3 COMMERCIAL DIVING EQUIPMENT AND PROCEDURES

J. Bevan

No other industry requires its workforce to operate in so hostile and alien an environment as the diving industry. Consequently, no other industry relies more heavily on the highest attainable understanding of related physiology and medicine. Indeed, it is the constant demand of the diving industry (together with that of the military) that has provided the driving force for the ongoing and essential research into underwater physiology and medicine.

The diving industry's total dependence on the critical constraints subsequently imposed by physiologists and doctors is reflected in the ever-increasing complexity of diving equipment and procedures. So much so, that, in general, the technology behind the means of bringing a diver to his task far exceeds the technology inherent in the task itself.

Nowhere, therefore, in occupational health and safety, can it be more important than in the diving industry for health professionals to have a working knowledge of the equipment and procedures of working in a hazardous environment. This chapter relates specifically to equipment and procedures of diving and does not apply itself to the occupational hazards of the diver's tasks, such as those associated with water-jetting (noise, injury), gamma radiography, welding and cutting (electric shock, ultraviolet light, burns and explosions).

DIVING SUITS

Keeping divers in thermal balance is an important aspect of diving safety and three basic types of suits are used: the wet suit, the dry suit and the hot water suit. The first two provide passive insulation, whereas the hot water suit provides active heating.

Wet Suits

The wet suit is constructed from foamed neoprene up to ¼ in thick and may have a nylon lining for additional mechanical strength. The thermal insulation is largely derived from the gas trapped within the closed cells of the foamed material, and so the suit is required to be close fitting to prevent flushing within the void between the diver's skin and the suit. Wet suits have the advantages of cheapness and robustness and do not fail when torn, and they also allow the diver the freedom to urinate without loss of insulation effectiveness. The main disadvantage is that the material is physically compressed at depth and both insulating and buoyancy properties are lost proportionally. Furthermore, taken into an atmosphere containing helium, this gas can diffuse into the material and reduce its insulating properties significantly.

Dry Suits

As the name implies, a dry suit maintains the body and underclothing of the diver in a dry condition. The material of the suit may not be significantly insulating and so thermal undergarments are usually worn. In order to keep the diver dry, seals are provided at the wrists and neck. The special advantage of dry suits is that the insulating gas layer beneath the suit may be maintained, despite increasing depth, by the addition of more gas as necessary. A further advantage is that the diver is essentially out of contact with the water and total separation is possible if needed, thus minimizing any risks associated with water pollution.

A disadvantage of the dry suit is that, if the buoyancy is not carefully controlled, it can cause the diver to be drawn into an uncontrolled and accelerating ascent or 'blow up' with an attendant high risk of pulmonary barotrauma. Alternatively, an uncontrolled descent can lead to a 'squeeze' when the suit painfully pinches skin trapped at folds as the gas layer is compressed. Other disadvantages, which are not so serious, include the need to avoid punctures or tears, as these allow water to enter and air to escape with consequent loss of thermal insulation and buoyancy. The seals at the neck and wrists are particularly vulnerable and it is rare for a diver to have a completely 'dry' dive. Small amounts of water usually find their way through pin-holes or past the seals, such as at the wrist where loss of roundness as tendons are flexed can cause channels to appear. Equally, urinating is neither so practical nor hygienic and can cause problems after several hours of exposure to cold, when the natural requirement to urinate either terminates the dive or introduces considerable discomfort.

Hot Water Suits

The hot water suit is arguably the most effective diving dress for comfort, thermal and physical protection (Fig. 3.1). It is used universally for deep, bell diving and extensively in the air diving range. It is unaffected by small cuts and tears and also provides the freedom to urinate. The main potential disadvantage is the possibility of skin scalds if control of the hot water temperature is poor. Scalding can be caused without the knowledge of the diver if the increase in the temperature of the circulating water is gradual. The heat sources at the surface for the hot water to these suits may be diesel-fired, steam or hot water heat exchangers. Diesel-fired heaters are the least popular due to their inherent fire hazard.

Buoyancy Aid

Variations in diver buoyancy can be caused in the shallow, air range due to changes in depth and at all depths by carrying tools, etc., or by changes in the diving equipment used. For these reasons, the diver's physical workload can be significantly reduced if he has the facility to adjust his buoyancy, particularly to achieve neutral buoyancy for mid-water swims to and from the diving bell. Special buoyancy compensators are therefore available, which the diver may inflate or deflate as necessary.

FIG. 3.1. Umbilical-supplied air diver with band-mask, demand underwater breathing apparatus, reserve 'bale-out' cylinders, hot water suit and pneumofathometer

BREATHING EQUIPMENT

Surface-Orientated Equipment

Surface-orientated diving refers to those diving operations where the diver travels between the surface and his worksite through the water column and without being protected within a closed diving bell. Thus he may swim, climb or be lowered in a basket or wet (or 'open') bell. The maximum depth of such operations is usually 165 ft (50 m) and air is normally the breathing gas.

Free-flow Systems

The simplest form of underwater breathing equipment is the free-flow, open helmet, first used commercially in 1829 by John and Charles Deane. It is still in use today to a very limited extent. This is the equivalent of an inverted bucket placed over the diver's head and provided with a free-flowing supply of air via an umbilical from a pump on the surface. The natural development of this arrangement leads to a free-flow mask or helmet with a neck seal ('neck dam') or connected to a dry suit as in the 'standard dress'. A high-volume air supply is essential for the safe operation of these helmets (Fig. 3.2). Free-flow helmets are often preferred by divers who are required to carry out high levels of physical work as they provide the least breathing resistance. A minimum supply capability of 170 litres/min has been proposed by Morrison and Reimers (1982), who also offer a description of the dynamic respiratory performance of this and other types of underwater breathing apparatus.

Demand Systems

The next level of complexity in design is the open circuit breathing apparatus in which air is supplied 'on demand', i.e., during the inhalation phase of the breathing cycle only. This is less wasteful of compressed air and so lends itself more conveniently to situations where air pumps are not used and the capacity of the air reservoirs is limited. The air is inhaled directly through a mouthpiece or an oral nasal mask, which may be contained within a face-fitting 'band-mask' or a helmet. Exhaled air is directed back into the water. An important advantage of the helmet over the band-mask is that the former keeps the ears of the diver dry and thus reduces the risk of external ear infections.

Demand valves ('regulators') are used universally in self-contained underwater breathing apparatus (scuba) equipment, which is the main type of breathing equipment used by recreational divers (Fig. 3.3). Scuba is not favoured in commercial diving because of its very limited endurance, the absence of an unlimited secondary, air supply in emergency and the lack of hardwire voice communications.

The purpose of the demand valve is to supply an adequate flow of gas, regardless of the changing ambient pressure and any variation in the supply pressure. In commercial diving operations, the air supply invariably arrives via a medium-pressure umbilical, approximately 10 atm (1 MPa) above ambient pressure, with a separate high-pressure emergency supply ('bale-out') carried on the diver's back.

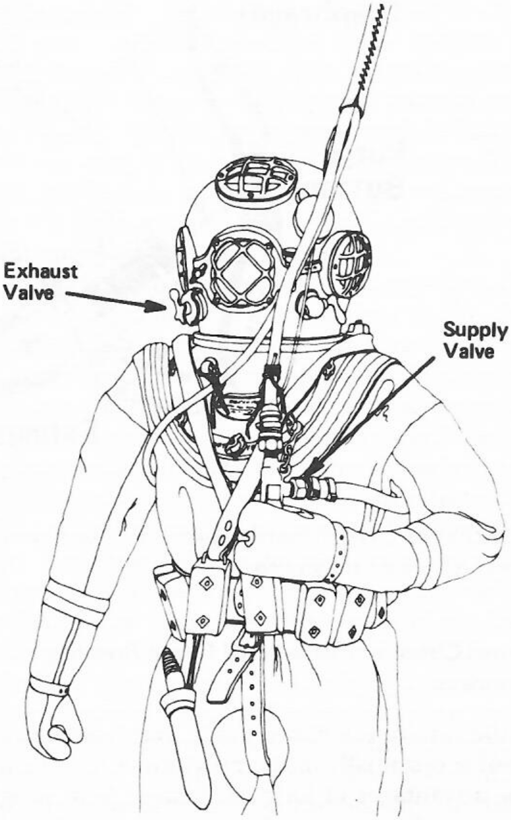


FIG. 3.2. Traditional ventilated helmet with standard diving dress

Nitrox Mixtures

Where extended bottom times are required that may be beyond the normal limitations imposed by the decompression constraints of air-breathing, synthetic mixtures of oxygen and nitrogen ('nitrox') are sometimes used. In these artificial mixtures, the oxygen percentage is raised above that found in air with a corresponding lower nitrogen percentage. This reduces the quantity of inert gas absorbed by the body during the hyperbaric exposure when compared to an equivalent air dive. The consequent decompression time penalty is therefore reduced. However, special care is required to keep within the ceiling value of 1.5 ata

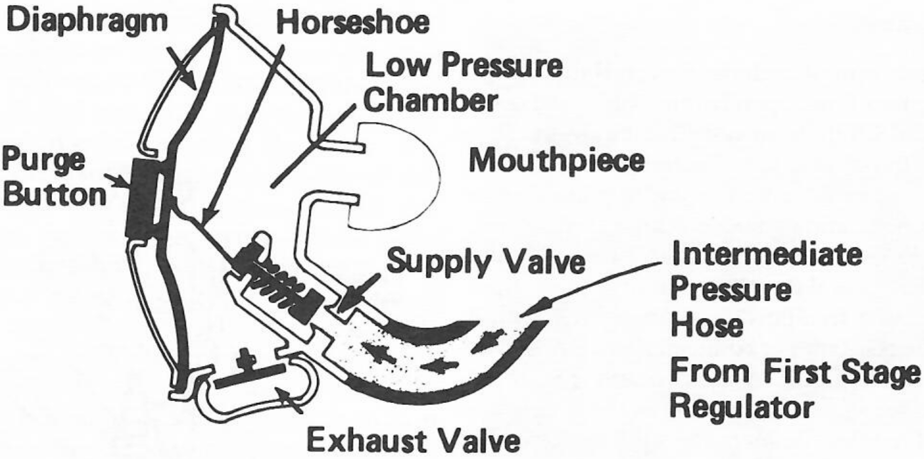


FIG. 3.3. Second stage of a two-stage demand valve

(150 kPa) of oxygen partial pressure exposure, or oxygen toxicity may occur.

Closed Circuit and Semi-closed Circuit Breathing Apparatus

In the surface-orientated mode, this type of equipment is essentially in the province of the military. The advantages of long endurance, light weight, low acoustic noise, minimum gas escape (bubbles) all lend themselves appropriately for clandestine operations (Fig. 3.4). In view of the minimal applicability to commercial diving of this equipment, which also needs a low magnetic signature, no further detail is included here. The equipment used in commercial deep diving operations is described below.

Mixed Gas

In order to dive beyond the air diving range (deeper than 165 ft or 50 m), far more elaborate

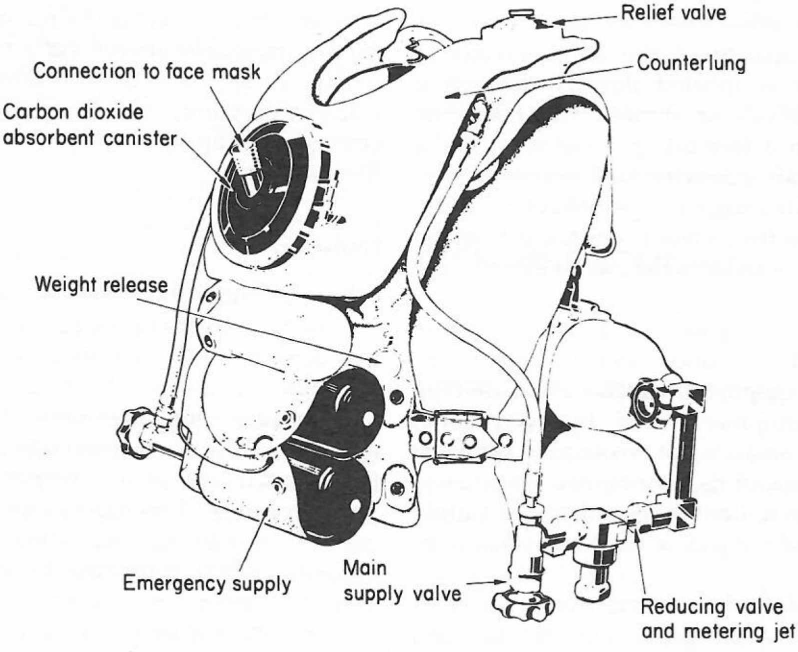


FIG. 3.4. A semi-closed circuit breathing apparatus

techniques and equipment are needed. First, the diver is provided with a breathing mixture of oxygen and helium ('heliox'). This gas is umbilical-supplied to the diver from a submersible compression chamber (SCC, SDC or closed bell). The gas may be breathed either open circuit, on demand or, for economy, the exhaust gas may be recovered and recycled via the bell.

Open Circuit Systems

With open circuit equipment, the diver has the options of breathing on demand only, or free-flow or both. It is common for his gas supply to be mainly on demand concurrent with a small continuous free-flow supply which de-mists his visor and ensures no carbon dioxide build-up in the helmet/band-mask. Should the diver become breathless due to physical exertion, he may increase his free-flow supply to reduce the work of breathing.

A secondary, emergency gas supply is provided by the high-pressure, bale-out cylinder(s) charged with an appropriate gas mixture, carried on the diver's back. The valves for controlling the free-flow and the emergency gas supplies are both located on the helmet or band-mask. Should the diver require to use his emergency supply, he closes his free-flow completely to conserve the very limited supply. The endurance of the emergency gas supply is proportionately diminished at greater depths. At extreme depths, the endurance may be unacceptably short and so special self-contained units are becoming available.

Gas Recovery Systems

A closed circuit gas recovery system can recover 80–85% of the gas breathed by a diver. This reduces costs and minimizes the gas storage requirements on the surface support vessel. Gas recovery systems fall into two general categories: (1) those which require an umbilical supply and (2) the self-contained back-pack systems. The former are in more general use even though they do significantly increase the diver umbilical size.

Umbilical-Supplied Gas Recovery Systems

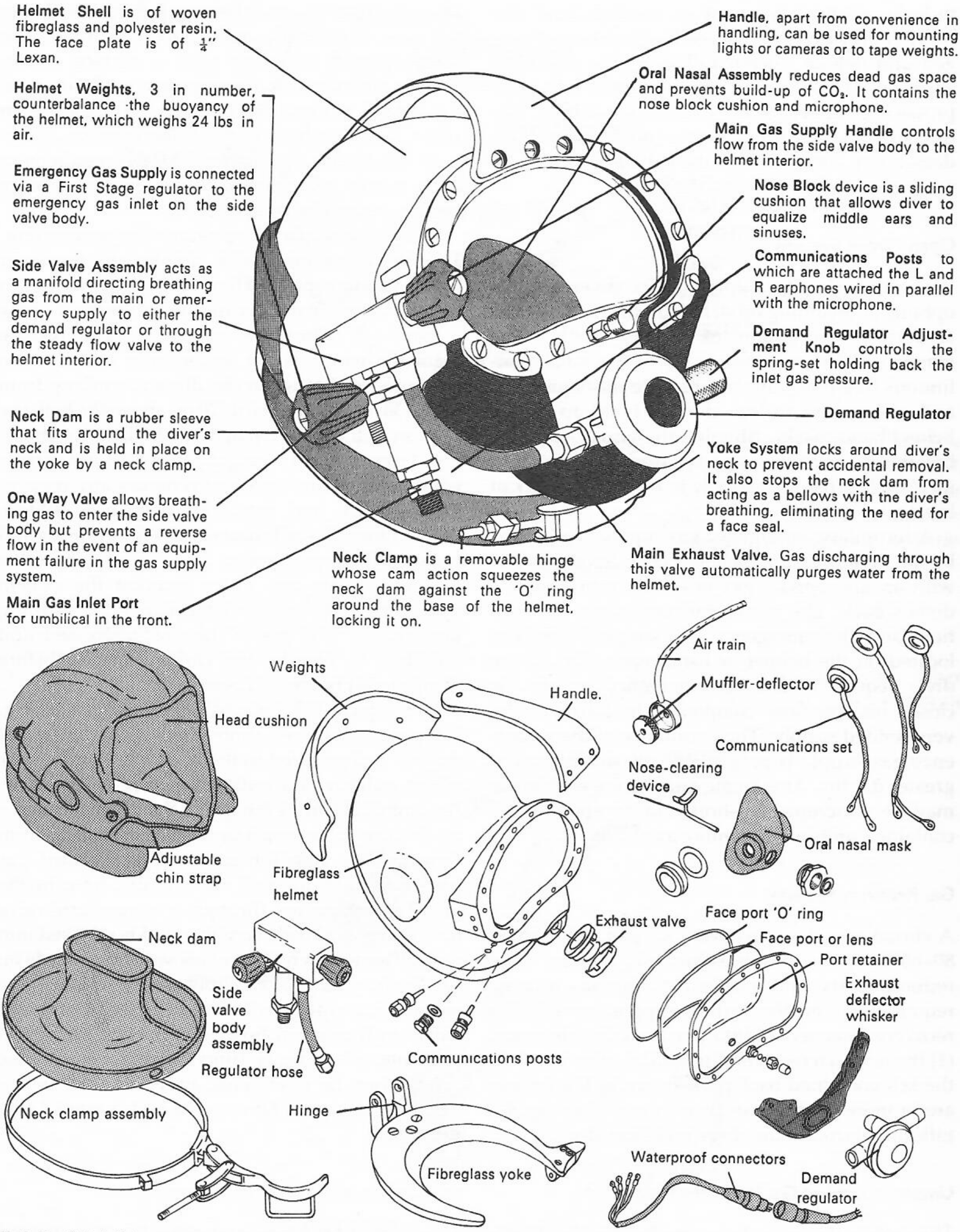
The umbilical-supplied systems recover the diver's gas via a special exhaust control valve, which carefully regulates the flow of gas out of the helmet. The recovered gas may be recycled via the diving bell only, or may be returned to the surface. The advantages of recycling with a surface facility include maintenance of equipment without aborting a dive, minimal interference with bell design and a greater depth range of bell excursions. However, the disadvantages include the requirement for a bigger bell umbilical, thus requiring more deck space and increasing costs.

In a typical surface loop return line system (Fig. 3.6), the breathing gas is supplied to the diver from topside control. The exhaled gas returns to the bell through a water trap which removes bulk moisture; it then flows through a back-pressure regulator which is set lower than bell internal pressure, so that when the diver is working from 100 ft (30 m) below to 66 ft (20 m) above the bell, the gas can still return by hydrostatic head of pressure. From the bell, the gas returns to the surface where a moisture separator removes any remaining moisture and metabolic oxygen is added. Before being filtered to remove solid particles and bacteria, the gas passes through a float valve which prevents any water entering the system which may have entered through a loose fitting underwater. The gas is then recompressed and scrubbed to remove the carbon dioxide before being stored ready for re-use.

In a typical bell loop, return line system (Fig. 3.7) gas from the bell atmosphere is compressed at the bell and pumped to the diver via a buffer tank which stabilizes the output pressure to the diver. An umbilical carries the gas to the diver through a non-return valve which prevents exhaled gas from flowing back into the gas supply. Exhaled gas passes back to the bell via a return hose in the umbilical; it passes through a non-return valve into a carbon dioxide scrubber and is released into the bell atmosphere. Since this system depends on the hydrostatic head of pressure to return the exhaled gas upwards to the bell, the non-return valve on the return hose is important because it prevents exhaled gas from flowing back to the diver when he is working above the bell (when exhaled gas cannot be recycled and is vented into the water).

Self-Contained, Closed Circuit Systems

This type of breathing apparatus is not in general use but available for specialist requirements. An example of a self-contained, closed circuit, mixed-



Helmet Shell is of woven fibreglass and polyester resin. The face plate is of ¼" Lexan.

Helmet Weights, 3 in number, counterbalance the buoyancy of the helmet, which weighs 24 lbs in air.

Emergency Gas Supply is connected via a First Stage regulator to the emergency gas inlet on the side valve body.

Side Valve Assembly acts as a manifold directing breathing gas from the main or emergency supply to either the demand regulator or through the steady flow valve to the helmet interior.

Neck Dam is a rubber sleeve that fits around the diver's neck and is held in place on the yoke by a neck clamp.

One Way Valve allows breathing gas to enter the side valve body but prevents a reverse flow in the event of an equipment failure in the gas supply system.

Main Gas Inlet Port for umbilical in the front.

Neck Clamp is a removable hinge whose cam action squeezes the neck dam against the 'O' ring around the base of the helmet, locking it on.

Handle, apart from convenience in handling, can be used for mounting lights or cameras or to tape weights.

Oral Nasal Assembly reduces dead gas space and prevents build-up of CO_2. It contains the nose block cushion and microphone.

Main Gas Supply Handle controls flow from the side valve body to the helmet interior.

Nose Block device is a sliding cushion that allows diver to equalize middle ears and sinuses.

Communications Posts to which are attached the L and R earphones wired in parallel with the microphone.

Demand Regulator Adjustment Knob controls the spring-set holding back the inlet gas pressure.

Demand Regulator

Yoke System locks around diver's neck to prevent accidental removal. It also stops the neck dam from acting as a bellows with the diver's breathing, eliminating the need for a face seal.

Main Exhaust Valve. Gas discharging through this valve automatically purges water from the helmet.

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FIG. 3.5. 'Superlite 17A' helmet. (Reproduced with permission from Sisman, 1982)

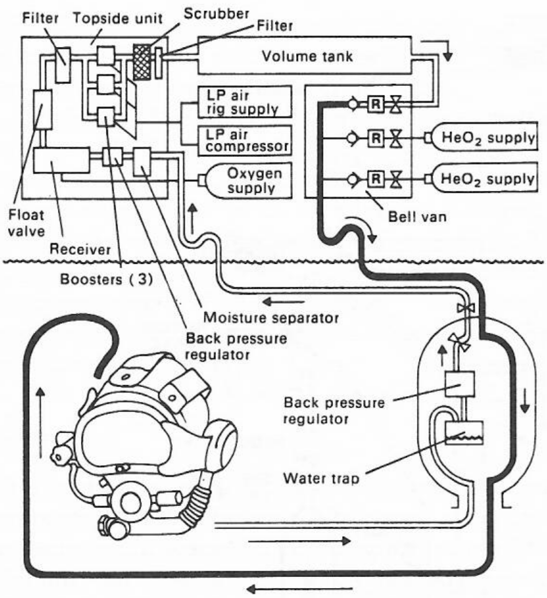

FIG. 3.6. 'Gasmizer' bell-loop, return line, gas recovery system. (Reproduced with permission from Sisman, 1982)

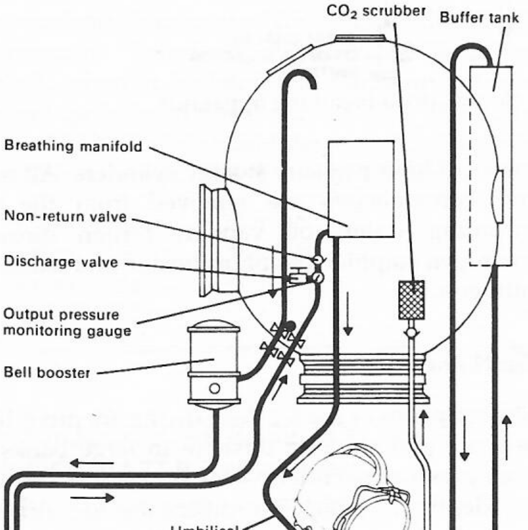

FIG. 3.7. Comex closed circuit breathing system. (Reproduced with permission from Sisman, 1982)

gas rebreather is shown in Fig. 3.8. The diver wears the backpack which contains oxygen, a diluent mixture, a carbon dioxide scrubber, a battery to power electronics and control valves, and moisture absorbent pads. The self-contained system does not require an umbilical but can use one for communications and depth monitoring. The diver breathes from a flexible bag, a 'counterlung', protected within the backpack. An exhaust hose carries exhaled gas to the backpack where excess moisture is removed by water traps. A radial scrubber removes the carbon dioxide and three oxygen sensors are used to control the oxygen added to make up for the metabolic consumption. The reconstituted gas is passed on to the breathing bag for rebreathing. Manual bypass valves enable the diver to take control of mixing if necessary. The diver is provided with two readouts: one, with alarms, indicates the optimum oxygen in the breathing gas and the other displays battery level and oxygen sensor outputs.

Bale-Out Systems

The normal bale-out or emergency gas supply arrangement for the mixed-gas, bell diver, is by provision of one or more back-mounted, high-pressure cylinders containing the appropriate gas mixture for the depth which is breathed on an open circuit principle. This is necessarily of extremely limited endurance and is bulky. At great depths, the equipment may be totally inadequate. To overcome this serious limitation, a closed or semi-closed breathing apparatus can be worn as the backpack.

An example of a semi-closed circuit arrangement is the Secondary Life Support system of Gas Services Offshore Ltd. The breathing apparatus is actuated by two non-sequential actions: on pulling the actuation cord, the counterlungs are released from their pouches. This also isolates the umbilical supply and opens the gas supply from the backpack cylinders. This allows a flow of gas into the breathing circuit, to maintain a safe breathing mixture. The second action is a quarter turn of the helmet interface valve. This projects a mouthpiece into the oral nasal mask. Exhaled gas passes through the helmet actuation valve and a non-return valve via an insulated hose to the carbon dioxide scrubber in the backpack. From there it passes through a thermal regenerator into the counterlungs. On inhalation, the gas is drawn

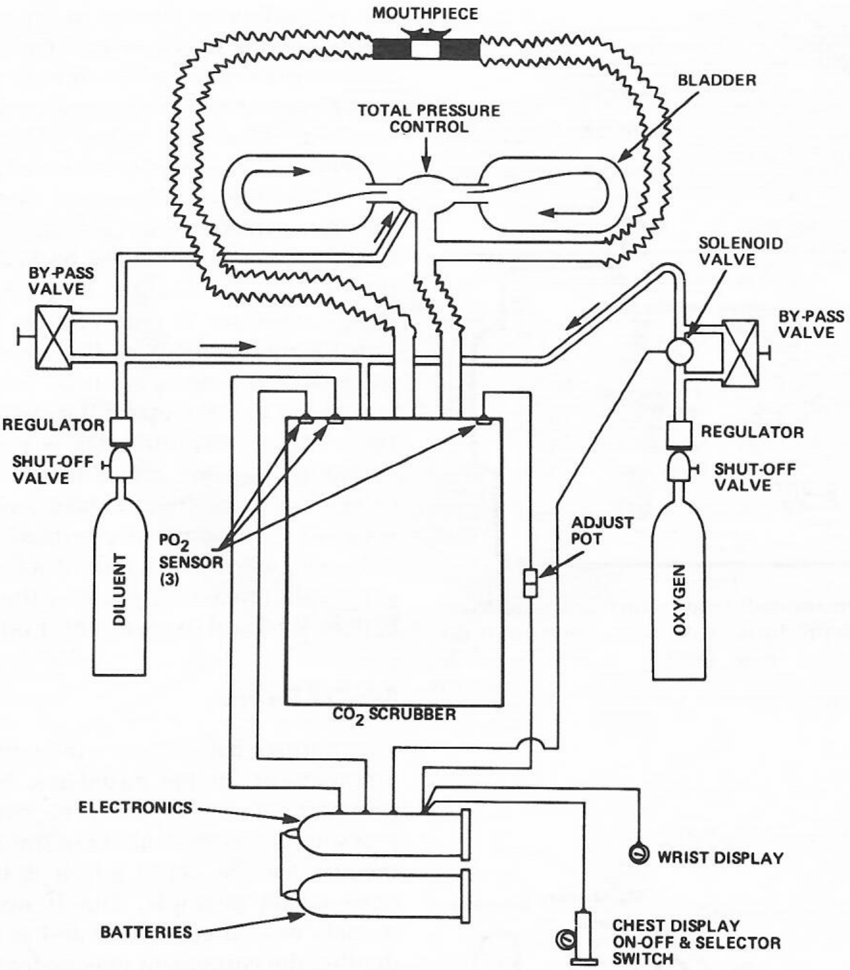

FIG. 3.8. Sensor-controlled mixed gas, closed circuit breathing apparatus

from the counterlungs, through the thermal regenerator once more and back to the mouthpiece via the helmet actuation valve. A demand valve ensures an extra gas supply if needed, thus dispensing with the need for a manual bypass valve.

Chamber Gas Recovery Systems

The gas recovery systems already described, all refer to the recovery of the diver's respiratory gases which would otherwise be released into the water. However, up to 70% of the gas lost in the course of the decompression of the deck compression chambers, medical locks and bell can also be reclaimed. The provisions for this include large volume, flexible bags to collect the gas from the DCC exhausts, compressors, filters, a molecular sieve bed, activated charcoal bed, catalyst bed and banks of high-pressure storage cylinders. All reactive contaminants are removed from the gas including water, oil vapour, carbon dioxide, hydrogen sulphide, sulphur dioxide and oxides of nitrogen.

Gas Mixing

Most supplies of gas for deep diving are pre-mixed onshore and shipped offshore in large banks of high-pressure cylinders. This is possible because the depths at which the divers are to work are normally known in advance and the required oxygen percentages are therefore predictable. Sometimes, however, these depths are not so easily predicted and plans can also change. In order to provide greater flexibility of diving depth capability, the diving vessel may have a gas mixer or 'blender'. Such units are capable of making on site whatever gas mix may be required from oxygen and helium (or heliox) banks.

To eliminate the risk of a diver accidentally receiving 100% helium in his breathing circuit, a safety measure introduced in the North Sea recommends that, apart from the case of calibration gases, no pure helium should be sent offshore. For example, a minimum of 2% oxygen in helium is recommended offshore which, for mixing purposes, would be appropriate for all diving down to 495 ft (150 m).

Gas Heating

The heating of inspired gas for the diver becomes more important as his depth increases and is compulsory in UK waters at depths greater than 495 ft (150 m). In practice, virtually all commercial mixed-gas diving includes a gas-heating facility. The equipment normally consists of a small hot water heat exchanger carried by the diver, which heats the respiratory gas just before it reaches the helmet. Additional flexible shrouds surrounding the remaining pipework between the exchanger and the helmet retain the hot water to maintain the heat in the gas. The hot water is derived from the suit hot water supply. The acceptance limits for gas heating are well established and current recommendations in the North Sea are detailed in Norwegian Petroleum Directorate Guidelines (1991), where it is stated that the temperature of humid gas should never exceed 37 °C or dry gas exceed 32 °C. Tests should demonstrate the ability to achieve the following gas temperatures:

■ 150 m (492 ft)	20 ± 2 °C
■ 200 m (656 ft)	20 ± 2 °C
■ 300 m (984 ft)	25 ± 2 °C
■ 400 m (1312 ft)	30 ± 2 °C

PHYSIOLOGICAL BASIS FOR UNDERWATER BREATHING APPARATUS (UBA) DESIGN

Underwater breathing apparatus must provide the diver with the appropriate respiratory gas mixture in adequate volumes, at reasonable flow rates, with acceptable temperature and pressure. Furthermore, the resultant work of breathing must be maintained within reasonable limits. Attempts by many distinguished scientists and doctors to define universally acceptable physiological standards have proven to be a minefield for good intentions. Consequently, manufacturers of UBA are still obliged to establish their own parameters and criteria. Confusion reigns when international standardisation of performance specifications is required.

In the following paragraphs, some selected factors (described in detail in later chapters) are summarized in relation to the design specifications of underwater breathing apparatus. These were reviewed by Morrison and Reimers (1982) in the third edition of this book, since when little has emerged to alter the basic principles (Flook & Brubakk 1992).

At normal barometric pressure, the maximum exertion of healthy subjects is usually limited by circulatory factors, and is reached only during extremely vigorous exercise (Cotes 1968). It is unlikely that such levels of exertion are attained underwater, but at increased pressure maximum oxygen uptake may be limited by ventilatory factors including the combined efforts of increased gas density and breathing apparatus performance (Morrison & Mayo 1973; Spaur *et al.* 1977). In an underwater emergency, the physical efforts of the diver should not be limited by his equipment and so the performance objectives and physiological acceptance criteria of breathing apparatus designs must reflect the maximum exercise intensity that may be anticipated in divers.

The performance of open circuit UBA depends on the responses of the demand valve to increased gas flow, increasing ambient pressure and decreasing gas supply pressure. It would seem reasonable that, to ensure a safe margin, an average diver should normally require no more than 80% of the maximum volume flow capability of a demand valve. Assuming the average diver breathing a dense gas mixture requires a maximum ventilation of 65 litres/min, a suitable standard for volume flow would be 80 litres/min throughout the working range of ambient and gas supply pressures.

Breathing Capacity

The maximum voluntary ventilation (MVV) is commonly accepted as a useful index of breathing capacity. Lanphier and Camporesi (Chapter 5, this volume) describe the relationship between gas density and MVV. The relationship between MVV and maximum sustained breathing capacity ($\dot{V}\mathrm{E}_{\max}$) of a diver must take the following additional points into consideration. First, the maximum ventilation that can be comfortably maintained for a prolonged period of work may be lower than that achieved during a brief MVV measurement. Secondly, the external resistance to ventilation caused by the UBA can reduce both MVV and $\dot{V}\mathrm{E}_{\max}$.

Several factors affect the resistance to ventilation of any particular UBA: the aerodynamic resistance which is the pressure differential along an airway necessary to cause the flow of gas (measured in centimetres of water per unit gas flow: cm H_2O/litre); the hydrostatic pressure imbalance (measured in cm H_2O), which is the differential water pressure existing between the hydrostatic pressure at the level of the lung centroid, $P\mathrm{LC}$, and the reference pressure of the gas supply, $P\mathrm{s}$ (the extent of positive or negative pressure breathing); the compliance which represents the elastic properties of the system measured as volume change per unit of applied pressure (ml/cm H_2O). All of these variables affect the pressure, P, required to produce a change in lung volume, dv, and together determine the work of breathing:

$$\int_{V_1}^{V_2} P \, \mathrm{d}v$$

The division of work between inspiration and expiration is affected by changes in hydrostatic pressure imbalance and compliance and this has important consequences for respiratory effort and fatigue. Thus to understand the respiratory demands of the diver, account must be taken of airway resistance, hydrostatic imbalance, compliance, inspiratory and expiratory work, and total work of breathing.

External Respiratory Work

Pressure–volume measurements of the performance of various types of breathing apparatus provide a useful indication of the respiratory loading. The resulting pressure–volume diagram reflects both external respiratory work (in terms of area under the curve) and peak pressures. It can also give some insight into the separate hydrostatic, elastic and resistive components of work. Fig. 3.9 illustrates typical pressure–volume (P–V) loops for common types of underwater breathing apparatus. The pressures are relative to the hydrostatic pressure at the mouthpiece with the diver in the upright position. The area of the P–V loop gives a measure of the respiratory work done (external resistive work).

The respiratory pressure variations of an open circuit demand regulator are almost all resistive when measured at the demand diaphragm. This results in the pressure and flow variations being in phase, as shown in Fig. 3.9b. Where assisted inhalation is incorporated, the inhalation pressure is relatively independent of flow and a flattened inspiratory loop is observed (Fig. 3.9a). Thus it can be seen that relatively small pressure variations can result in substantial respiratory work rates.

The respiratory pressure variations in a neck-seal helmet are mostly hydrostatic and elastic. This leads to helmet pressure and flow rates being virtually out of phase and results in the thin, sloping P–V loops of Fig. 3.9e,f (Reimers 1974). Consequently, large respiratory pressures can be generated by relatively little external resistive respiratory work. There is, however, an additional external elastic work component. The respiratory pressure variations in semi-closed circuit apparatus can contain significant flow-resistive, hydrostatic and elastic components. Their P–V loops and pressure–time traces can assume many forms. Two examples are illustrated in Fig. 3.9c,d.

Limits of External Respiratory Work

Silverman *et al.* (1945) have calculated that external respiratory power should not exceed 0.6% of the total body work rate. Cooper (1960a,b) calculated the external work of breathing from various respiratory equipments using pressure–volume data from exercising subjects, and also from a sine wave pump to simulate ventilation. Cooper noted that Silverman's estimate of external respiratory power was based on mean respiratory pressure and flow rates. Assuming a sinusoidal respiratory wave form and laminar flow conditions for Silverman's fixed resistors, Cooper (1960b) recalculated the recommended external respiratory power to be 0.74% of total body work rate. On the basis of his own work and that of Silverman *et al.* (1945), Cooper defined limits of external respiratory work

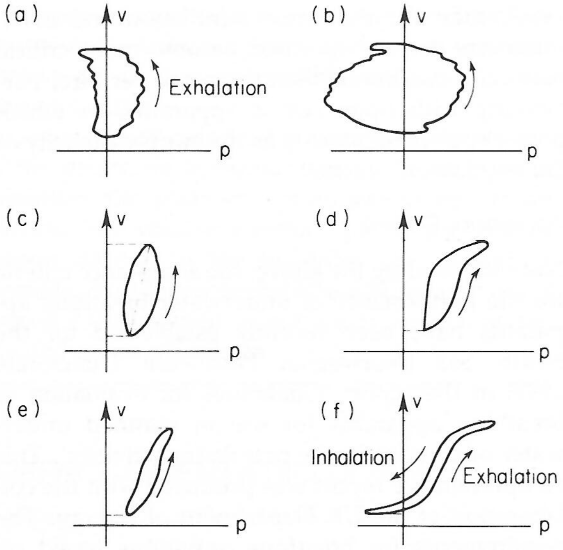

FIG. 3.9. Typical pressure–volume diagrams for underwater breathing apparatus. (Top) Open circuit demand (a) with venturi, (b) overbreathed. (Middle) Rebreathing apparatus (c) in correct trim, (d) with excessive relief pressure. (Bottom) Free-flow helmet with neck-seal (e) in correct trim, (f) overbreathed

(Fig. 3.10). The maximum tolerable workload above which serious discomfort and physiological embarrassment may occur was defined as 0.25 kg m/litre (2.45 J/litre, 1 kg m = 9.81 J), and the recommended limit of external respiratory work to ensure comfortable breathing was limited to half this value (0.125 kg m/litre).

Senneck (1962), who also reviewed the work of Hart (1943) and Silverman *et al.* (1945, 1951), proposed a non-linear standard for respiratory power (kg m/min or W), which is much more stringent than Cooper's ideal standard at low ventilations but becomes progressively more liberal at ventilations above 50 litres/min (Fig. 3.10). Senneck's (1962) curve was intended to distinguish between 'noticed' and 'unnoticed' resistances.

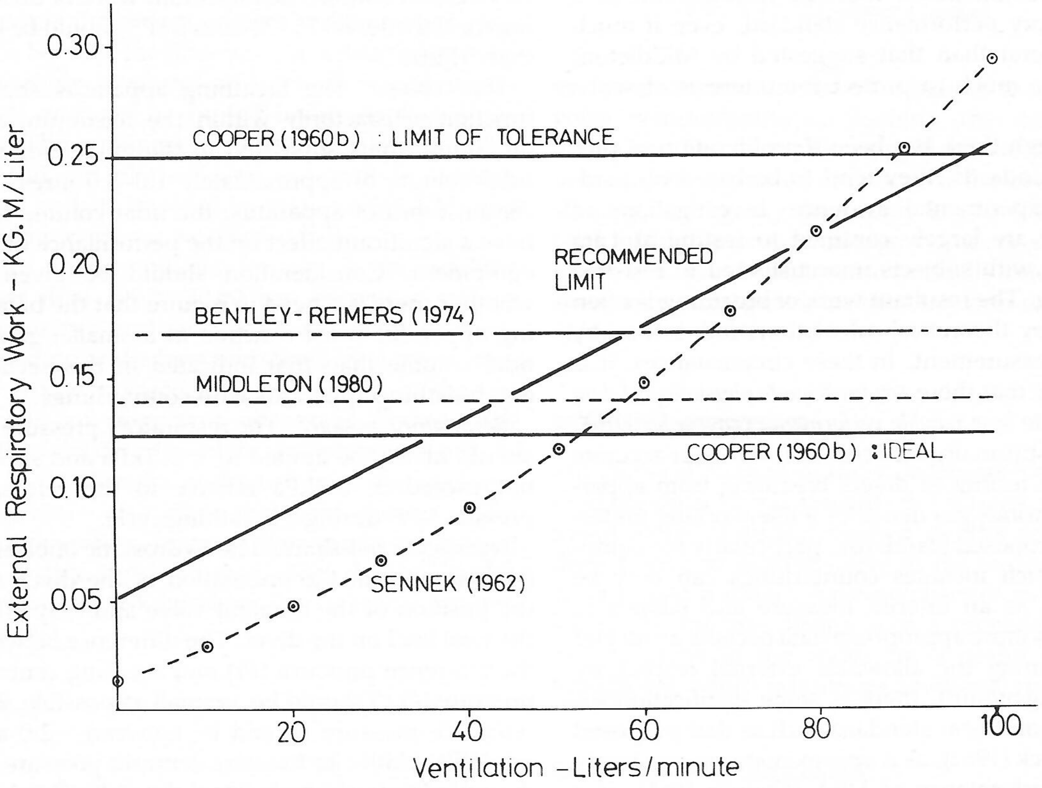

FIG. 3.10. Recommended limits of external respiratory work proposed by various investigators (kg m = 9.81 joules)

TESTING OF UNDERWATER BREATHING APPARATUS

Reimers (1974) proposed a comprehensive set of standards for the testing of underwater breathing apparatus (UBA). The external work was limited to 0.17 kg m/litre in accordance with Bentley *et al.* (1973) and equipment was to be tested to 62.5 litres/min. Middleton (1980) carried out independent investigations, but his standard appeared to be designed to meet manufacturing capabilities rather than physiological requirements. However, it may be argued that it is unrealistic to set standards which are practically unattainable. The main shortcoming of the standard is that it set no requirement beyond 40 m (132 ft)—a depth often exceeded by scuba divers—or beyond a RMV or 62.5 litres/min. Nevertheless, the tests showed a very wide distribution of performance among the regulators currently being manufactured and clearly demonstrated that the introduction of a compulsory performance standard, even if much more liberal than that suggested by Middleton, would do much to protect the interests of scuba divers.

Although there has been a proliferation of proposed standards, they tend to be based on inadequate experimental evidence. Investigations of tolerance are largely confined to testing at 1 ata (101 kPa) with subjects unaccustomed to resistive breathing. The resultant work of breathing is often derived by theoretical calculations rather than by direct measurement. In these circumstances, it is fair to say that there are *inadequate physiological data on which to base reliable performance criteria for UBA*. There is still an urgent need, therefore, for accurate tolerance testing of divers breathing from apparatus at various gas densities while working underwater. Proposed standards, particularly for equipment which includes counterlungs can only be regarded as an interim measure and subject to change as more appropriate data become available.

In defining the allowable external respiratory power (kg m/min), there is some justification for using a non-linear standard such as that proposed by Senneck (1962), as it approximates more closely to the performance of UBA (Cooper 1961). If a linear power standard is chosen (Silverman *et al.* 1945; Cooper 1960b; Bentley *et al.* 1973; Middleton 1980), then the maximum ventilation and maximum gas density specified become more critical boundary conditions than the work per litre, particularly with open circuit apparatus, in which power rises precipitously as the supply capacity of the regulator is reached.

Acceptance Criteria

Notwithstanding the above, the acceptance criteria for the performance of underwater breathing apparatus have been recently established for the North Sea (Norwegian Petroleum Directorate 1991) in the report 'Guidelines for evaluation of breathing apparatus for use in manned underwater operations in the petroleum activities'. This comprehensive report was produced with the collaboration of the UK Department of Energy. The requirements for breathing apparatus based on physiological factors include:

Respiratory minute volume. The breathing apparatus should function satisfactorily within the maximum and minimum limits stipulated by the guidelines at a respiratory minute volume (RMV) of 15–75 litres BTPS/min. The maximum work of breathing for the interval 75–90 litres BTPS should be less than 5 J/litre.

Tidal volume. The breathing apparatus should function satisfactorily within the maximum and minimum limits stipulated in the guidelines at a tidal volume of approximately 1.0–3.0 litres. For certain types of apparatus, the tidal volume may have a significant effect on the performance of the equipment. Consideration should be given to whether there is a need to require that the breathing apparatus must function at a smaller/greater tidal volume than that indicated in this section, e.g. breathing apparatus with counterlungs.

Respiratory pressure. The respiratory pressure (P) should ideally be limited to ± 1.5 kPa and should not exceed ± 2.5 kPa relative to the reference pressure ($P\mathrm{r}$) during a breathing cycle.

Hydrostatic imbalance. The hydrostatic imbalance (HI) varies with the orientation of the diver and the position of the demand valve and may affect the total load on the diver. The difference between the reference pressure ($P\mathrm{r}$) and the lung centroid pressure (P_{LC}) should be as small as possible. The reference pressure should be between -2.0 and $+1.0$ kPa relative to the lung centroid pressure, or if applicable to the suprasternal notch. This limit applies whether the diver is standing in an upright position or is lying face down.

Maximum over-under-pressure. In the event of equipment failure, the over-under-pressure should be as low as possible and should not exceed ± 6.0 kPa.

Carbon dioxide content of inspired gas. The design of the breathing apparatus should be such as to minimize the inspired concentration of carbon dioxide. The volume weighted partial pressure of carbon dioxide in the breathing gas should, if possible, be limited to 1.0 kPa and should never exceed 2.0 kPa when tested under conditions stipulated in the guidelines.

SURFACE-ORIENTATED DIVING

Water Access and Egress

Facilities for the diver to enter and exit the water are of paramount importance to the surface-orientated diver and, not infrequently, the weakest spot in the overall safety of a diving operation. This is because the diver may be subjected to overwhelmingly powerful and turbulent water conditions and can be hurled bodily against structures. The arrangements for getting divers safely into and out of the water can include ladders, special baskets lowered by cranes (Fig. 3.11) and handling frames or wet (open) bells.

Since the umbilicals for air divers working deeper than 100 ft (30 m) can become a serious encumbrance and even a hazard in themselves, the tending of the long umbilicals from the surface can become impracticable. In such cases, the wet bell has an important advantage because the length of the diver's umbilical need then be only as long as the distance of the bell from the worksite. This feature also gives the diver greater safety when operating from a dynamically-positioned (DP) surface support vessel, since the umbilical is not placed at risk by being drawn into a rotating thruster.

Wet Bell

This consists of a work stage fitted with a space at head-level which can be filled with air into which a diver can rise until his head and chest are clear of the water (Fig. 3.12). This improves comfort and the diver can even remove his helmet to improve voice communications, flushing the cavity as necessary. The normal air supply for the divers is provided by a surface umbilical to the bell and a standby, emergency air supply is provided by a bank of high-pressure storage cylinders attached to the bell. Wet bells are also normally fitted with seats, air control panel, facilities for diver umbilical storage and tools.

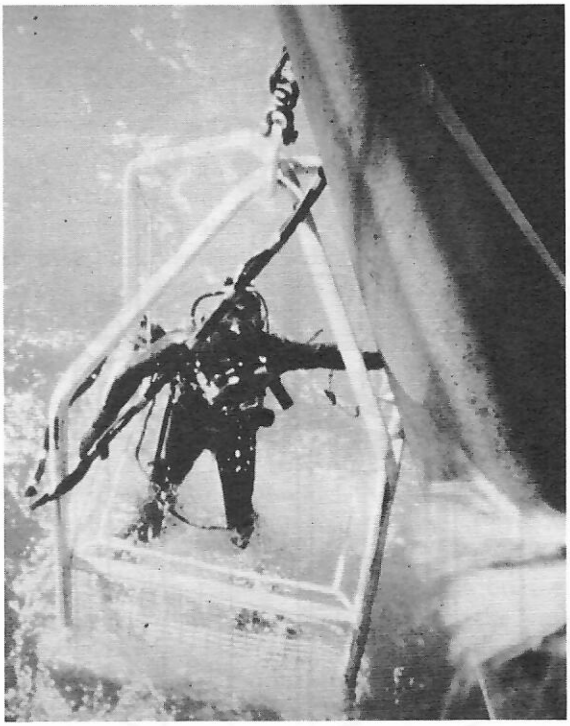

FIG. 3.11. Air-diver's basket

In-Water Decompression

The classical method of diver decompression is to raise the diver slowly towards the surface, making timed stops at predetermined depths until the diver is free to ascend safely to the surface. The diver would normally have no changes in breathing gas or mixture during such a procedure, but oxygen stops in the water are a useful option, though one which introduces additional risks.

Depth Monitoring and Control

This is a critical aspect of in-water decompression. Monitoring is normally achieved using a 'pneumo-

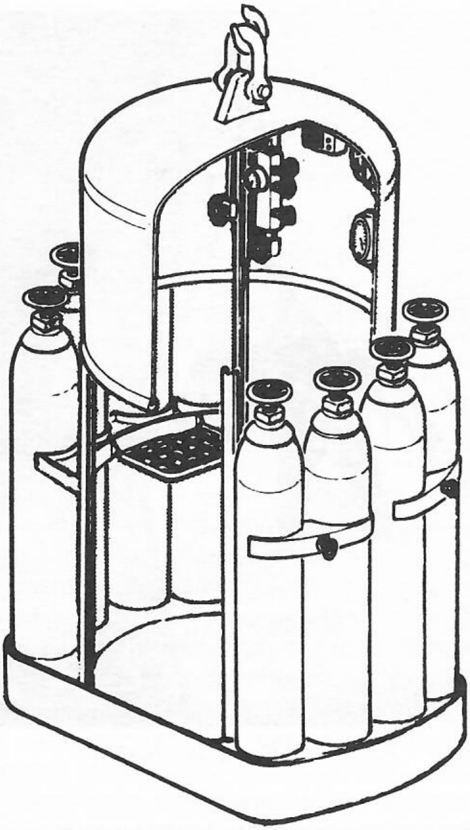

FIG. 3.12. Wet ('open') bell. (Reproduced with permission from Sisman, 1982)

fathometer'. This is a simple, reliable and accurate method whereby a source of compressed air is piped down a small-bore, flexible tube which has an open end at the diver. An accurate pressure gauge graduated in equivalent depths is connected to the line at the surface. The attendant or supervisor can measure the diver's depth simply by admitting compressed air into the tube until the pressure stops rising. At this point, the air has been forced down to the end of the tube and is escaping freely at the diver. The use of a pressure-transducer carried by the diver and on-line visual display unit (VDU) display of the ongoing dive profile to the dive supervisor is now a requirement of some compressed-air diving contracts. Besides the obvious advantages of demonstrating the precise descent rates (perhaps when the diver has ear-clearing difficulties) and ascent rates, which are critical to safe decompression, the system encourages compliance with the agreed decompression tables. It also provides a permanent computer-based record, which can be used to meet contractural and administrative needs and for retrospective analysis of decompression risk factors. The control of diver depth is usually achieved by raising/lowering the diver within a basket or wet bell.

Surface Decompression

To avoid protracted periods decompressing in the water, a surface decompression procedure allows the diver at a selected point during the in-water decompression to interrupt the normal procedure and make a rapid ascent to the surface. He then enters a DCC and is immediately recompressed to a depth slightly greater than that which he had previously left. Extreme care is required to ensure that the interval of time between leaving the last in-water stop and arriving back at the predetermined pressure in the DCC is kept as short as possible and never longer than 5 min. For this reason, it is essential that the diver has rapid access to the DCC on surfacing and that the location of the DCC has taken good account of this. This technique was designed to eliminate the need for in-water stops in circumstances where these might be particularly hazardous, but also makes it possible to undertake surface-orientated dives of longer duration than would be impractical if restricted to in-water decompression.

Deck Compression Chamber (DCC)

For surface decompression purposes, the DCC is usually a small, two-compartment chamber that can accommodate two men. Facilities for oro-nasal administration of oxygen or oxygen-rich mixtures are provided for routine or therapeutic decompression procedures. An oxygen dump facility is normally provided to remove exhaled gas from the DCC or, in its absence, the chamber gas must be analysed and flushed periodically to prevent too high a partial pressure of oxygen developing within the DCC with its associated fire risk.

Mini-Bell

In order to extend with safety the limited bottom time associated with surface-orientated diving, including surface decompression, still further a bell system has been developed which represents a compromise between wet bell and closed bell procedures (Fig. 3.13). In this arrangement, the bell and divers are lowered to their working depth and raised to their initial decompression stop levels as in normal wet bell diving with in-water decompression. Then, at a predetermined depth, the divers climb completely into the bell and close a pressure-sealing door. They are raised to the surface where the bell is mated to a DCC. The divers transfer under pressure into the DCC and carry out the final (and usually lengthy) stages of their decompression in relative comfort. As the divers are at all times within the depth limit of the surface-orientated standby diver, the mini-bell technique allows for both divers to be outside the bell at the same time as they would during a wet bell dive. They would not be able to do this from a closed bell in a deep mixed gas dive where there must always be one diver in the bell performing bellman duties.

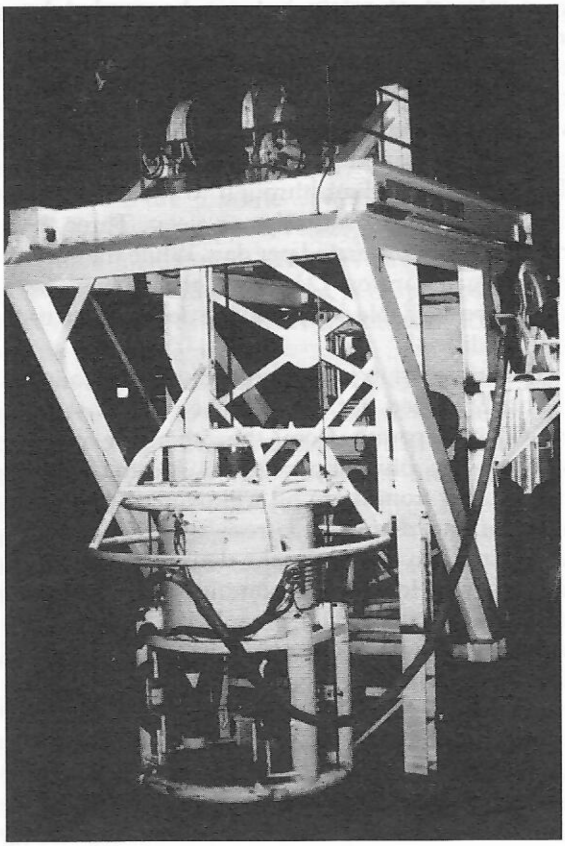

FIG. 3.13. A mini-bell diving system. (Courtesy of Ocean Technical Services Ltd)

MIXED GAS DIVING

Mixed gas diving is synonymous with bell diving and is the system used for diving beyond 165 ft (50 m), but may also be used at shallower depths. It may be conveniently subdivided into two basic types of operation: bounce diving and saturation diving.

Bounce Diving Procedures

A bounce dive is one in which the divers' exposure to the bottom pressure is usually limited to about 30–60 min in order to minimize their subsequent decompression period. To achieve this brief exposure, the diving bell is first lowered to the working depth while maintaining internal atmospheric pressure. An outer door on the bell trunking is kept closed by the higher external pressure. When the divers are fully dressed and prepared to go to work, the internal pressure is raised rapidly by the divers until it reaches external pressure at which point the outer door falls open. Great care is taken to keep the dive duration to a minimum as each minute of exposure introduces a disproportionately lengthy decompression penalty. If the task requires more time than the maximum safe dive duration permitted for that depth, then it must be left unfinished, or the schedule extended into an 'emergency', extended bottom time or even converted into a saturation dive if the task so warrants.

As soon as the diver has returned to the bell, the inner door is closed and the bell immediately raised. On confirmation that a seal has been obtained between the decreasing external pressure and the higher internal pressure, the divers immediately commence their own decompression. With some decompression tables, a few in-water stops may be conducted with the bottom door open until the duration of later stops is sufficient to close the bottom door and commence the bell recovery. Once at the surface, the bell is mated to the DCC, which is at a shallower decompression stop pressure than that which the divers in the bell are approaching. When the bell has been secured to the DCC trunking, the outside crew equalize the pressure between the DCC and the trunking, which allows the DCC/trunking door to open freely. As the bell pressure is allowed to fall, it meets the same pressure as the trunking and DCC, at which point the divers are able to open the inner door of the bell and climb through to the DCC. This procedure is termed 'transfer under pressure' (TUP). Refreshments, dry clothes and any other requisites for the divers can be passed in to them via a small lock. The decompression time spent in the DCC will depend on the depth and duration of their bell dive and usually ranges from 2 to 12 h. The whole operation requires strict timing and control. Inaccurate timing causes a high incidence of decompression illness, which may be of a serious variety.

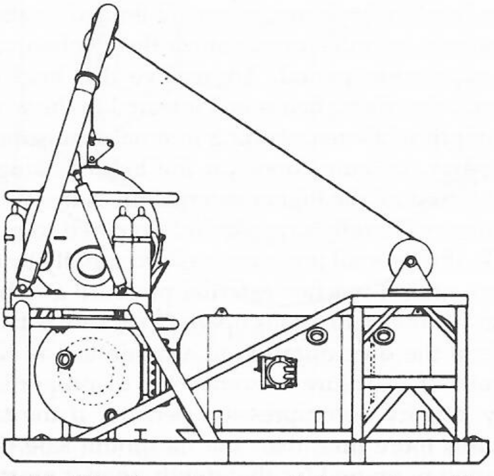

Fig. 3.14. Mixed gas, bounce diving system. (Reproduced with permission from Sisman, 1982)

Saturation Diving Procedures

For some tasks the need for longer dive durations and more working divers necessitates the use of saturation techniques. Saturation diving systems are much larger than bounce diving systems because up to some 16 divers will be maintained under pressure and for as long as 4 weeks. Such systems can operate 24 h a day and, consequently, a large surface support crew of 10–35 men working on a shift basis is also required.

Diving Procedures

A saturation dive is initiated when the divers enter the DCC. They are pressurized to a 'storage' (or 'living') depth at which the DCCs are maintained for the duration of the bottom time. The storage depth is arranged to be slightly shallower than the planned working depth. When diving operations are scheduled to commence, two or three divers per working shift commute to work using a large diving bell. As the diving bell descends past the pressure of the storage depth, the inner door is unseated by the increasing external pressure and fully opened by the divers within. Once at working depth, the divers allow sufficient water into the bell to ensure that they can exit and enter with the minimum of effort. On large construction sites, it is occasionally expedient to maintain separate teams of divers in separate DCCs at different storage depths to provide the capability to work simultaneously at different depths using a two-bell system. This is also possible sequentially in a single-bell system. The bell may be at a working depth for periods approaching 8 h with any one diver making a lock-out of up to 4 h at a time. Times in excess of these are not regarded as in the best interest of safety but can be needed by a welder making a root pass. When the bell returns to the surface, it is mated with a special DCC, the transfer chamber. This DCC is a 'wet' facility in which the divers generally have enough room to get undressed and cleaned up and use a toilet. They may then climb through to their respective living chamber to eat, relax or sleep. Three 'bell-runs' may be conducted per day. While the surface crew usually are on 12 h shifts, three supervisors should be available so one can be dedicated to each shift of divers.

The supervision of the actual diving operation is normally carried out from a 'dive control' station, which is separate from the 'chamber control' station. The dive supervisor is located at dive control and from there he will oversee the separation of the diving bell from the DCC and its launching into the sea by the dedicated bell handling system. He will be in continuous voice contact with the divers inside the bell via a helium unscrambler which improves the intelligibility of the divers' voices. All voice communications between the bell and dive control are continuously recorded on magnetic tape to provide a retrospective investigative capability in the unlikely event of an accident. The supervisor is also provided with a TV monitor showing the interior of the bell and its occupants. He can control the descent and ascent of the bell and manages all aspects of the diving

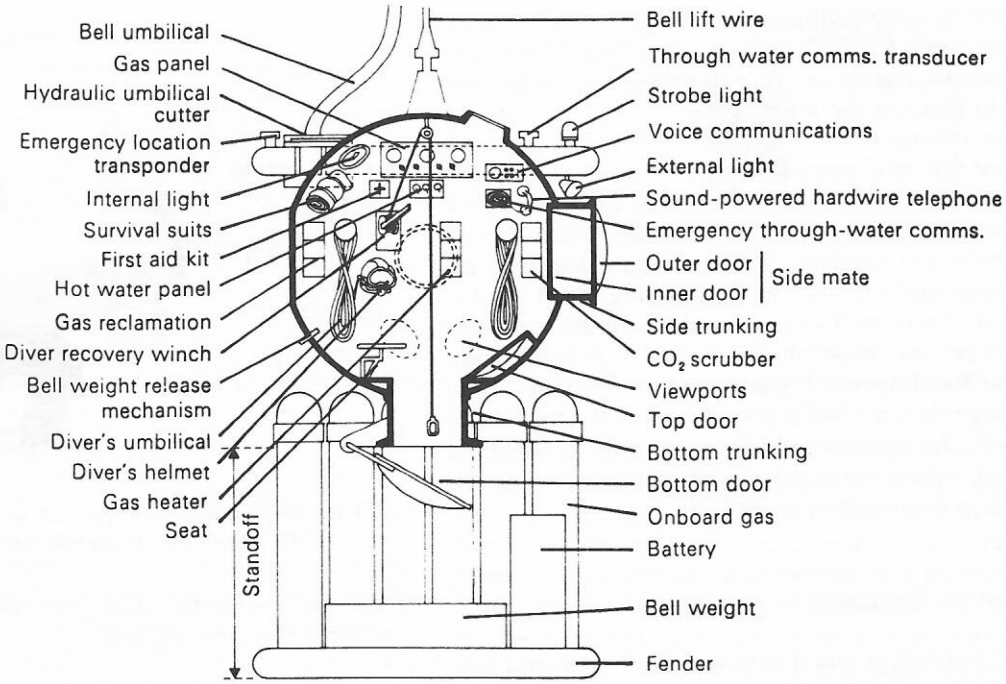

FIG. 3.15. Mixed gas, diving bell basic layout. (Reproduced with permission from Sisman, 1982)

operation including the work to be carried out. The diving supervisor also has voice communications with the 'marine control', such as the bridge of a diving support vessel, and co-ordinates any ship's manoeuvres with the divers. He also has voice communications and perhaps closed circuit TV coverage of any other critical deck activities such as crane operations.

When compared to a bounce dive, the absence of the constraint to complete the task within about 30 min is a significant advantage. By taking the potential for undue haste out of the procedure, a significant increase in safety is achieved. The saturation decompression procedure is also far simpler, using a slow-bleed of near-constant speed throughout.

Diving Bell Equipment

The diving bell and equipment for a bounce dive are essentially the same as for a saturation dive, the only differences being that saturation bells are usually larger and more suitable for longer duration bell-runs, possibly for three men. Figure 3.15 illustrates most of the major components of a typical bell.

Due in part to the introduction of return line systems, which require an additional, wide bore gas hose to be incorporated in the divers' umbilicals, and the requirement for an emergency thermal insulation garment for each diver, each of which is bulky even when compressed and packed, the remaining space inside a diving bell has diminished drastically. The problem may be so bad that in many cases one diver's umbilical has to be stored outside the diving bell so that the first task of the first diver is to bring it in to enable the second diver to get dressed.

Unconscious Diver Recovery Procedures

Should a diver become unconscious during a bell lock-out, the supervisor is likely to discover the problem quickly since he is listening to the diver continuously as well as to the sound of his breathing. Also, bell diving operations often have a small, remotely operated, unmanned vehicle (ROV) mounted with a TV camera ('the flying eyeball') with which the supervisor can monitor continuously the divers' activity.

In response, either the bellman can don an emergency breathing mask and go to his rescue or the second diver (if there is one) can go to the unconscious diver's help. If necessary, the rescuer will turn on the unconscious diver's free-flow to ensure any water in the helmet is driven out and that the diver receives an unrestricted gas supply. The unconscious diver is brought back to the bell trunking and a diver recovery hook, which is routinely left hanging in the trunking for such an eventuality, is secured to a lifting point on his body harness. The rescuer then climbs back into the bell and hoists the unconscious diver up using the hand-operated winch and assisted by buoyancy when the bell is partially flooded. Once in the bell, the unconscious diver's helmet is removed and, when necessary, cardiopulmonary resuscitation is immediately applied.

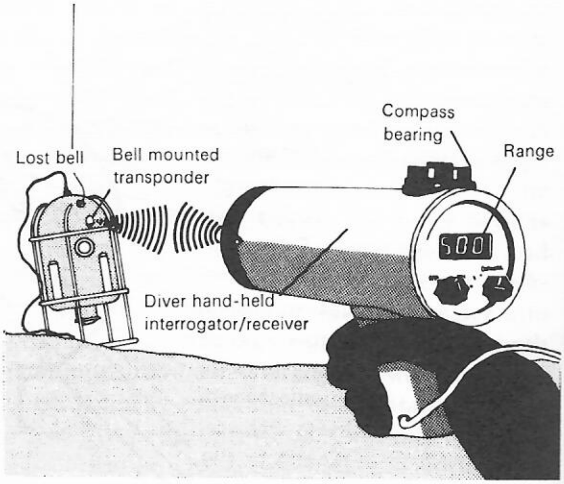

FIG. 3.16. Emergency bell relocation. (Reproduced with permission from Sisman, 1982)

Lost Bell Procedures

A 'lost bell' is a bell with which all cable and umbilical connections have been lost. In such an eventuality, the occupants close the inner door and obtain a seal by adding a small amount of 'deep mix' gas from the onboard supply. They then don their emergency thermal garments and initiate the oxygen maintenance supply from the onboard emergency oxygen cylinder. They also breathe via emergency soda lime filters to absorb CO_2 and, incidentally, heat the respiratory gas. They have an emergency battery on board to power lighting and any other emergency services, such as the through-water telephone and the emergency location transponder. They also have the facilities to disconnect the main lift cable, to sever the bell umbilical, ditch the bell weight and achieve positive buoyancy, all from within the bell, when appropriate. To assist the relocation of the bell by a rescuing bell diver, the bell is also equipped with an external strobe light and a 'pinger' transponder. This particular device responds to interrogating acoustic signals from a diver-held pinger and transmits an answering signal which is used to obtain a bearing on the lost bell (Figure 3.16). The rescuing diver or vessel can then obtain a direction in which to travel to find the lost bell. When the rescuing bell arrives alongside, depending on the nature of the accident, the divers can opt to carry out a through-water, bell-to-bell transfer. This is made possible by a rescuing diver carrying a spare helmet and umbilical from his bell to the lost bell which each stranded diver can use in turn to transfer to the rescuing bell.

Life-Support Procedures

A specialist crew of life-support technicians based at a chamber control station attend to all the life-support requirements of the team of divers under pressure. Carbon dioxide filters require periodic replenishment, oxygen is added as required and gas analysis is carried out continuously to ensure that the correct levels are maintained within their narrow margins. Gas management requires the careful analysis, control and logging of gas mixtures, stocks and any transfer from one bank to another. Temperature and humidity levels are kept within comfort ranges. Meals are locked in regularly and a careful watch kept to prevent dangerous materials being inadvertently admitted into the chamber, such as poisonous or fire hazard materials. The provision of hot and cold running water and the safe flushing of toilets all require attention. Closed circuit TV cameras on all the DCCs provide continuous visual supervision. In the rare event of any decompression illness being reported, the technicians are responsible for managing the administration of any special gas mixtures. They have voice communication with all the DCCs, via helium unscramblers, and there is usually provision of radio and tape-cassette players piped to each bunk for the entertainment of the divers. A detailed description of life-support activities is given in Sisman (1982).

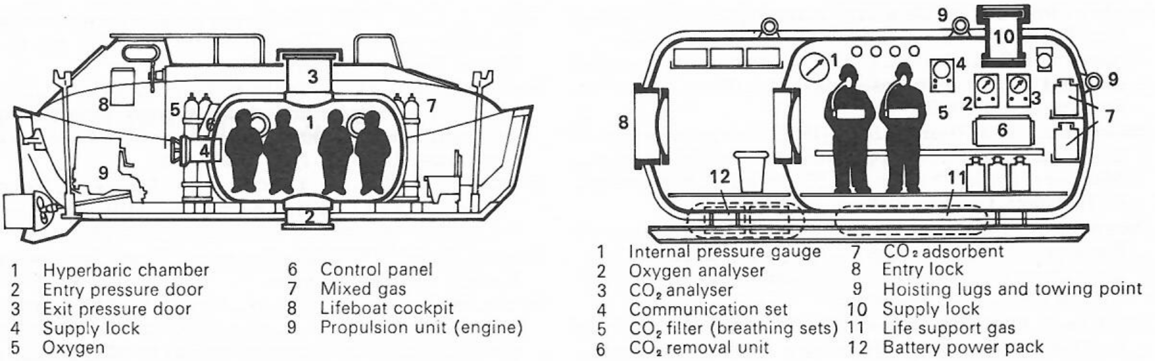

FIG. 3.17. (a) Hyperbaric lifeboat and (b) rescue chamber. (Reproduced with permission from Sisman, 1982)

Medical Evacuation Procedures

In the case of a diver suffering a serious injury or suddenly being stricken with some major illness that requires immediate hospitalization, a 'hyperbaric ambulance' service is available in the North Sea. Referred to as the 'fly-away TUP system', it consists of a titanium, seven-man, single-lock, helicopter transportable chamber and a titanium, one-man, portable chamber. The one-man chamber is used to transfer the patient from the main DCC on the surface support vessel to the seven-man chamber waiting in a helicopter on the helideck. Once transferred into the seven-man chamber, where an attendant and a doctor provide interim treatment, the helicopter delivers the system to an onshore hyperbaric medical facility where the seven-man chamber can be mated directly to a large chamber fitted out with full surgical facilities. However, in more than 10 years it has not yet been used in this emergency role (see Chapter 10, this volume).

Emergency Evacuation Procedures

In the event of a major catastrophe requiring the evacuation of an entire team of divers under pressure, two basic types of facilities are available: hyperbaric lifeboats and hyperbaric rescue chambers. Access to the rescue units are by means of a length of trunking reaching from the DCC to the unit on deck. Once inside the rescue unit, the system is disconnected as in a normal TUP operation and the rescue unit is freed for launching. The rescue units are all capable of functioning independently and can maintain adequate life-support facilities for the entire duration of the decompression, though the preference is to mate the chamber with another diving system to carry out the decompression. The hyperbaric lifeboat consists of a compression chamber installed in an otherwise conventional lifeboat, while the rescue chamber is a simpler arrangement of a chamber fitted out to float free. A disadvantage of the rescue chamber is that there is no outside crew to supervise the decompression if it is launched into the sea. In any case, the preferred option is to postpone the decompression until after a TUP with another diver system. The preferred arrangement is to lower it on to the deck of a rescue vessel where it can at least receive outside attention and perhaps be taken to another diving system for TUP. In both systems, seats with restraining harnesses are provided, sea-sickness is inevitable and maintenance of thermal balance is difficult, with a tendency to hyperthermia rather than hypothermia if there are many divers in the system.

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