver's thermal protection to a wet suit or dry suit. Dry suits provide better thermal protection, but they are much more expensive then wet suits. Further, when used in construction tasks (as opposed to inspection or scientific study), a dry suit rapidly moves from a dry suit to a damp suit. Then it soon becomes a not-very-good wet suit from abrasion and puncture hazards. Neither a wet suit nor a dry suit provides very satisfactory long-term thermal protection in very cold water and abrasive construction tasks.

A diver can move scuba equipment to a job site quickly. With proper training, precautions, and preparation, the diver can make inspections or complete light working tasks in shallow water. Prudent dive firms limit scuba to daylight hours and inspection or light work. The U.S. Bureau of Reclamation (USBR), a federal government entity, does not permit the use of scuba unless the contract language specifically sanctions it or the contracting officer authorizes it in writing (USBR 1987). The Occupational Safety and Health Administration (OSHA) requires a chamber for operations deeper than 100 ft. A recompression chamber increases the capital cost and mobilization effort so much that it robs scuba of most of its advantages.

Scuba is also an unstable platform. Difficult to use in any current, scuba diving in flowing waters becomes rapidly prohibitive. The work required to swim against a 1-knot current [0.5 m/s (1.7 ft/s)] requires heavy exertion and robs the diver of any ability to complete work tasks.

SCUBA BREATHING MEDIUMS

In scuba, air dominates as a breathing medium. Mixed gases do appear, but underwater construction services rarely use mixed-gas scuba. Divers have, however, used pure oxygen, heliox, and enriched air nitrox for specialty reasons.

Military divers use rebreathers (either oxygen or mixed gas) to eliminate the possibility of detection from a trail of exhaust bubbles. The complexity of such devices is significant and reliable design becomes a serious issue. Rebreathers take the exhaled gas and chemically scrub out carbon dioxide. They then return either the pure oxygen or the inert gas (biologically inert, typically nitrogen or helium), with replacement oxygen added, to the diver.

The simplest rebreathers use pure oxygen, but divers cannot safely use pure oxygen at depths much greater than 20 ft. Pure oxygen at elevated pressure can negatively trigger the central nervous system (CNS), which causes convulsions. Whole oxygen is routinely administered to divers at depths as great as 60 ft while the diver remains quiet and still in a controlled environment, usually a recompression chamber. Deeper than 60 ft, a CNS ''hit'' is nearly guaranteed. Complete discussions of oxygen toxicity are included in Shilling et al. (1976) and Hills (1977).

Cave divers are particularly attracted to rebreathers. In reusing the inert gas (helium or nitrogen), they consume only the oxygen necessary for metabolism; in this way, they only have to carry replacement oxygen deep into the flooded cave passages. In a similar fashion, some have used rebreathers with heliox to permit the use of scuba at mixed gas depths. No underwater construction operation would choose this method over a surface-supplied technique; the physical risks are just too great.

Interest in using scuba with enriched air nitrox has recently grown among research and sport divers. Because inert gas is the culprit in decompression, diluting the inert gas with more oxygen reduces the partial pressure of the inert gas (partial pressure is the pressure contributed by one component of a gas mixture to the total pressure), thus reducing the decompression debt. Increased oxygen percentage (and subsequent partial pressure) creates an oxygen toxicity hazard. Balancing the percentages to create a partial pressure at depth within a safe oxygen toxicity margin is part of the skill required in enriched air nitrox diving. Commercial construction diving companies rarely use any form of scuba nitrox. They prefer the safety and control provided by surface-supplied diving techniques. Some interest, however, in using nitrox in surface-suplied diving to extend no-decompression limits is growing among a few commercial diving service providers.

SURFACE-SUPPLIED AIR, NO DECOMPRESSION

The simplest surface-supplied air, no decompression, systems are about as expensive as good quality scuba. It is less portable than scuba, but it opens the opportunity to many advantages. Its main features are a portable air compressor, umbilical, and dive mask or helmet. It shares low operational costs with scuba, but is more difficult to mobilize and requires a more substantial platform for launching diving operations.

By definition, surface-supplied air diving uses air exclusively as a breathing medium. A compressor that supplies 0.5 surface m^3/min (18 surface ft^3/min) at 690 kPa (100 psi) can support one diver up to 30-m (100-ft) deep. Although this 0.5 m^3/min is far more air flow than the respiratory volume, it allows 0.13 ambient m^3/min at the deepest depth [4.5 ft^3/min (ACFM)], enough to ventilate a mask or helmet with a free-flow stream. With an unlimited air supply, the dive durations become limited by decompression requirements and diver endurance.

To remain within the no-decompression zone, divers regulate their dive times to stay within the limits shown in Table 1. Decompression imposes these limits because the physiological response to dissolved gases and changing pressures can cause serious injury if mishandled. The result of mishandling decompression is decompression illness, (''the bends''), which is described in more detail later. Although surface intervals between no-decompression dives and altitude above sea level will alter no-decompression limits, Table 1 suggests that at depths <10 m (<35 ft), fatigue would overcome the diver before decompression becomes an issue.

In surface-supplied diving, the umbilical bundle becomes many things. It delivers the endless supply of air and connects the diver firmly to the dive station. It limits mobility but provides significant safety. Included in nearly every umbilical bundle is a hardwired communication line.

Communication makes the difference between ineffective and excellent operations. Safe use of power tools (primarily pneumatic and hydraulic) becomes possible. The natural human speech link also allows cooperation with other trades, cranes, technicians, and supervisors. Such benefits have turned

TABLE 1. No-Decompression Limits (Sea Level and No Repetitive Dives)

Depth [m (ft)] (1)	Bottom time (min) (2)
0–9.1 (0–30)	Unlimited
9.2–10.7 (31–35)	310
10.8–12.2 (36–40)	200
12.3–15.2 (41–50)	100
15.3–18.2 (51–60)	60
18.3–21.3 (61–70)	50
21.4–24.4 (71–80)	40
24.5–27.4 (81–90)	30
27.5–30.5 (91–100)	25

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the professional surface-supplied diver into a productive worker. Once supplied by an umbilical and blessed with communications, commercial divers are routinely completing heavy labor that includes all manner of rigging, assembly, pipefitting, underwater burning/welding, and detailed inspection.

The umbilical is also a tether that restrains the diver from losing his or her way in turbid waters. Although scuba is extremely unstable, the umbilical diver does not suffer as much in currents and waves. The addition of current shields or cages for restraint or protection further enables surface-supported diving to push operations into flow conditions well beyond where scuba becomes useless.

With some increase in complexity, the dive operation can add a hot-water system. A surface-supplied diver may use the same wet suit or dry suit as the scuba diver; however, adding a hot-water system eliminates all thermal stress. Hot-water systems take water from the body of water in which the diver is working and pumps it through a heater/heat exchange. The heated water then travels down a hose in the umbilical bundle to where it attaches to a special suit. The suit distributes the hot water over the diver's body and exits at the cuffs and neck. This total thermal protection is a great boon to worker endurance in cold waters.

All these new advantages do, however, come with a price. It takes more planning and effort to move surface support equipment to a dive site. Surface-supplied equipment does, however, completely surpass scuba's capabilities. A surface-supplied diver can undertake any reasonable underwater task. In no-decompression diving, the diver's limits are fatigue in shallow depths (<10 m) and decompression in deeper depths. Undertaking sustained operations in depths >18 m (60 ft) without using decompression is impractical due to the manning requirements for short-duration bottom times. Between 18 and 30.5 m, limited duration (nonsustained) in-water operations are cost effective. Deeper than 30.5 m, safety regulations require a recompression chamber. Once a recompression chamber is at the dive site, surface-supplied operations with decompression become attractive.

SURFACE-SUPPLIED AIR, SURFACE DECOMPRESSION

OSHA requires a chamber on all commercial dive sights that use decompression in the dive procedures or where diving depths are >100 ft. The addition of a chamber results in significant cost increases; it is expensive, needs greater air supply to operate, and requires more knowledgeable personnel who are experienced in chamber treatment and risks. Chambers weigh between 1 and 3 ton; the ability to transport and move this weight adds to the cost. It also requires an even more substantial platform to support chamber operations as part of the dive station.

There are other additional components aimed at both careful depth control and alternative air supply (bailout bottles). Decompression schedules depend on depth-time profiles, so accurate depth measurement requires multiple pneumofathometers (calibrated pressure sensors commonly used in diving to measure depth). Increased risk of decompression illness and greater depths make diver bailout systems mandatory for safe operations.

Surface-supplied diving with decompression possesses all the advantages of the no-decompression mode. Further, for the penalty cost of the recompression chamber, one buys depth and duration. Typical safe practice policies for diving companies allow a bottom time of 140 min at 18 m (60 ft), shallow for decompression diving; 80 min at 30 m (100 ft), moderate depth; and 40 min at 57 m (190 ft), deep air. Specific limits are set by company policy and may vary from firm to firm. They are usually set for each 3-m (10-ft) depth increment. The limits reported here are common private industry dive policy, which also allows a ''repetitive'' dive (second dive in the work day) within 12 h. Government regulators also get involved in setting depth limits. OSHA limits air dives between 57.9 and 67 m (190 and 220 ft) to 30 min. European regulations limit air dives to <50 m (165 ft).

Recompression chambers allow surface-decompression using oxygen. In this procedure, the diver leaves the bottom, headed to the chamber. There may be some brief stops (in-water decompression), but the objective is to place the diver in the controlled environment of the chamber as early as possible. At some chamber pressure depth, usually 12 m (40 ft), the diver breathes pure oxygen. Breathing pure oxygen reduces the inert gas partial pressure to near zero and greatly accelerates the decompression process. Because the diver is quiescent, risk of CNS oxygen toxicity is small at this depth [or even up to 18 m (60 ft)].

Limitations on operational depth arise from two areas. Dominant is nitrogen narcosis. Starting just beyond 30 m (100 ft), nitrogen in normal air begins to have a narcotic effect. This effect is similar to nitrous oxide. Some think that the solubility of nitrogen into fat tissue around brain nerve cells alters neurochemical transmission between neurons. The narcosis is generally a pleasant ''high'' with reduced cognitive capacity. Recovery is complete upon return to normal pressures. Intoxicated behavior in an underwater environment, however, can be fatal. Nitrogen narcosis begins mildly and increases with depth. By 50 m (165 ft), it affects most divers. By 61 m (200 ft), it can be seriously debilitating. There is some apparent accommodation; continued deep air diving appears to decrease the debilitation.

The second factor is CNS oxygen toxicity. There is no accommodation to CNS oxygen toxicity. At 67 m (220 ft), the partial pressure of oxygen is 160 kPa (1.6 atmospheres) and poses a slight threat for seizures. Depths beyond this increase CNS toxicity risks.

SURFACE-SUPPLIED GAS

To overcome the limits caused by nitrogen narcosis and oxygen toxicity, commercial divers use mixed gas. Surface-supplied nonair nitrox mixtures provide no benefit to commercial diving operations that have chamber recompression readily available. Enriched air reduces decompression debt, but with a chamber and oxygen surface decompression techniques, the commercial companies realize no significant benefit. There has been some interest in using surface-supplied enriched air for increased no-decompression diving to extend the no-decompression limits, but this has not become an extensive approach to commercial diving. Reducing oxygen content (altering air in the other direction) increases nitrogen partial pressure and its associated narcosis. Therefore, the dominant mixed-gas inert component is helium.

Mixed-gas diving requires additional equipment and manning over deep air. Beyond all the equipment for deep air dives, mixed gas requires banks of bottled gases and components to collect and distribute the gases to the dive station and divers. In mixed-gas diving, in-water decompression times become longer; therefore, OSHA rules require open bottom bells for diver comfort and as a safety refuge if gas supplies fail. With this requirement comes bell winches and davits, more gas lines, and a communication line to serve the bell.

Equipment required for gas diving escalates over that for air, and operational costs soar. Keeping a remote diving location supplied with tubes of bottled gases is logistically significant and costly. To reduce consumption of bottled gases, helmets used in gas diving must provide for demand-only breathing. Air diving helmets often just free flow air to the

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diver, but this would be prohibitively costly when using mixed gases. The added divers, necessary to keep operations sustained and continuous, loads the diving payroll. Technicians trained and experienced in the specialties of gas handling and distribution add to the team costs.

Substituting helium for nitrogen eliminates the narcosis, and reducing the percentage of oxygen eliminates the oxygen toxicity threat. Common standard mixtures are 84% helium and 16% oxygen (84/16) or 90% helium and 10% oxygen (90/10). The 84/16 mixture is barely adequate oxygen at the surface. As the diver goes deeper, the oxygen partial pressure increases well into an adequate range. At 90 m (300 ft), even 84/16 has too much oxygen to avoid toxic results. Beyond this depth, operators use 90/10 or an even lower oxygen mix.

Another benefit from helium is that it is a ''faster'' gas. Helium diffuses faster when decompression starts and thus shortens decompression for a heliox dive compared to an equivalent depth and time air dive. Unfortunately, increasing depth rapidly masks the decompression advantages of heliox diving. These great depths require extensive chamber decompression preceded by significant in-water decompression. The in-water decompression allows a diver's body to eliminate enough gas so that he or she can tolerate a brief interval of low (atmospheric) pressure between the last water stop and the chamber. Once in the chamber, recompression collapses (or, some think merely reduces the size of) any bubbles that have formed in the diver's body. In the deep dives of mixed gas, gas volumes and gradients become so large as to require extensive in-water decompression before the diver can safely experience the brief surface interval between the last water stop and the chamber. Typical decompression numbers for deep air might be 52 m (170 ft) for 40 min, resulting in about 30 min in-water decompression and 1 h in the chamber on an oxygen schedule. A typical gas dive, 73 m (240 ft) for 60 min, results in 3 h in-water decompression and 4 h of chamber decompression (total decompression time of 7 h for 1 h of productive bottom time). Although deep air allows repetitive diving (more than one dive per diver in a 12-h period), gas diving requires that a diver remain out of the water for a minimum of 12 h after leaving the chamber.

As the operation goes deeper, the safe bottom times get shorter and time lost to decompression gets greater. Although surface-supplied gas diving still supports operations in the >90-m (300-ft) range, bottom times are usually very short; much beyond 90 m, 20 min is a typical limit. Then, all the required decompression activity puts strains on budgets. Divers who have completed dives within the last few hours will all be in chambers. A chamber lock also must be available for any diver in the water who might experience an accident or aborted dive. More chambers, gas handling equipment, and all the compressed air capability to support a mixed-gas operation is expensive—a long way from scuba and shallow air costs.

Mixed-gas diving does not relinquish any of the umbilical advantages of surface air diving except long bottom times. However, it wrestles with the increasing depths and decompression until it is prohibitively inefficient while costs continue to mount. Decompression issues just keep compounding. What divers need is release from this decompression demon.

SATURATION DIVING

The defeat of the decompression demon comes at a high price. Saturation diving conquers the decompression dilemma, but a saturation diving complex requires several components, each of them expensive. It also imposes severe conditions on the divers' lives, a factor that also carries a cost in requiring increased compensation to the individuals who must make such sacrifices.

Deck Decompression Chamber (DDC)

The most visible component in a saturation system is the DDC, which is a human occupancy pressure vessel that houses the saturation divers. Between ''bell runs'' (in-water work periods), the divers eat, sleep, and complete hygiene tasks in the DDC; that is, they ''live'' in the DDC. At the end of the task, or when rotating crews, the divers also endure decompression in the DDC.

DDCs have several locks, and the chamber may be separated into two areas so that half can decompress one crew while operations continue from the ''inner'' lock. There are also entrance locks for transferring large items, locking in more team members, or introducing medical help. Smaller locks transfer tools, diving equipment, food, and sundries. A saturation DDC also handles water flows, power, and sewage to and from its high-pressure environment to the normal environment around it. It contains atmosphere sensors and some atmosphere control components.

Personnel Transfer Capsule (PTC)

The PTC mates to the DDC. Divers transfer, under pressure, from the deck chamber to the PTC, also known as ''the bell.'' Sealed and separated from the DDC, the bell carries dive team members down to the work depth where they equalize the pressure and pop open a bottom hatch. Divers can then exit the PTC through the hatch. The PTC contains the individual diver umbilicals, emergency gases, heat radiators, lights, a small scrubber for the PTC atmosphere, and other support components. A main saturation umbilical feeds it with all the power, hot water, and gas supplies needed to maintain the diver(s) both in the bell and in the water.

Control House

The control house component goes by several names and has several different designs. From this control center, supervisors and technicians monitor the PTC, divers in the water, and DDC. Sensors, communications, and raw gas supplies come into the house. Life-support controls for all three areas (in-water, PTC, and DDC) exit the house. It is also the central control for coordinating the divers' work with the other construction operations.

Life-Support Equipment

Coursing through the control house, DDC, and PTC are components and lines of the atmosphere control system, diving gases, power, and thermal protection. The life-support equipment is an aggregation of subsystems that maintain a liveable environment inside the DDC and PTC. It also supplies diving gases and hot-water thermal protection to the working divers. Its tasks are as simple as supplying warm bathing water after a bell run and as complex as maintaining pressure profiles to match a long-term decompression schedule while mixing oxygen percentages in a narrow acceptance band and removing waste gases.

Saturation allows very deep and lengthy operations. Breathing gases supplied to the diver are usually artificial and costly. Operators can conduct saturation excursion dives on demand-breathing equipment, but this method exhausts gases into the water and wastes a costly resource. The industry developed gas reclaim equipment that collects the diver's exhaust at the helmet and returns it along another umbilical line to the surface. At the surface, reclaim equipment scrubs the exhaled gas of carbon dioxide and other contaminants, injects replacement oxygen, and returns it to the system. The capital cost of this reclaim equipment is high but can achieve reclamation rates approaching 90% of the inert gas.

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Ancillary Equipment

A saturation complex includes all the equipment required for mixed gas and deep air diving. Several small subsystems serve the major saturation missions. For example, a very large saturation umbilical supports the PTC. Also, the PTC requires a large, smooth-operating winch to transfer it, with the divers, to and from working depth. The saturation umbilical requires techniques and equipment to handle its bulk. Backup generators supply power if ship power fails. Efficient operation also requires communication links from the control house to all internal and external saturation areas as well as to other construction crews supporting the underwater work. Each piece of equipment needs maintenance and operator technicians.

Brief Saturation Theory

How the saturation diving complex purchases unlimited bottom time involves the mechanism of inert gas solution and dissolution in the human body. When inert gas migrates into solution in body fluids, over time it approaches a saturation limit. For a given partial pressure, body fluids will absorb a maximum inert gas quantity (into solution). When depth changes perturb the balance achieved by living at atmospheric pressure, the amount of dissolved inert gas moves toward a new saturation point. The saturation point is an equilibrium between the new pressure depth and gases in body solution. Reaching this saturation equilibrium takes time.

In scuba or surface-supplied diving, a return to the surface reduces the pressure back to normal long before the diver approaches saturation. The return to normal pressure interrupts inert gas absorption. However, the gas that has already dissolved returns to the gaseous state. If the dissolved gas returns to a gaseous state in a large enough quantity before the time spent in decompression has allowed sufficient gas elimination, bubbles materializing in the body cause damage. This is decompression illness.

If the diver does not return to surface pressure but remains instead under pressure, inert gas continues to dissolve into the tissues until it reaches the saturation point. Once it does reach saturation, no more inert gas enters a dissolved state in the body fluid. The diver has incurred all the decompression debt he or she is going to incur at that depth.

With saturation technology, divers can remain at working depth for several days, even weeks, and work with no lost time from daily decompression. Only when the job is complete, or when it is time to relieve the work crew, does decompression begin. The decompression time will be the same for 60 days at depth as that for 6 days at depth, which is roughly 1 day of decompression per 30 m (100 ft) of saturated depth.

Saturation Gases

Because saturation delivers unlimited bottom time, it has been used at surprisingly shallow depths. Construction diving has used saturation as shallow as 27 m (90 ft) to complete the long bottom times required by hyperbaric welding. Marine biologists use a different operational style (habitat rather than DDC) and maintain very shallow saturations for their work. Shallow to deep covers the complete band of available diving gases.

Air saturations carry some advantage. Being saturated on air to depths up to 15 m (50 ft) provides a diver with an advantage in that he or she can descend to greater depths and return to the storage (saturation) depth within no-decompression limits. Deeper than 15 m on air, divers incur another type of oxygen toxicity, pulmonary oxygen toxicity. Very long exposures, such as those in saturation, to oxygen partial pressures >50 kPa (>0.5 atmospheres) produces lung damage. At just below 15 m, the oxygen partial pressure in air reaches this 50 kPa. Nevertheless, shallow saturations provide extended bottom times at significant depths. Saturated at 13 m (43 ft) on air, a diver can spend 8 h at 26 m (85 ft) and return directly to the saturation depth, no decompression required. Commercial diving interests have made only limited use of this method. Their expertise in surface decompression using oxygen often yields a more cost-effective alternative. However, marine biologists use air saturation with excursions extensively and the technology is well developed (Hamilton et al. 1988a,b).

Because it leads to even higher oxygen partial pressure than air, enriched air nitrox is unuseable in saturation. Nitrox that contains lower percentages of oxygen does, however, have something to offer. Nitrogen is a fraction of the cost of helium, and some researchers have claimed that a saturation-induced accommodation to narcosis allows saturated divers to reach 76 m (250 ft) on nitrox with remarkably reduced narcotic sensitivity. This narcosis accommodation is not, however, consistently reported (Bennett 1993). Nevertheless, saturations at storage depths to 37 m (120 ft) on nitrox are well proven and excursions to as much as 76 m may be useable. Excursions to 58 m (190 ft) are certainly useable. Like air saturation, industry participants have made only limited use of this medium. Marine biologists have taken greater advantage of nitrox saturation than commercial dive operators; however, they have limited experience with it as they rely more heavily on air saturation with deeper excursions.

Heliox is the standard breathing medium in saturation diving, and the commercial diving industry is very comfortable with it. Saturated divers have completed sustained operations (30 days) in depths beyond 300 m (1,000 ft) of seawater using helium. Shorter duration dives to great depths have reached 488 m (1,600 ft). The major barrier to continued helium use at great depths is HPNS. At depths beyond 180 m (600 ft), it becomes increasing noticeable (Shilling et al. 1976):

> HPNS is a syndrome of neurological and physiological dysfunctions which appear in [divers] compressed to high hydrostatic pressures. Onset and severity seem to be a function of both compression rate and absolute pressure. The condition has been characterized by motor disturbances (such as tremor and uncontrolled muscle jerks); somnolence; significant EEG changes (which may signal imminent convulsions); and visual disturbances, dizziness, and nausea.

Slow compression rates can relieve its onset and severity, but significant efforts at breaking past HPNS have centered on gas mixes. Trimix was the first successful HPNS avoidance gas and consists of helium, nitrogen, and oxygen. Theoretical physiological reactions at a cellular level to high-pressure helium and nitrogen are counterbalancing in effects. Successful chamber dives (simulated dives with human occupants in a pressure chamber rather than open water) to 610 m (2,000 ft) demonstrated the usefulness of trimix blends.

Hydrogen also has played a role in HPNS avoidance (Gardette et al. 1997). Chamber dives to 700 m (2,300 ft) and open-water dives to 534 m (1,752 ft) demonstrated hydrogen's effectiveness as a deep saturation breathing medium.

THE WORK OF DIVING

The offshore oil industry purchases the bulk of construction-related diving services. Oil development includes construction, inspection, and maintenance of all submarine oil-related structures. Dams, power plants, locks, and waterways also purchase diving services for underwater construction or inspection of

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their infrastructure. The bridges that cross waterways require periodic diving inspections, and retrofits of bridge piers and foundations call upon construction divers. Ports, marinas, and harbors have structures that often need attention from construction divers. All kinds of pipeline and communication/power-cable water crossings are subject to requiring diving services. Potable water storage tanks also employ divers for inspection and maintenance. Although not strictly civil construction, the same skills are often employed in ship husbandry for below-water inspections and repairs. If it floats, holds back a body of water, or is submerged, a structure may need diving services some time during its life cycle.

Professional construction divers acquire knowledge and skill in rigging, assembly, and fitting. They use hydraulic and pneumatic tools to increase their productivity. Extra skills for construction diving include burning steels and other metals underwater with oxy-arc systems. Also, divers/welders can complete code welds in either wet environments or in dry special-built habitats.

Besides the heavy work often involved in cleaning a surface to reach it for inspection, many commercial divers have abilities in non-destructive testing. The most common underwater nondestructive testing methods are ultrasound and simple underwater video records; however, mag-particle, eddy current, X-ray, and cathodic electrical potential readings are also available.

Despite all these diver capabilities, no one should be misled into believing that technology has made construction diving easy. Besides the limitations imposed by decompression and the threat to survival imposed by the alien environment, divers face a host of adversities. Underwater projects are seldom placed in warm, clear waters. A working diver is besieged by working blind in a cold medium that may numb even the sense of touch. He or she deals with buoyancy that provides the advantage of the ability to ''fly'' around an off-bottom work site, but it impedes stability and hampers one's ability to apply force. Working blind, weightless, cold, possibly fighting currents, and having constantly to attend to a trailing umbilical that finds everything on which to foul is not the ideal working environment. The purchaser of construction-related diving services should not hire diving services based merely on the fact that someone owns the means to get themselves into the water. A sign outside a prominent diving company of the 1970s said it well: ''The title 'diver' does not bestow a panacea for the skills you lack; it merely entitles you to a unique form of transportation to the work site'' (from a sign outside Taylor Diving and Salvage, Belle Chasse, La.).

Diving costs are a complex mixture of depth, specific underwater activity, geographic location, and market conditions. Although these rates vary widely, providing some sample costs is possible. Presented here are broad price samples based largely on prices for offshore services in the Gulf of Mexico. Bear in mind that offshore services are often higher than inshore because they typically anticipate continuous, 24-h/day service and the remote, harsh environments are hard on equipment, personnel, and maintenance schedules.

Many diving companies that provide competent construction services do not have rates for scuba; however, especially in shallow water inspection, scuba has its place. Recent OSHA decisions have established that a minimum dive crew size should be three people. Likely rates (early 2000) for such legal, competent scuba services will not be much below $100/h (a three-person team). Scuba rates could easily range up to rates for basic surface-supplied air.

Surface-supplied air with no decompression was recently quoted as $1,800 for one daily 12-h shift for two divers, one tender, and a minimum equipment package. For the 24-h/day operations that are more typical in offshore work, this same diving mode would require twice as many personnel. However, because it would use the same equipment package, the cost is not quite double that of a 12-h day. Two 12-h shifts result in a cost of $3,250/day.

With surface decompression capability, the rate becomes $3,400–$4,500 (depending on depth) per daily 12-h shift for one supervisor, two divers, two tenders, and a large air package that includes a chamber. A two 12-h shift day rate would be between $5,900/day and $8,100/day.

Gas diving requires a diving supervisor, gas manifold operator, three divers, three tenders, and a mixed-gas diving package. The rate for one 12-h shift per day on this package is $7,400/day–$9,200/day (again, the price varies with depth). For the two-shift 24-h operation, such mixed-gas diving would cost between $12,800/day and $16,400/day.

By its nature, saturation is a 24-h/day diving operation. Saturation alone, without any vessel or other support, runs $24,000/day–$30,000/day. For offshore work, these systems often come with their own dedicated work vessel for a rough cost figure of around $50,000/day.

The prices provided above for surface-supplied air/gas and vessel/saturation combinations came from current price estimates provided by a Gulf of Mexico offshore firm (J. McClaugherty, business service manager, Torch, Inc., Houston, Tex., personal communication, January 2000). The stand-alone saturation and scuba estimates come from the writer's experience and judgment. These Gulf Coast rates are influenced by recent competitiveness in available offshore work for the 1999 work year. One also should note that the manning for each surface-supplied mode quoted here is minimum and would not allow continuous operations. Personnel adjustments must match the depth and task at hand, and price increases would be likely. It also is probable that Gulf rates would have increased since the writing of this paper.

Any effort to systematically extrapolate these rates to other areas is difficult, at best. The volume of work available to providers in the Gulf region allows many of these companies to operate on lower per job margins. Alternately, the sophistication of Gulf Coast diving companies requires many of them to carry very large overheads to maintain their advanced capabilities. Because they are only called upon for shallow air work, some inland companies maintain a surprisingly low rate structure. The Gulf Coast also is nearly devoid of any diving labor unions. Because diving is both labor-intensive and obviously dangerous, rates for diving services dominated by union agreements are considerably higher.

CONCLUSIONS

Depending on the depth, and nature of the task, there are five modes of diving available for construction activities. Diving here is defined by direct, ambient water pressure intervention by a human. One-atmosphere suits, manned submersibles, and ROV also are available but were not covered in this article.

Scuba provides limited usefulness in shallow-water, light work circumstances. Surface-supplied air diving provides great advantages in depth and work efficiency. Adding surface decompression capability extends the advantages of surface-supplied air into deeper depths but for an increasing cost. Surface-supplied mixed-gas diving continues this trend by providing greater depths and increasing costs. Saturation provides new diving opportunities by eliminating daily decompression and providing unlimited bottom time.

Table 2 provides a summary of the use of each diving mode. The diving modes are classified as scuba, surface-supplied air with no decompression, surface-supplied air with decompression, surface-supplied gas, and saturation. Where appropriate, breathing mediums provide subclassifications of the modes.

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TABLE 2. Diving Mode Summary

Mode (1)	Gas (2)	Depth [m(ft)] (3)	Note (4)
Scuba	Air	0–30.5 (0–100)	Can be used deeper, but chamber required; limited to inspection and light working dives
	Enriched air nitrox	10–40 (35–100)	Extends no-decompression bottom times—sport divers use nitrox to 130 ft; however, commercial divers are required to have chambers in depths >100 ft
	Heliox	—	Specialty use, military and cave diving.
Surface-supplied air, no decompression	Air	0–30.5 (0–100)	Continuous sustained operations in <18 m (<60 ft); shorter tasks to 30.5 m (100 ft)
Surface-supplied air with decompression	Air	12–67 (40–220)	Uses chamber and surface-oxygen decompression
Surface-supplied gas	Heliox	50–110 (165–360)	Deeper depths have very limited bottom times
Saturation	Air	0–15 (0–50)	Limited commercial use; excursions deeper
	Nitrox	14–58 (45–190)	Limited commercial use
	Heliox	30–500 (90–1,600)	Most common saturation gas
	Trimix	150–610 (500–2,000)	Deepest dives (>500 m) only in chambers
	Hydrogen process	185–700 (600–2,300)	Deepest dives (>534m) only in chambers; hydrogen was in breathing mix for current deepest open water dive record

Underwater construction capabilities provided by commercial divers are impressive. However, the alien and threatening environment, short bottom times for all but saturation, and increasing high costs hamper their productivity.

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