10

Life-support Systems and Commercial Diving Equipment

The subject of life support under conditions of pressure involves the widest range of scientific and technical skills with as much emphasis on aspects of human engineering as on space technology. The obligations and social responsibilities that are implied or set out in the *Safety and Health Regulations for Men and Women at Work in Industry* are no less applicable to divers. The primary considerations for a life support system are that it should be capable of the following:

1. Ensuring an oxygen partial pressure (Po_2) within defined limits
2. Restricting carbon dioxide to defined limits
3. Controlling temperature and humidity within a narrow range
4. Removing toxic substances from the breathing gases such as CO, methane, oil, dusts and microbes

Secondary considerations, not necessarily of secondary importance because in combination they can be damaging, are:

1. Supply and removal of domestic water
2. Supply of food and drink
3. Sanitary facilities
4. Illumination and noise levels
5. General living conditions

Table 10.1 Design factors for integrated life-support systems

Individual life support	*Collective life-support*	
	Primary	Secondary
Diving gear Breathing equipment Absorbent units (scrubbers) Emergency breathing equipment	Oxygen Carbon dioxide removal Temperature and humidity control Removal of toxic substances	Water supply Food supply Sanitary facilities Accommodation Communication Illumination and noise level Entertainment Firefighting

6. Communications
7. Entertainment
8. Fire hazard

The study of individual primary life support systems where they are applied to breathing systems in diving equipment is dealt with later in this chapter dealing with commercial diving equipment. Here we examine how collective life support systems, as installed in decompression chambers, deep diving research facilities, submersibles fitted for diver lock-out and habitats, need to take account of these primary considerations.

Primary Life-support Factors

Oxygen Partial Pressure ($P\text{O}_2$)

The supply of the oxygen at the correct partial pressure is fundamental to all life-support systems. Most aspects of diving theory related to physiology and decompression depend upon the partial pressure of the various gases and in particular oxygen. Dalton's law of partial pressure states that the total pressure of a gas mixture is the sum of the partial pressures of all the gases in the mixture, assuming that temperatures and volumes remain constant. Therefore at sea level where pressure is 1 bar and the air is assumed to contain only nitrogen and oxygen in a 79 : 21 ratio, the partial pressure of oxygen is 0.21 bar and that of nitrogen 0.79 bar which corresponds to 21% oxygen and 79% nitrogen in the air. Medical studies have shown that the human body can accept a reduction in oxygen content to 14–15%, corresponding to 0.14–0.15 bar and an absolute minimum of about 11%. This corresponds to a partial pressure of oxygen of 0.11 bar on the surface and will cause oxygen deficiency symptoms known as hypoxia. These symptoms are particularly dangerous because, unlike other manifestations of distress which can be experienced by divers, the symptoms of lack of oxygen are rarely recognized by the affected person himself. He has difficulty in standing upright and walking properly, suffers loss of coordination and his lips go blue resulting in rapid unconsciousness. There are no early symptoms and the onset is swift and dangerous.

An increase in oxygen partial pressure above certain levels under pressure can be equally dangerous, leading to oxygen poisoning. Although pure oxygen can be breathed on the surface and at shallow depths, any further increase of the partial pressure of oxygen above certain levels may cause irreversible changes in the alveoli. A general concensus is that oxygen partial pressures of above 0.6 bar for more than 12 hours will cause irritation of the lungs and therefore there is a reasonable assumption that partial pressure of between 0.2 bar and 0.5 bar can be safely used for within reasonably unlimited periods under pressure. In general, oxygen partial pressures should be kept as low as

Table 10.2 Oxygen consumption related to working performance

Work	*Oxygen consumption* (litres/min	*Breath volume* (litres/min)	*Power* (W)
Rest			
lying	0.25	6	—
sitting	0.30	7	—
standing	0.40	9	—
Light work			
walking slowly on solid ground*	0.60	13	25
walking at 3.2 km/hour	0.70	16	30
swimming slowly at 0.9 km/hour*	0.80	18	40
Medium work			
walking on soft ground*	1.1	23	70
walking at 6.5 km/hour	1.2	27	80
swimming at 1.6 km/hour*	1.4	30	95
fast walking on solid ground*	1.5	34	105
Hard work			
swimming at 1.85 km/hour*	1.8	40	130
fast walking on soft ground*	1.8	40	130
bicycling at 21 km/hour	1.85	45	140
running at 13 km/hour	2	50	145
Very hard work			
swimming at 2.2 km/hour*	2.5	60	185
running at 15 km/hour	2.6	65	200
running up stairs (100 steps/min)	3.2	80	250
running up hill	4	95	290

*Under water.

possible, even though this may extend the length of the decompression, since it avoids the danger of oxygen poisoning.

Opinion is divided as to what are the reasonable permissible limits of higher oxygen content for shorter exposures in the shallower ranges during decompression. Although 100% oxygen can be breathed to depths of 18 m (equivalent to an oxygen partial pressure of 2.8 bar) this partial pressure should not be exceeded and administered only for short exposures. This is variable as it can be influenced by the following:

1. The duration of exposure
2. The work load
3. The carbon dioxide content of the inhaled gas
4. The physical condition of the diver

Unlike hypoxia, or lack of oxygen, the symptoms of oxygen poisoning usually give adequate warning and the trained diver should immediately recognize them for what they are. Twitching of the

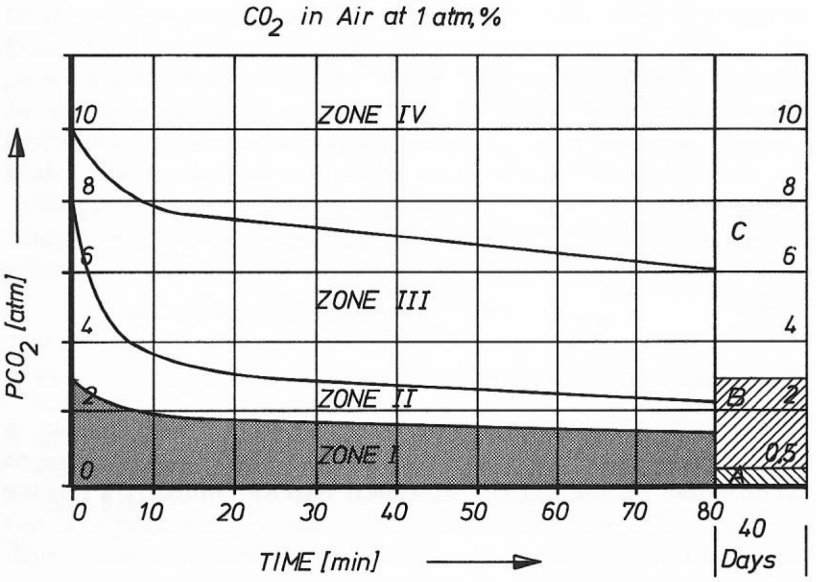


Fig. 10.1. Physiological effects of carbon dioxide in relation to quantity and exposure time.

facial muscles and lips, together with nausea, dizziness and tunnel vision, changes in hearing aptitude, the sensation of ringing in the ears and breathing problems are singly or together the early warning signs of oxygen poisoning. A diver may become confused, distressed and uncoordinated before the final manifestation of severe convulsions with ultimate unconsciousness. The uncontrolled movements of the body during the convulsions can increase the risk to the diver, particularly below water but also in a chamber. The interior design of the chamber should take this into account by providing fittings without sharp cutting edges or projections which might cause injuries to a diver in a convulsive fit.

Carbon Dioxide Partial Pressure ($P\text{co}_2$)

The air that we breathe contains about 0.03% carbon dioxide. This is equivalent to a partial pressure of about 0.0003 bar and it would be desirable if this low value could be maintained throughout in breathing gases under pressure within the life-support systems. Technically this is possible, but the extent of technical effort needed would not be justified, as the human body can fortunately tolerate higher carbon dioxide pressures. Fig. 10.1 shows the permissible carbon dioxide levels by partial pressure. Zones I and II are areas where carbon dioxide partial pressures are permissible, as shown, for short- and long-term exposures up to 40 days. This illustrates that carbon dioxide partial pressure of between 0.005 and 0.03 bar are acceptable in compression chamber atmospheres. This source, published in the NOAA diving manual, represents one viewpoint but others consider the limit of 0.03 bar as being too high and restrict the upper limit to 0.005 bar, but this is perhaps too cautious. For the design of equipment a maximum permissible carbon dioxide partial pressure is 0.015 bar. The effects on the respiratory system of increasing the partial pressure show in an increased breathing rate and at 0.05 bar there is a very pronounced shortness of breath which leads to muscular spasms. If the concentration rises further the body stiffens and the subject becomes unconscious at 0.1 to 0.15 bar partial pressure. Carbon dioxide poisoning is brought on more quickly when combined with too low an oxygen content (hypoxia). Fortunately the recovery from carbon dioxide poisoning is quick after the removal of excess gas and flushing with clean breathing gases.

Temperature and Humidity

In normal ambient conditions we generally accept that a comfortable temperature range is between 18 and 22°C depending to some extent on the degree of physical activity. Similarly a relative humidity of between 50 and 65% is pleasant. These criteria do not change under pressure as long as the composition of air is maintained. In other words the temperature and humidity within their ranges remain the same even at pressures of 5–6 bar.

There is, however, a fundamental change when helium is substituted for nitrogen as the inert gas to overcome nitrogen narcosis and as a lighter gas for easier breathing and quicker decompression. The thermal conductivity of helium is almost seven times as great as that of nitrogen and therefore heat is drawn out of the body much more rapidly. To prevent this dangerous heat loss from the body the oxy-helium breathing gas and chamber gas need to be heated to a higher temperature than for air. Where the helium mixture is high, around 95%, the gases have to be heated to between 30 and 36°C, temperatures that would normally be uncomfortably warm. The same humidity levels of between 50 to 65% are normal.

Under normal atmospheric conditions the body gives off a certain amount of metabolic heat as a normal function. The maintenance of set temperatures will help to achieve thermal equilibrium, making up the metabolic heat loss and keeping the internal body core temperature within safe limits. An excessive rise in core temperature will result in hyperthermia or conversely a reduction in hypothermia. Variations can and are tolerated by the human body but the flexibility of the body, as in most bodily functions, is finite and dependent on the degree of variation from a norm. A reasonable norm for a core temperature is 37°C with the breathing gas in the chamber at 35°C. In diving bells the chamber gas ideally is at 30°C. If these are accepted upper limits it would be impossible to drive the core temperature upwards.

The technical solution, whether using chemical, hot water or electricity systems, should be designed so that the transfer medium does not exceed set limits on the system. On hot water systems as supplied to divers in the water not only temperature but also the flow needs monitoring. Safety systems should be fitted to all systems differing in the type of heating system to which they are applied.

Electrical suits should have a failure mode so that the diver is not exposed to shock or high-temperature hazard.

A system as important as heating, whether supplying heat to a chamber or to a diver in the water, must have a separate back-up, particularly with regard to diver heating systems outside the bell. The back-up systems must be ready to start at an instant's notice.

When designing the dehumidification system for compression chambers the various sources of moisture need to be considered. They are as follows:

1. Body evaporation and respiratory exhalation
2. Precipitation of moisture from CO_2 chemical reaction
3. Evaporation from domestic sanitary and water supplies, particularly from use of showers
4. Increase of humidity from external access to water interface compartments, i.e. divers transfering from bell to compression chambers

The first two causes of humidity, the human body and the chemistry of carbon dioxide absorbents, can be accurately calculated. Only operating experience and the type of diving cycle will provide the extent of additional dehumidification resources needed to control the relative humidity within acceptable limits.

Removal of Toxic Contaminants

Apart from the limits on breathing oxygen, carbon dioxide and the other aspects of temperature and humidity control there are other lesser but important excess substances that need to be considered in some way or other. Table 10.3 lists the contaminants and the exposure limits. Under saturation conditions over long periods the removal of H_2S, hydrogen, hydrocarbons, ammonia, sulphur dioxide, carbon monoxide, methane, oil vapours, small substances, dusts and microbes may become necessary. Carbon monoxide is produced by the body at an average rate of 0.3–1.0 ml/hour. On closed-circuit life-support systems these accumulations, at first negligible, will increase and eventually need to be removed. In addition to CO other contaminants may be produced from internal paint surfaces and instrumentation, such as glue, or may originate in a faulty compressor. For long periods under pressure a limit of 50 mg/m^3 is considered reasonable, this being equal to a volume percentage of 0.0050 (vol%) (DIN 3188). The toxic effect on the human body of carbon monoxide is directly related to the percentage of the gas in the total mixture and not the partial pressure, whilst the toxicity of oxygen and carbon dioxide is related to the partial pressure of the gases in the mixture.

An acceptable carbon monoxide limit, by American standards, is 20 ppm.

The effects of other extraneous toxic substances are known for normal atmospheric conditions and exposure times have been laid down so as not to exceed safe limits. In the absence of generally

Table 10.3. Typical contaminant exposure limits (at atmospheric pressure)

Substance	*8-hour weighted average limit*	*Ceiling concentration*	*Comments*
Ammonia	50 ppm	—	—
Carbon dioxide	5000 ppm	—	—
Carbon monoxide	50 ppm	—	—
Freon-12	1000 ppm	—	—
Hydrogen chloride	—	5 ppm	—
Hydrogen fluoride	3 ppm	5 ppm	10 ppm for max 30 min
Mercury	—	0.1 mg/m^3	—
Nitric oxide	25 ppm	—	—
Nitrogen dioxide	5 ppm	—	—
Oil mist	5 mg/m^3	—	—
Ozone	0.1 ppm	—	—
Phosgene	0.1 ppm	—	Freon decomposition
Stibene	0.1 ppm	—	Lead-acid battery
Sulphur dioxide	5 ppm	—	—

From Bishop, (1973) *The Underwater Handbook*. New York: Plenum Press.

acceptable limits on all these toxic gases whilst under pressure in hyperbaric conditions, the values listed in Table 10.3 represent the medical limits for an eight-hour day and a 40-hour week. They are based on a total working life of 40 years and are considered safe with no harmful consequences in later life.

Secondary Life-support Factors

Water Supply (Fresh Water)

The requirement for fresh water for drinking, washing and for sanitation is dependent on the type of diving and an essential part of the secondary life-support system. For relatively short periods of pressurization associated with bounce or intervention diving there is no need for a permanent supply of water. Small quantities for drinking can be passed through the supply lock which should be a standard part of any compression chamber. For long periods under pressure, where divers are in saturation, a permanent running supply of fresh water is essential for drinking, washing and sanitary purposes. The normal requirement per person is 2–3 litres of pure water for drinking, 20 litres for washing and 15 litres for sanitary systems. The water needs to be supplied internally at 5–6 bar above the internal pressure of the chamber.

Food and Drink

For short duration under pressure the need for food and drink can be met with light refreshments and calorie requirements are met most conveniently by hot soups and drinks, passed through the supply locks normally fitted to surface compression chambers. Diving bells are not normally designed to have supply locks as the divers are transferred under pressure to deck compression chambers. However, detachable supply locks can be fitted to diving bells in the event of a transfer under pressure not being feasible and these small locks can be fitted over a porthole or observation window, enabling the divers to remove the window and pass small amounts of food and water through the opening.

For long exposures and under saturation conditions careful diet control is vital. Because saturation diving demands a large number of personnel under pressure to carry out work continuously under a shift system, the amount of food that needs to be passed into the hyperbaric chambers can be considerable. The diameter and volume of a supply lock is therefore an important design factor in the construction of a chamber. The selection and preparation of food needs to be laid down by dieticians, taking into account the amount of work carried out, the probable energy expended and other factors, not least that helium-enriched gases allow a significantly greater heat loss than breathing air, thus necessitating a compensating increase in daily calories. The calorie requirement is assessed to be 4000 to 6000 calories per day, considerably in excess of the human body requirement at atmospheric pressure. The increased diet needs to contain the correct proportions of proteins, carbohydrates, fat, minerals and vitamins and the selection of the type of food is largely determined by the effect of pressure on the food matter and changes that occur in taste and smell. Although feeding is complicated the needs of the human body for liquids are relatively unchanged at about 2–3 litres per day. The type of liquid is limited to some extent since alcoholic or carbohydrate-based liquids are unsuitable whilst coffee, tea and fruit juices are all acceptable.

A number of points that need to be considered are as follows:

1. Meals should not be prepared inside the chambers because of the dangers of smoke and toxic gases contaminating the atmosphere.
2. Certain food stuffs, raw or cooked, can generate flatulence when eaten and should be excluded from the special diet prescribed.
3. Bread and rolls will deform under pressure, rice congeals, bananas will spoil although oranges will maintain their shape and consistency. These are examples of the effects of pressure on food.
4. Generally a low-fat diet is prescribed to reduce the danger of thrombosis.
5. Cans of food or liquid should not be passed into the chamber as they may implode because of differential air pressures and be difficult to open. Stainless steel cutlery and tableware should be used as plastic is not suitable.

6. The selection of the diet must take account of extraneous gases emitted; these must be within the capability of the life-support system as, if toxic, they must be removed.
7. In under-water habitats, notably in future projects, where food is prepared in the habitat, the usual strictures apply to the thawing of frozen foods, which must not be subsequently refrozen.
8. In hyperbaric rescue chambers food packs not affected by being pressurized need careful selection and the amount must be controlled by the maximum number of occupants for a minimum period of time before recovery and transfer. The knowledge gained from the experience of astronauts in outer space in similar conditions of confinement has helped in the use of hyperbaric feeding and dietary control.

Sanitary Installations

Some classification societies lay down design criteria for the installation of sanitary systems in saturation hyperbaric complexes. In earlier designs the toilet and washing facilities including the shower arrangements were a part of the living accommodation but experience has shown the need for independent pressure chambers to fulfil this function. This allows the chamber to be depressurized, empty, at various times to be cleaned out and disinfected. Whilst some designs allow for a central sanitary chamber which can be used by more than one living chamber, this arrangement has the disadvantage that different pressures and possibly dissimilar mixtures are needed for the competing needs of personnel from different living chambers. Clearly the best arrangement is to connect the separate chambers fulfilling these functions to each living chamber, notwithstanding the additional cost and the need for additional space.

The standard internal fittings of a central or independent chamber will include the following items:

1. Handbasin with hot and cold water
2. Fixed or hand shower with temperature regulation
3. WC fitted with safety exhaust system
4. Drainage system with sewage tanks. The tanks are pressure-proof and a 30–50 litre capacity tank will normally be sufficient for four people under pressure

In hyperbaric rescue chambers a dry toilet can suffice for a limited period.

The design criteria and implementation into systems are discussed in more detail in Chapter 3.

Accommodation

In modern deep diving systems the average volume per diver in the living accommodation is about 5 m^3. National regulations in some countries, for example the UK, legislate a minimum headroom allowing the occupants to stand up if time under pressure exceeds 12

Table 10.4. Space conditions in modern deep diving systems, diving simulators and under-water habitats

System	*Total volume* (m^3)	*Volume per diver* (m^3)	*No. of separate rooms*	*Internal diameter of chamber* (mm)
Deep diving systems				
Arctic Seal	75	6.25	8	2150
Seaway Falcon	40	4.5	4	2150
Diving simulator				
Cartagena	33	8.25	4*	1750/2900
Zürich	24	8	3*	2000
Under-water station				
Helgoland	40	10	2*	2460
Aegir	48	12	2*	2750

*Excluding wet chamber.

hours. In the earlier days when exposures under pressure were limited to hours rather than days no minimum volumes were ever considered and volumes of less than 2 m^3 per diver were usual and there were no facilities for standing up.

In Table 10.4 are listed the volumes of some systems for different purposes. The operational systems used commercially off-shore, particularly when built into ships, are often constrained by space limitations which do not apply to diving simulators, where no restrictions exist, except for cost. Under-water habitats require greater volumes per person whether they are pressurized or not. Volumes quoted include, and are not in addition to, the fittings such as bunks, tables, cupboards etc. To achieve the best balance of efficiency and comfort, the basis of human ergonomics, careful pre-planning is needed to use the limited space to maximum advantage. Within these structures the main considerations are comfortable sleeping and seating arrangements responding to the individual needs of a diver for privacy and quietness. The bunks should have first claim on space to allow for maximum comfort and size and must be designed to be least affected by the rolling motion of the ship.

Tidiness is a fundamental discipline and the stowage spaces should be designed to hold all small loose equipment and personal possessions. Small design considerations, such as the relative efficiency of sliding doors over hinged ones, need to be settled at the earliest design stage and not during fitting out prior to the first mobilization. At this later stage, however, the choice of colours can be considered to give some warmth to the surroundings. For instance interiors painted in white suggest a cold environment whereas green will be warmer and more pleasing.

Table 10.5. Communication systems for compression chambers diving simulators and deep diving systems

Acoustic	*Visual*	*Audiovisual*
Telephones (electric or sound-powered)	Television (vision only)	Television
Press-to-talk systems (sound-powered)	Telewriter	
Talk-back systems	Indicator panel	
Radio systems (wireless)		
Helium voice unscramblers		
Alarms and bells		

Communications

Communications are an essential part of any operation—to the diving bell when the divers are working, to the compression chamber and during the intervening transfer under pressure. A primary and back-up system are minimum requirements for any system, whatever its design and use. The main need to communicate intelligibly, particularly when breathing lighter inert helium gas mixtures, requires helium voice unscramblers. The following systems are used or considered:

1. Sound-powered systems requiring no power
2. Press-button communications systems with loud speakers and amplifiers
3. Talk-back communications systems with loud speakers and amplifiers (not often used due to their higher failure rate)
4. Helium voice unscramblers with amplifiers and loudspeakers (essential for helium-breathing systems)
5. Radio communication for use with hyperbaric rescue chamber when the chamber has been launched into the sea, and communication maintained with a surface vessel

Certain other refinements can be incorporated into diving systems such as television for monitoring inside the chambers, usually restricted to the larger systems both off-shore and simulators on land, and in under-water habitats. The method of transmitting a drawing or hand-written message through telewriters is being considered. Warning devices to indicate communication systems failure, either by indicator lights or by horns, have already been incorporated.

Lighting and Noise Levels

As far as possible the minimum levels of lighting and noise level standards as applied to normal industrial practice should apply to the interiors of hyperbaric chambers. Further design factors apply to maintaining different standards applicable to working areas and rest areas. Although these standards are easier to implement in diving simulators, certainly with regard to noise levels, as the gas supply and compressor facilities can be separated some distance away from the chambers, certain steps can be taken in hyperbaric systems in vessels to reduce noise. This is not always successful as there is also the additional noise from the ship's own machinery. The application of modern techniques using sound-proofing materials can reduce noise levels, especially in the gas circulation, compression and reclamation systems where continuous changes in pressure produce very high noise levels. Noise levels inside the chamber should not exceed 60–70 dB except during short periods of gas changes and pressure changes when levels should not exceed 90 dB (under some circumstances 105 dB).

Similarly lighting levels should vary with area. The diving bell which is the working area should have strong positioned lights to produce the best non-diffused light in the water, directed onto the work and without glare. Lighting inside the chambers should be capable of being controlled so that lights may be reduced for sleeping and increased to give a pleasant light for resting and eating. Table 10.6, based on the German DIN standards, may be used as a guideline.

Table 10.6 Lighting requirements for various areas

Type of area	*Power* (lux)
Working	150–250
Diving bell	100–110
Living	50–100
Sleeping	20–30

Entertainment

For long periods of saturation, sometimes up to 30 days, there is clearly a need for alternative and optional channels of entertainment. The inherent problems of boredom, possibly interspersed with peaks of stress occurring at different times for individual divers, can to some extent be catered for by having television, film and wireless all available with individual headsets so that low noise levels are maintained. In addition games and literature should be available.

Fire Hazards

The systems for firefighting are covered in Chapter 2, but clearly prevention is fundamental and design and operational considerations should take into account the selection of materials inside the chamber to minimize the risk of toxic gases being released.

Primary Life-Support: Technical Solutions

To produce a safe primary life-support system, removing the toxic gases and maintaining the internal atmosphere in the correct proportion and at the optimum temperature and humidity, allows a number of options. We discuss here the most practical and usual methods as applied to hyperbaric systems. The life-support system applied to transportable recompression chambers for divers has been covered in Chapter 5.

Oxygen Supply

Open air circuit

In compression chambers operating in the air range normally from 0 to 50 m the oxygen supply is guaranteed by the need to ventilate the chamber with clean air to remove the CO_2. Compression chambers filled with air will normally operate on the open-circuit principle where the quantity of fresh air supplied will be proportional to the number of people breathing inside the chamber with an equivalent exhaust of gas to maintain the same correct pressure. For practical purposes the average CO_2 exhaled per person is 0.45 litres/minute and as the maximum permitted CO_2 level should not accumulate above 0.015 bar, the amount of air ventilation needed to disperse this is 30 litres/person/minute. With an oxygen percentage of 21% in the air the oxygen that is supplied in this ventilation to remove CO_2 is already 6.3 litres/minutes, and this will increase proportionally with pressurization, i.e. at 3 bar it will be 18.9 litres. Therefore in chambers where air is the breathing gas and the open-circuit method of ventilating or flushing the system with more air is used, the critical partial pressure relates to CO_2 elimination in which case the oxygen requirement is satisfied.

Closed mixed gas circuit

Outside the normal commercial air diving range between 50 and 60 m where helium is introduced as an inert gas, the closed-circuit system is used for reasons of respiratory control, noise and, not least, cost. The removal of CO_2 by ways other than flushing the system described later requires separate means of re-supplying the chamber atmosphere with oxygen. The supply of oxygen is normally in high-pressure cylinders although theoretically it can be supplied from a liquid oxygen source or solid chlorate candles. The supply of pure oxygen for breathing in the later stages of decompression or for therapeutic treatment is discussed in Chapter 2. The supply of the correct amount of oxygen in the chambers for normal breathing to maintain the correct partial pressure of oxygen is discussed here. Fig. 10.2 shows a standard oxygen supply system as a separate part of the total life-support system for a deep diving system. The system can be subdivided into a number of groups but the overriding design factor must take into account that oxygen, being highly inflammable, requires additional safety factors and the careful selection of materials for handling purposes.

The oxygen supply banks are usually in separate stowages. Individual 50 litre cylinders can be racked together in bottle racks of 10 to 12 cylinders with a charging pressure of 200 bar. In drilling rigs, platforms and vessels these racks are usually stowed on the upper deck. Modern diving support vessels have special stowage facilities below decks for oxygen and often have built-in bulk stowage facilities. Manifold gauges show the storage cylinder pressure and through high-pressure stainless steel or copper alloy piping the oxygen pressure is reduced at source to about 40 bar and distributed to

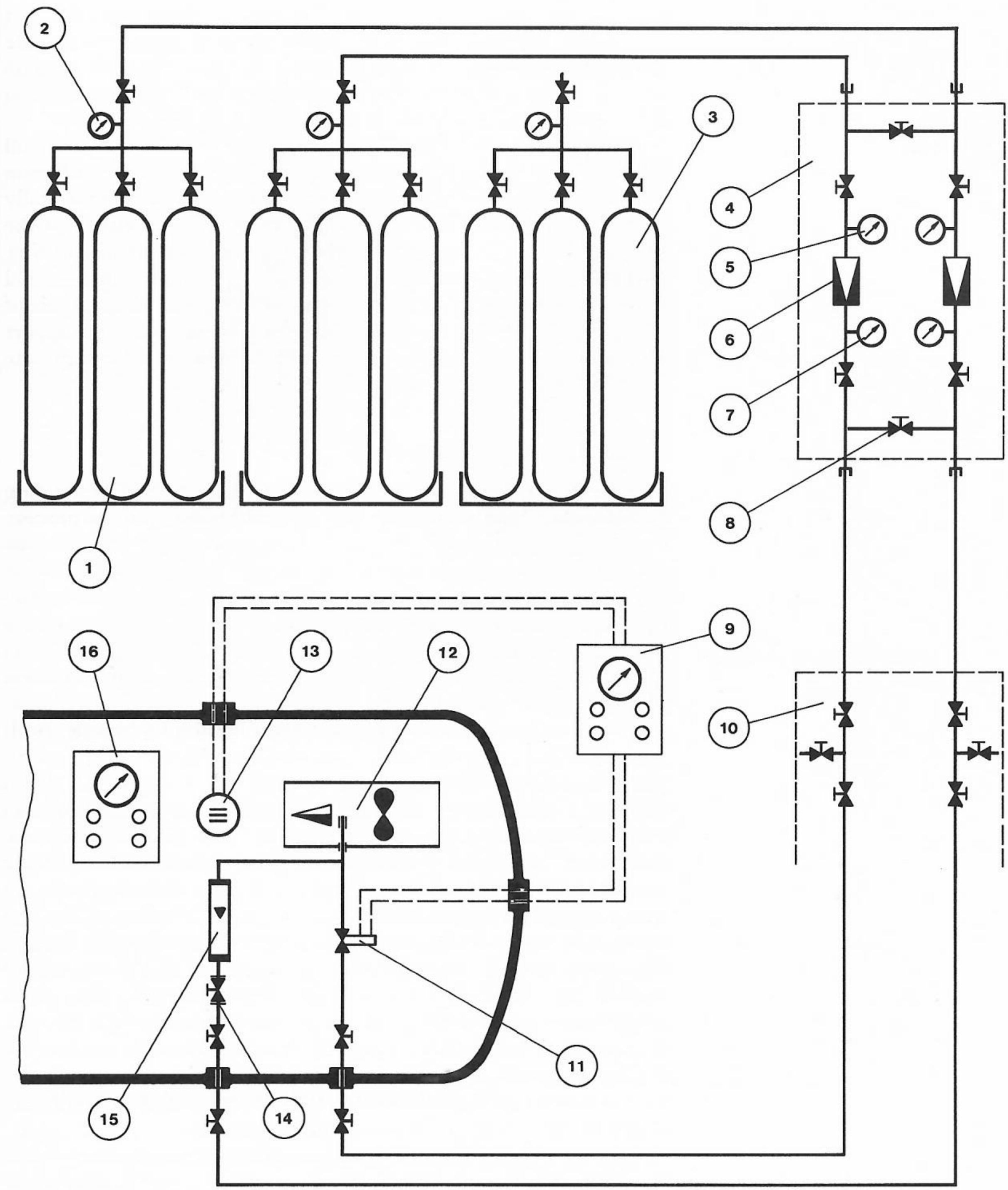


Fig. 10.2. The oxygen system of a typical deep diving system.

1	oxygen storage bank	7	operating pressure gauge	12	blower
2	storage pressure gauge	8	cross-connect valve	13	oxygen sensor
3	oxygen storage bank (reserve)	9	oxygen meter	14	fine adjustment valve
4	oxygen distribution panel	10	control panel (section)	15	flowmeter
5	high-pressure gauge	11	solenoid	16	internal oxygen meter
6	pressure regulator				

the various chambers via the control panel where flow is regulated and monitored to maintain the correct partial pressure in the chamber. Automatic partial pressure control systems operate between preset high and low levels controlled by solenoids and by an O_2 partial pressure control meter.

For safety reasons shut-off valves are fitted each side of the hull penetration of the chamber and the best place for the oxygen diffusion into the chamber to give quick and even distribution will be normally behind a blower or adjacent to the circulation flow inlet into the chamber. Alarms are usually fitted on O_2 partial pressure monitoring systems which sound in the event of any malfunction with a manual override. Flow meters to measure the volumes are an integral part of the system. As this is a very sensitive part of the total life-support system it should have a complete back-up system with duplicate instrumentation and cross connections.

Carbon Dioxide Removal

Theoretically there are more than 30 different methods of eliminating CO_2 from a gas mixture and some even produce O_2 in the process. Experiments conducted show that lithium peroxide (Li_2O_2), lithium oxide (Li_2O) and manganese oxide (MgO) can eliminate CO_2. There are procedures which wash out carbon dioxide (monoethanolamine) but require high energy in the process. CO_2 can be frozen out, a method which presented many mechanical problems to Jaques-Yves Cousteau during the *Conshelf III* experiments. The most common process for elimination of CO_2 is using absorbent lime, referred to as soda-lime or baralime, or to a lesser extent lithium hydroxide. Both these chemicals, absorbent lime and lithium hydroxide, are used in granulated form and cannot be re-used. They vary little from different manufacturers. Lithium hydroxide is more efficient than absorbent lime, absorbing nearly twice as much CO_2 for the same amount of absorbent, but is very much more expensive and therefore used in circumstances where weight and space considerations are paramount. These considerations apply to use in submersibles and one-atmosphere vehicles. For design considerations applying to deep diving systems calculations are based on the use of absorbent lime ($Ca(OH)_2$). The efficiency of the absorbent will alter with temperature and humidity and designs must take this into account. Temperatures below 20°C should be avoided if possible and also too dry an absorbent. The absorbent should have the minimum water content stated by the manufacturer. If the circulating gas is too dry the absorbent may need to be humidified artificially.

Deep diving systems may often combine the CO_2 removal and temperature humidity control systems in one unit and it is usual to do so in modern systems. In small compression chambers and in diving bells the CO_2 absorption units are separate, comprising a refillable cannister for the chemical, a blower capable of circulating gas through the unit and into the chamber and an electric drive that is either in a sealed unit using low voltage or air- or water-driven, to reduce fire and explosion hazards.

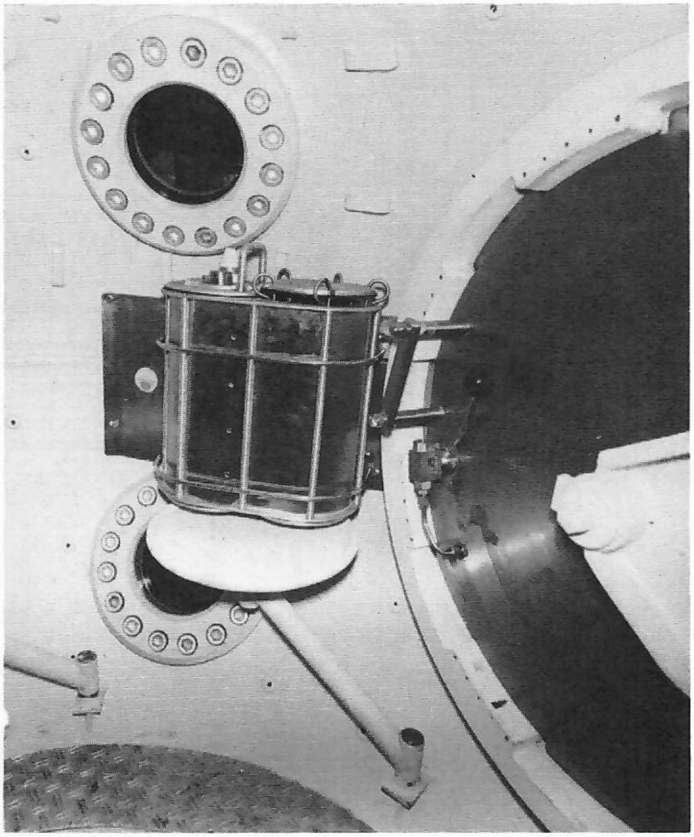


Fig. 10.3. Lindbergh Hammar carbon dioxide absorption unit.

Fig. 10.3 shows a unit designed by Lindbergh Hammar which is commonly used. The oval casing is stainless steel, as is the refill cannister for the chemicals, with sufficient volume to cater for the maximum number of divers and the operating depth. The blower is driven by a sealed explosion-proof electric motor. Clearly the correct positioning of the unit inside the chamber is very important to achieve the most efficient circulation of gases.

For large deep diving systems with perhaps as many as 24 divers at various stages of saturation for periods of 30 days or more, many large systems are needed, where the small separate units would be insufficient in terms of reliability, endurance and efficiency. Three principle designs are shown in Fig. 10.4. In A, the low-cost system, the blower and refillable cannister are inside. The major disadvantages are the increased noise level, limited maintenance and repairs and the dependence on the divers to refill the cannisters themselves. In B all the obvious disadvantages of the internal systems are overcome by designing the CO_2 unit externally except for the higher costs associated with additional penetrations, pipework and pressure vessels. The higher cost is not nowadays considered to be relevant because of the need for high safety factors in this part of the life-support system. In C a compromise between the external and

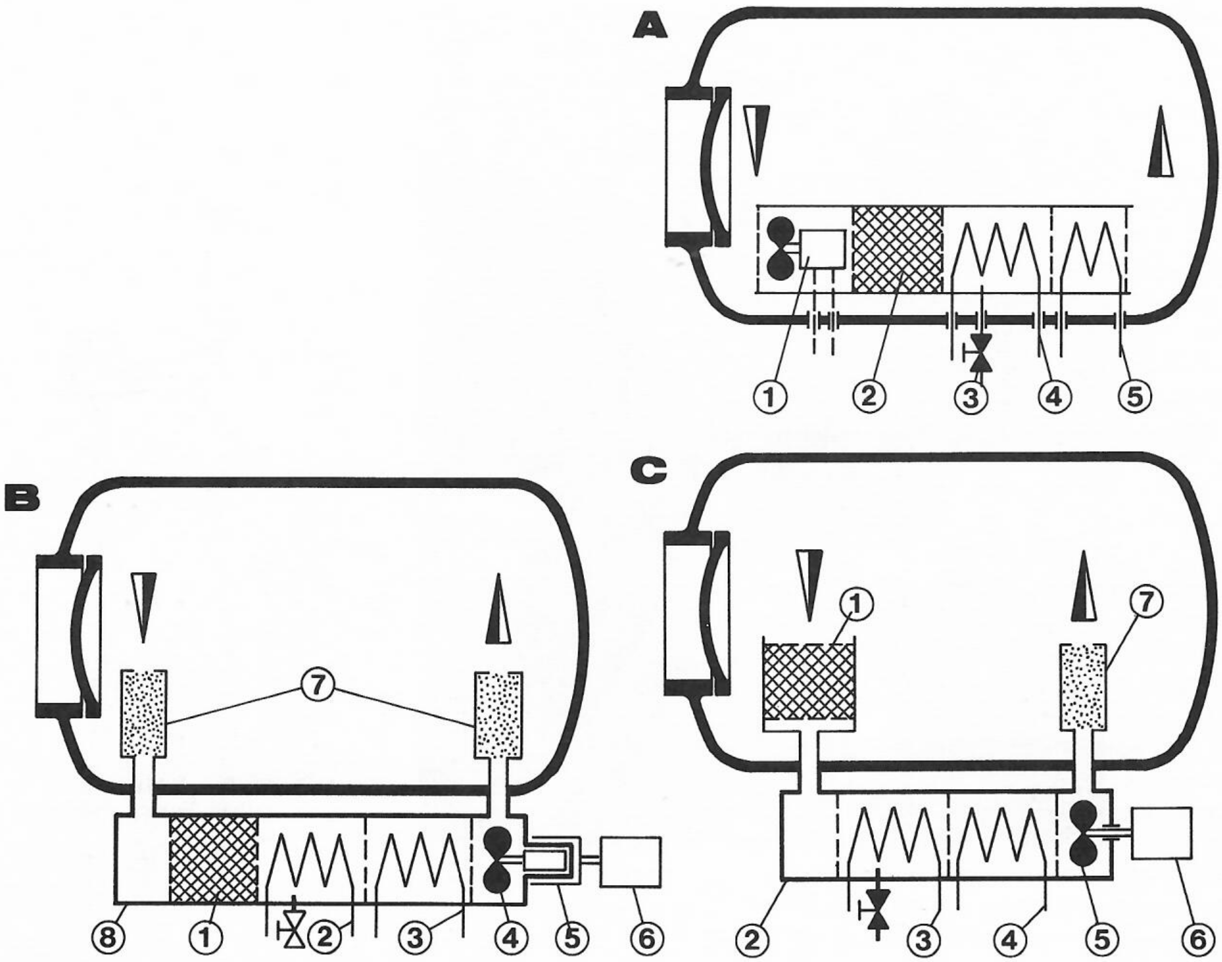


Fig. 10.4. Basic designs for life-support systems.

A Internal life-support system
1 blower
2 carbon dioxide absorber
3 dewatering valve
4 cooling/dehumidification
5 heating

B External life-support system
1 carbon dioxide absorber
2 cooling/dehumidification
3 heating
4 blower
5 magnetic clutch
6 driving motor
7 silencer
8 pressure vessel

C Semi-external-internal life-support system
1 carbon dioxide absorber
2 pressure vessel
3 cooling/dehumidification
4 heating
5 blower
6 driving motor
7 silencer

internal systems shows the blower and heat exchanger outside the chamber, enclosed in a pressure vessel, and the CO_2 absorber inside the chamber in a non-pressure-proof container. Clearly combining the advantages and disadvantages of both the other systems, the main technical consideration is the design of a blower drive inside a pressure chamber. Normal electric motors cannot be considered because of the serious fire risk from sparking. Electric drive is possible using metal-clad gas-tight designs with forced helium ventilation to purge the

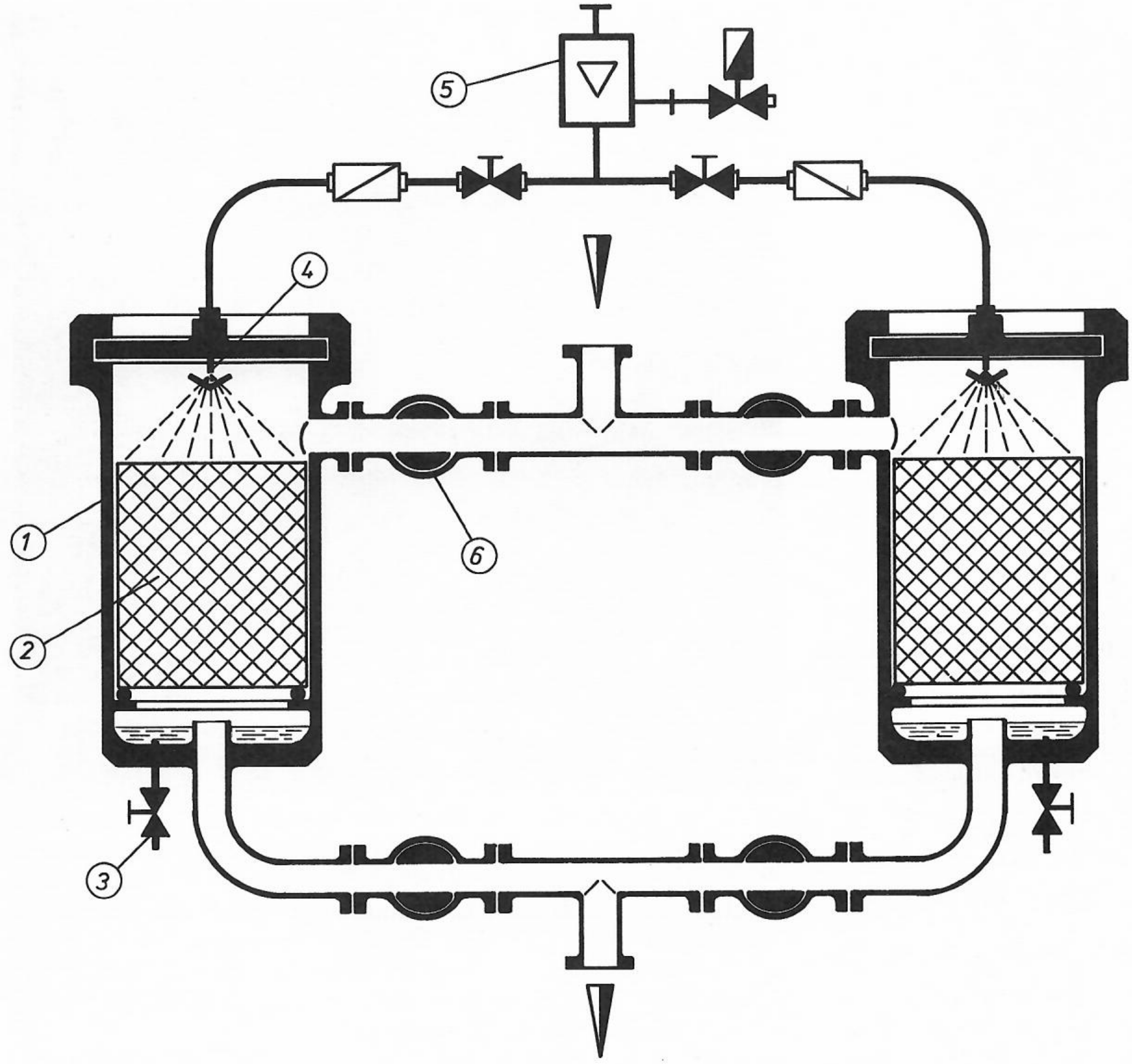


Fig. 10.5. Carbon dioxide absorber with absorbent humidification for an external life support system.

1	CO_2 absorbent casing	4	atomizer
2	absorbent cartridge (rechargeable)	5	high-pressure pump
3	dewatering valve	6	shut-off valve

unit. Other options are hydraulic fluid drives, air-driven motors and magnetic clutches through pressure-proof casings with motors at surface pressure.

Fig. 10.5 illustrates an external life-support system using two filter systems operated either together in parallel or separately isolating one for refill or maintenance purposes. In this Dräger system the filters,

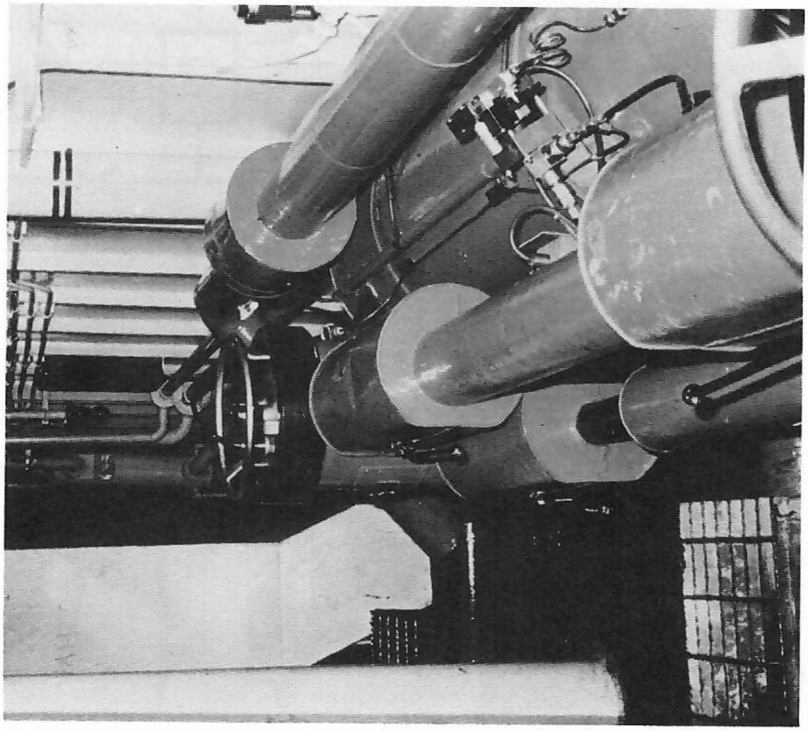


Fig. 10.6. Carbon dioxide absorber, recuperator, blower and drive.

often referred to as scrubbers, are arranged vertically and hold 10-litre absorbent refill cartridges. The pressure-tight lids are constructed with either a bayonet or U-shaped clamp ring. A water atomizer is fitted inside the pressure vessel which, in the event of relatively low humidity conditions and a circulation of dry gases, can increase the humidity to a set degree. Fig. 10.6 illustrates a complete CO_2 unit with blower, recuperator, shut-off valves and heat insulation. Gas flows and the quantity of chemicals have been calculated to provide for CO_2 removal for six divers up to 50 bar.

Complete Integrated Life-support Systems

The integration of the oxygen supply and the CO_2 can now be considered. In Fig. 10.4A the internal CO_2 life-support system has a very limited application nowadays as the more complex deep diving systems use the external and internal/external systems. However, these external systems cannot be used in under-water habitats (the subject of life support in these habitats is discussed separately in Chapter 6). In diving bells the main requirement is to monitor oxygen partial pressure, eliminate carbon dioxide and provide heating if required. Because the purpose of the diving bell is to provide an effective worksite platform for limited periods, only the basic essential needs of the divers need to be considered and as these have to be provided mainly through the umbilical they are

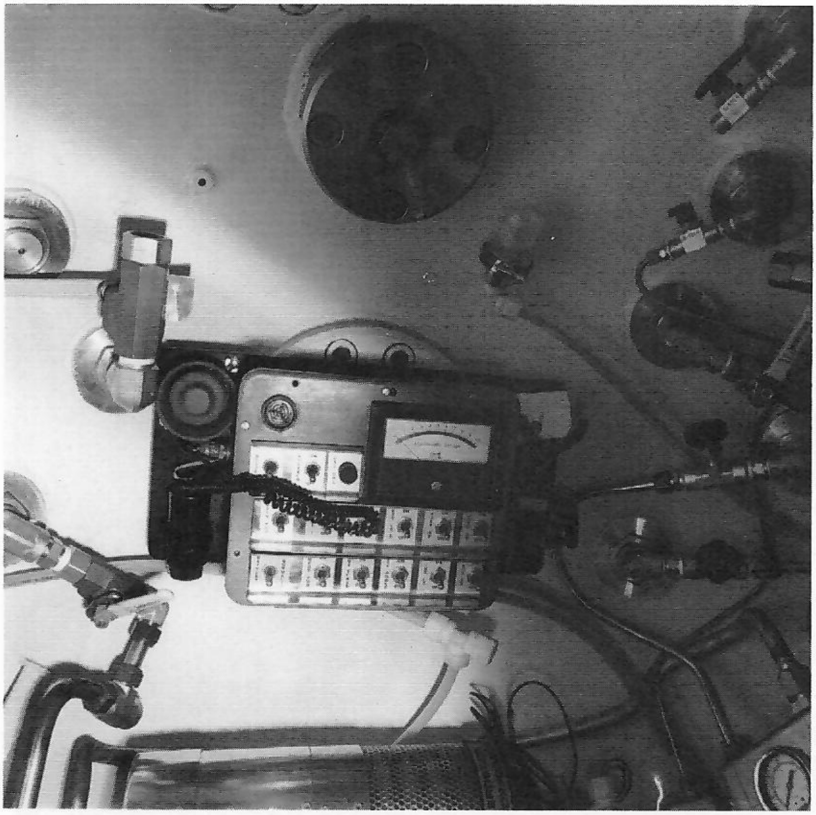


Fig. 10.7. Oxygen meter integrated into control panel (by Saturation Systems).

competing for limited services. In a total closed-circuit system where gases are supplied to the diving bell and subsequently returned to the surface for reprocessing, all the oxygen monitoring and replacement and the CO_2 scrubbing is carried out on the surface. An oxygen meter integrated in the control panel produced by Saturation Systems Inc. is shown in Fig. 10.7. However, in limited operations where the bell divers can control their own gas supply CO_2 scrubbers and oxygen monitoring equipment are provided inside the chamber. For CO_2 removal there are a number of units available. The unit by Lindbergh-Hammar, shown in Fig. 10.3, is compact and very suitable. The same stringent measures against fire and explosion apply to diver bells as well as compression chambers with regard to electric motor safeguards. To avoid problems of corrosion all important components should be made from stainless steel.

Since diving bells, by the nature of their work in the sea, are exposed to cold for long periods, especially in connection with under-water construction work, provision must be made to keep the temperature above 30°C if possible. This can be achieved by using electrically heated radiators but with limited efficiency. A more practical way, if hot water is already being used via the umbilical to the divers, is by heat exchangers and a blower. A water heater unit which works on this principle is shown in Fig. 10.8.

Fig. 10.8. Hot-water-supplied heat-exchanger with electric blower for heating diving bell (by Kinergetics Inc.).

Heating coils can be fitted with some limited success between the bell hull and external insulation which will retain some heat for limited periods of time in the water. Further research into diver heating and bell systems is still necessary and the development of heat pumps deriving energy from the surrounding sea offers some interesting possibilities.

There have not been any agreed standards as to the requirements for diver heating systems in diving bells and for divers in the water. In the colder waters of north-west Europe, a major area of activity, some form of external active body heating should be available at a depth below 50 m. The heating of respiratory gases, normally oxy-helium mixtures, to 30°C is normal practice at diving depths in excess of 150 m. To be less arbitrary, some operational limitations with regard to the type of dive and the length need to be considered. If the temperature of the water is about 10°C active body heating should be provided if the time spent in the water exceeds 1 hour. If the temperature is about 15.5°C then 4 hours is a reasonable diving period without active heating.

Whatever form of active heating is used it must be carefully controlled. There are also dangers in overheating the divers. Hyperthermia can set in after an exhausting dive with heated suits and, after their removal, can lead to unconsciousness. This may be attributable to release of tension, an overheated hot water suit and gas. This creates too high an injection temperature with the inability to eliminate the heat quickly enough. The margin to turn a heat loss into a heat gain is very small. Diver heating systems should be designed on the basis of active diver insulation heating to maintain the thermal equilibrium without the body having to sacrifice its own heat. Unlike the effects of different gases, the parameters of which are well known, much more study is needed in this field.

With regard to the heating of the diver directly through active insulation heating, this can be achieved through three methods:

1. Diesel-fired heater
2. Electrical resistance device
3. Steam generating device

All the systems are designed to take sea water, heat it to a desired temperature, pass it to the diver and dump into the sea again. Each should have safety features to identify the following:

1. Loss of sea water flow
2. Failure of temperature control
3. Loss of heat transfer medium

Diesel-fired heaters are the most common because they require the least outside logistical support. However, they are complicated pieces of machinery and serviceability and maintenance are problems, particularly in fire detection circuits, dirty fuel and temperature oscillations. Some regulations also state that in off-shore operations diesel-fired heaters should be in an explosion-proof housing and protected from the elements.

Electrical resistance heating ranging from 100 to 150 kVA are now becoming commonplace. Adequate precautions against shock should be taken in the design and in this respect the heating elements should heat fresh water which in turn heats the salt water through a separate heat exchanger.

Heating systems using a chemical reaction have been developed. Salt baths of molten salt provide a form of latent heat and can be used for heating water in suits as well as inside chambers. Further developments may give some autonomy to the diver by replacing the hot water umbilical with a closed-circuit hot water suit using a chemical pack as the heat source.

Integrated life-support units in the external mode are shown to have clear advantages and in spite of the cost are generally accepted in deep diving systems. Fig. 10.9, based on a Dräger system, illustrates the most important components of a life-support system and how they function together. The system is based on a maximum operating pressure of 50 bar and designed to eliminate CO_2 and regulate temperature, humidity and the partial pressure of oxygen. The nucleus of the system is the CO_2 scrubber, blower and electrical heater. The cooling system needed for lowering the humidity is electrically operated and the humidity and temperature sensors inside

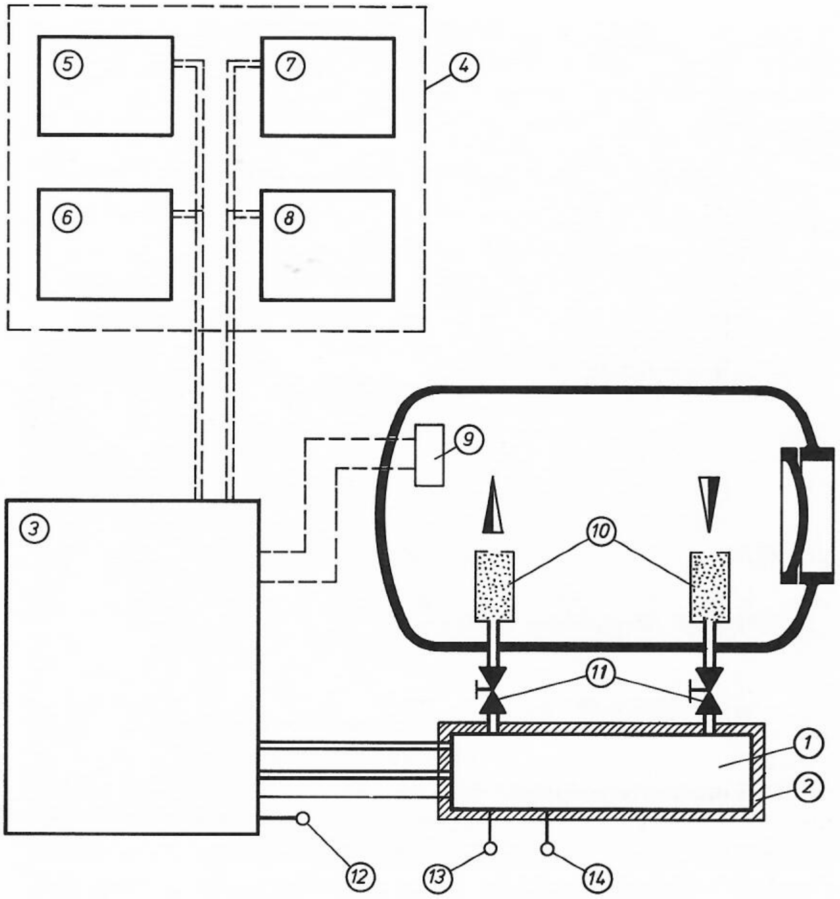


Fig. 10.9. Block diagram of an external life-support system.

1	CO_2 absorber and recuperator
2	insulation
3	cooling aggregate
4	control panel
5	reference input (temperature)
6	actual value read-out and plotter (temperature)
7	reference input (humidity)
8	actual value read-out and plotter (humidity)
9	combined temperature and humidity sensor
10	silencer
11	shut-off valve
12	electric connection
13	water connection for atomizer
14	electric connection for heater

the chamber are monitored from the control panel and with pre-set limits can control the temperature and humidity in the life-support system.

CO_2 scrubbers shown in more detail in Fig. 10.5 have already been described. With a total dual capacity of 20 litres of absorbent lime, sufficient for absorbing 2000 litres of CO_2, the system will maintain this level of efficiency if the circulating gas is not excessively dry. An atomizer is fitted to achieve the correct humidity and the water produced can be drained through a drainage valve which must be fitted to the system. One of the filters can be filled with charcoal or similar material to remove impurities and in this arrangement care should be taken to ensure equal flow characteristics in both scrubbers,

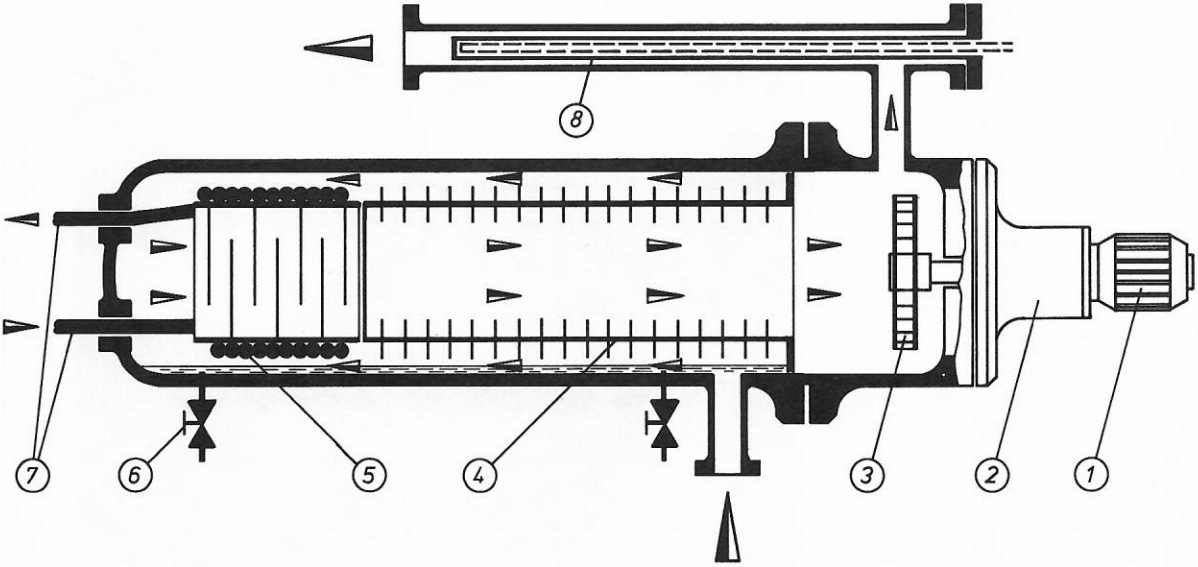


Fig. 10.10. Recuperator, water cooler, circulation blower and heater.

1	electric motor	5	cooler
2	magnetic clutch	6	drainage valve
3	blower wheel	7	brine inlet and outlet
4	recuperator	8	heater

avoiding too great a resistance in one or the other. In the event of the humidity rising above acceptable limits and the cooling system not functioning, the filters can be partially fitted with silica gel in order to absorb some of the water.

Ideally the CO_2 absorption system and the recuperator, water cooler and circulation blower are designed into one unit (Fig. 10.10). Inside the recuperator chamber the gas coming from the CO_2 absorber releases energy to the heat exchanger and is cooled down in the water cooler (to below a certain dew point temperature) until reaching the correct relative humidity. The gas in the recuperator reverses direction after being cooled and passes over a heating coil before re-entering the chamber. As previously mentioned the temperature and humidity are automatically controlled with sensors fitted inside the chamber. The whole assembly should be well insulated to reduce any effect of the temperature outside including pipework and CO_2 scrubbers. Drainage valves should be fitted at the lowest points.

The blower and magnetic clutch system indicated in Fig. 10.10 should be very reliable and fail safe even during long-term operations. Such a system in use generates a flow of gas of 100 m^3/hour with a pressure differential in the order of 0.010–0.015 bar and a fan speed of 3000 rpm. The blower or fan wheel is driven without mechanical contact by a magnetic clutch inside a pressure- and gas-tight casing. This design ensures that the electric motor is separated from gas mixtures and conforms with the maximum safety codes to eliminate fire risks associated with oxygen content.

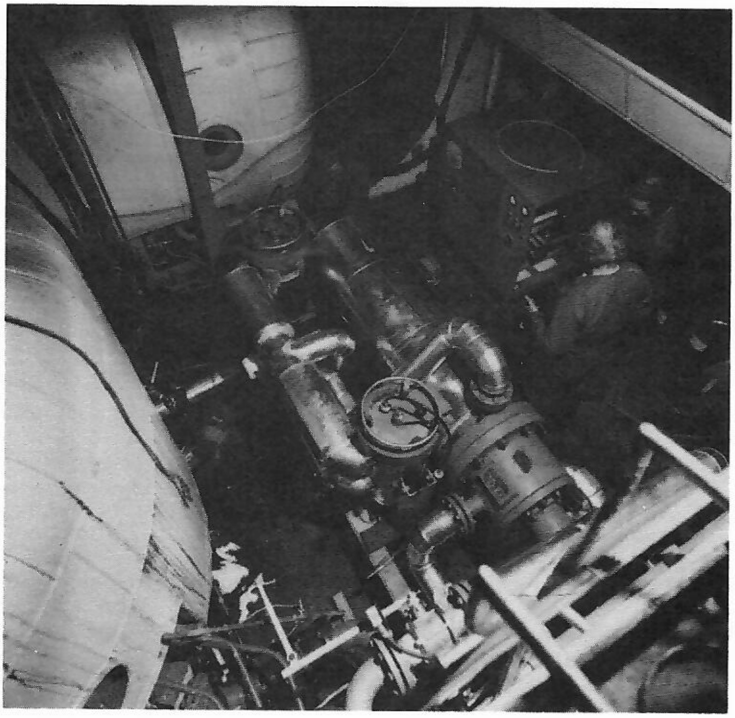


Fig. 10.11. Supply unit and cooling aggregate for an external life support system on the *Arctic Seal*. The system is designed to supply two gas circuits simultaneously.

A sensor can be fitted in the fan to read the flow and this information in respect of gas circulation can be indicated on the control panel.

The recovery of the heat from the heat exchanger is not important and normal heat losses will do this. However, after the gases have passed through the cooling system to achieve the correct humidity they may need to be heated to the correct temperature. In helium-based breathing mixtures the heat losses in the human body are considerable due to the conductivity of the gas and this has to be readjusted in the reheating process. For this purpose an electric heater is placed in a short pipe (Fig. 10.10) directly adjacent to the blower. The gas is separated from the heating elements to again eliminate fire risk and the elements are in the order of 4 kW output. The temperature is regulated by the temperature sensor inside the chamber which will cut out the heating system if temperature rises above a pre-set figure. If this installation is correctly designed and efficiently installed additional separate heaters should not be needed inside the chamber except during pressure changes during decompression. The separate heaters for this purpose, or if the gas heater fails, can be supplied by hot water from the main supply. An additional heating system can be fitted with electrical heating circuits between the external hull of the chambers and the insulation material. This can be effectively used in separate sections to heat parts of the

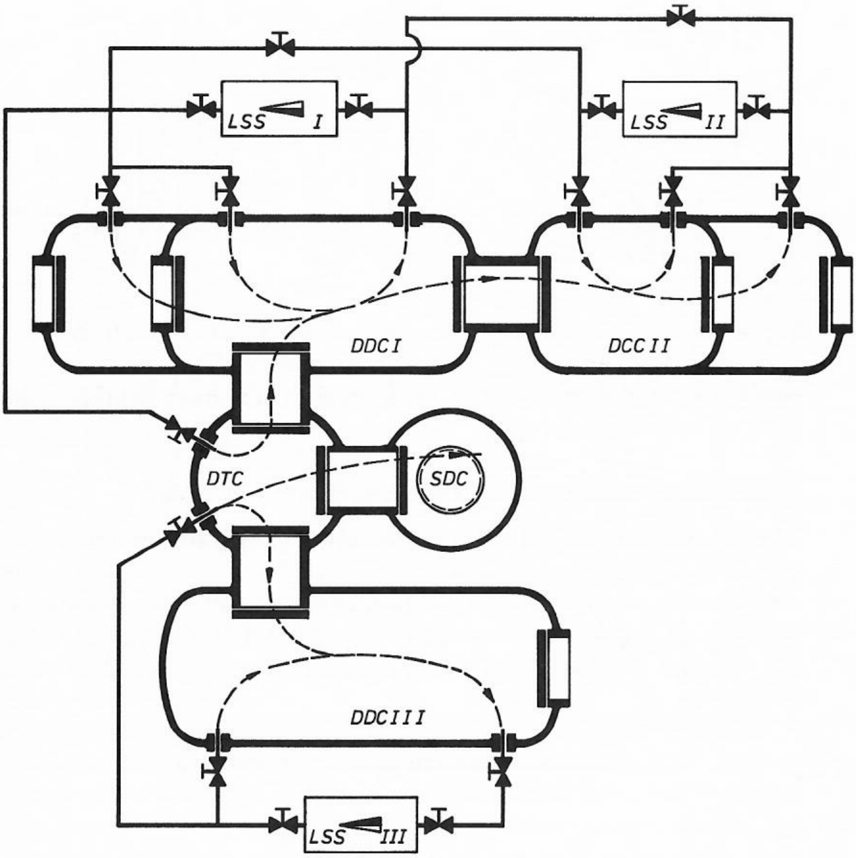


Fig. 10.12. Integration and cross-connection of life-support systems into multiple-chamber complexes.

chamber to compensate for fluctuations and temperature gradients which can occur inside pressurized chambers.

Cooling is carried out by an enclosed unit consisting of the cooling unit itself, the water or brine tank and its pump and a cabinet containing the controls as shown in Fig. 10.11. Standard commercial units are acceptable, designed for either air or water cooling. The cooling liquid is circulated around the system and kept at a set temperature, taking into account the heat absorbed from the heat exchanger in the recuperator. The cooling system is thermostatically controlled between pre-set ranges with the input supplied from the temperature and relative humidity sensors in the chambers.

Ideally a separate life-support system should be designed for separate chambers within a complex and this is necessary where chambers are at different pressures and operating in different circumstances. However economy is good design and where chambers are at the same pressures and same breathing mixtures one system can be designed to undertake the life-support functions of both with cross connections. A stand-by system must be available to be connected into the system as shown in Fig. 10.12. An additional flexible cross-connection can connect the diving bell to the life

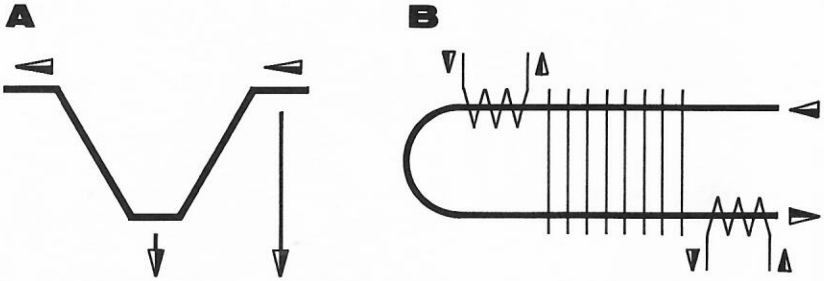


Fig. 10.13. Basic heat balance (A) and counter-current heat exchanger (B).

support system in the event of an emergency requiring the use of the SCC as a deck chamber.

Semi-external/Internal Life-support Systems

The basic features of the systems are shown in Fig. 10.4 and there are various design options open. The CO_2 scrubber can be located inside the chamber, and the blower, dehumidification and heating units can be sited externally within a pressure-proof vessel. If silica gel is used as a drying agent to control humidity this part can also be sited inside the chamber.

An interesting solution on these lines is produced by Kinergetics Inc. The CO_2 scrubber, dehumidification and heating systems, as well as the blower, are installed inside the chamber with the cooling liquid regulator and pumps outside. The cooling liquid is pressurized and also applies pressure to turn the fan in the blower through a magnetic clutch. The basic heat exchange process and recuperator are shown in Figs 10.13 and 10.14. The diagram shows the whole system both inside and outside the chamber, indicating the independent functions of CO_2 removal, dehumidification and temperature control. A rechargeable absorbent container, holding 16 kg and made of stainless steel, is rated for a gas flow of 1400 litres/min. The gas is dehumidified passing through the drying loop after it has passed through the counter-current heat exchanger and been partially cooled down. Further cooling takes place to the required humidity and temperature. The water condensate formed is automatically drained through a valve. This system is claimed to achieve 85% energy saving using the counter-current heat exchanger, compared to a uniflow system described previously. The heating of the gas is carried out in the final phase with hot water, under pressure which drives the fan turbine. Additional heating, if required during peak periods, is provided by an electric heater. The entire system illustrated in Fig. 10.14 and the chamber unit in Fig. 10.15 show the three separate gas phases and the two liquids for heating, power and cooling and the sophistication reached to provide an automatic operation.

Emergency Breathing Systems

Life-support systems can fail and stand-by systems can also be

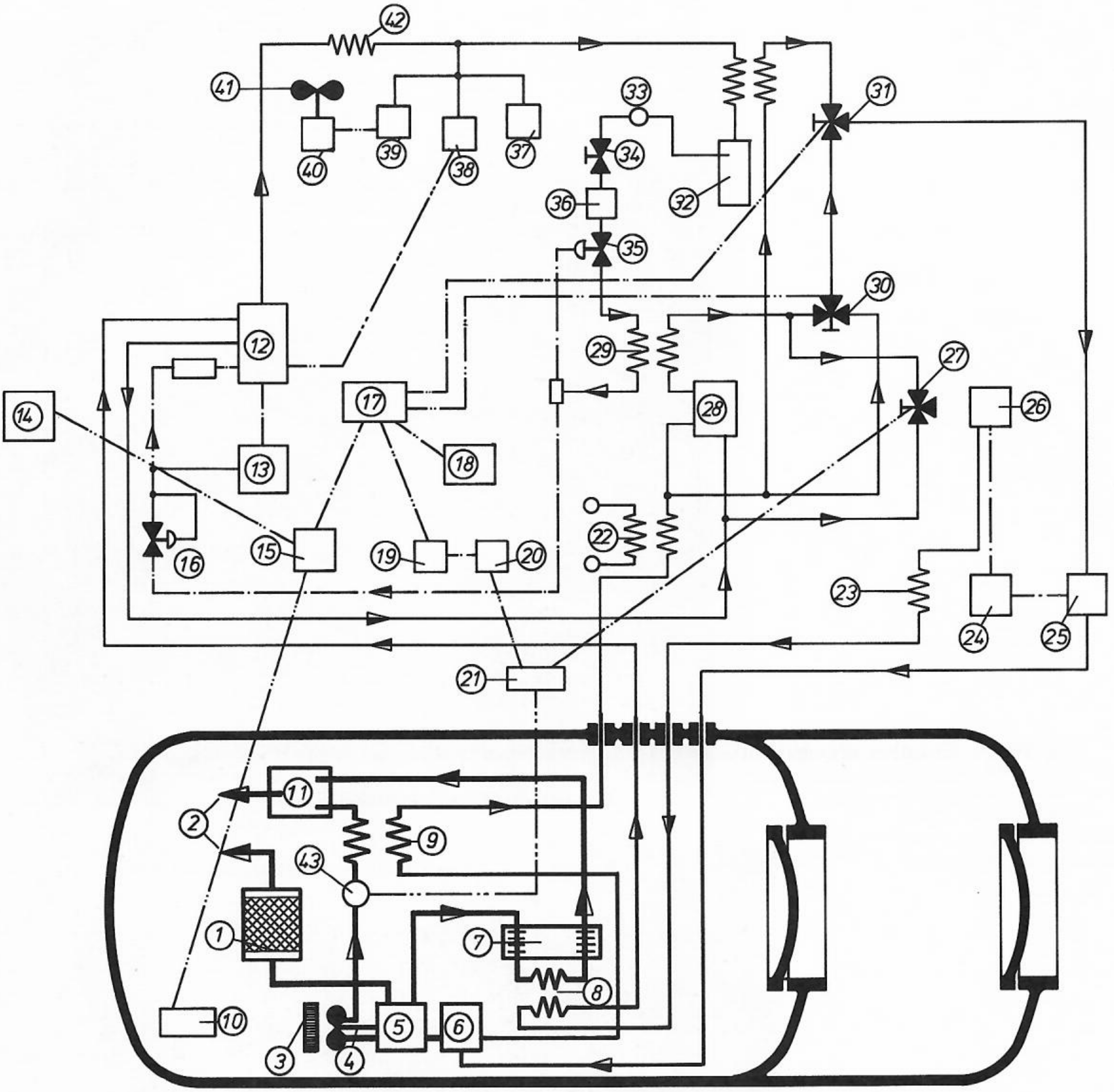


Fig. 10.14. Flow diagram for an external/internal life support system (by Kinergetics Inc.).

1	CO_2 absorber
2	conditioned breathing gas
3	dust filter
4	fan
5	blower magnetic coupling
6	water motor
7	counter-current heat exchanger
8	cold finned tube heat water trap
9	hot finned tube heat-exchanger
10	temperature sensor
11	plenum
12	compressor
13	low-pressure switch
14	temperature read-out
15	temperature read-out
16	back pressure regulator
17	temperature control
18	power supply
19	set point control (temperature)
20	set point control (humidity)
21	humidity control
22	electric heater
23	motor cooler
24	pump motor
25	fluid pump (primary, hot)
26	fluid pump (secondary, cold)
27	control valve (humidity)
28	accumulator
29	evaporator
30	control valve cooling
31	control valve heating
32	receiver
33	sight glass
34	hand valve
35	expansion valve
36	drier filter
37	water cut-in switch
38	high-pressure safety switch
39	motor switch
40	electric motor
41	fan
42	condenser
43	sensor

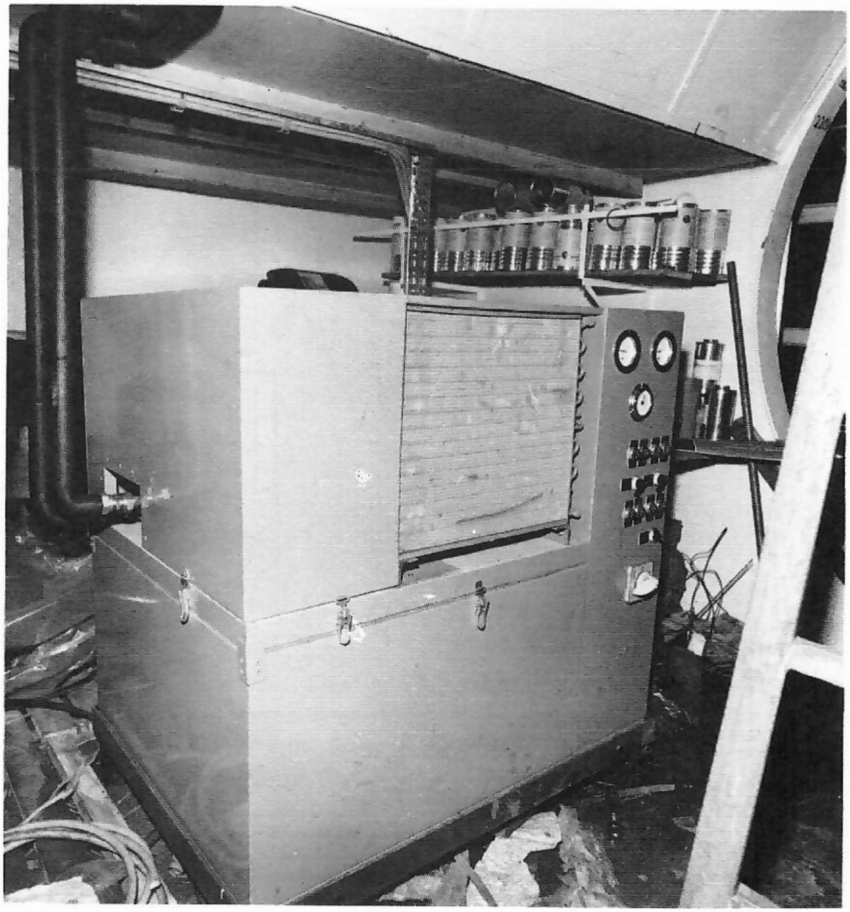


Fig. 10.15. Chamber aggregate of the Kinergetics Inc. life-support system.

Fig. 10.16. Personal rescue oxygen breathing unit (Comex).

Fig. 10.17. Cylindrical carbon dioxide filter unit by Dräger, installed vertically, with pressure-proof circular bayonet lock for replenishment.

inoperable in situations where there has been a power failure or damage through unforeseen causes. Collision, fire or grounding of the vessel can provide the circumstances that make it necessary to provide an emergency breathing system which does not rely on power. Chamber fire, explosion or breakdown in the supply of oxygen from other causes are real hazards and must be provided for by BIBS (built-in breathing system). These systems provide individual oral–nasal breathing masks already fitted inside the chambers. The breathing mixture, suitable for the occasion, is automatically provided, reduced to the correct pressure, and either closed-circuit or open-circuit depending on the pressures in the chamber. These systems are described in more detail in Chapter 2. BIBS usually have a small connecting hose but with quick connectors they can be moved around to alternative connections inside the chamber. Independent breathing sets can be provided giving maximum mobility but limited endurance.

There are a number of systems available. A Comex breathing system is shown in Fig. 10.16. In the event of the main CO_2

absorption system failing, by inserting a filter cartridge holding several litres of absorbent into the breathing system and exhaling into the surrounding atmosphere, the occupant can survive. At the end of the endurance of the filter it can be replaced as required.

Commercial Breathing Equipment for Divers

The development of breathing equipment has generally been able to keep pace with, and meet the needs of, under-water technology. These developments are naturally becoming constrained by the inevitable barrier imposed in the deeper depths by man's ability to withstand the pressure and at the same time to carry out useful work. The work is directly related to the exploration and production of off-shore oil and gas. Sport diving, using the ubiquitous scuba equipment, was established before the commercial requirement but, within the air range the equipment is still widely used for commercial purposes and is therefore covered in this chapter. The different types of breathing equipment are discussed in detail but a description of any specific manufactured equipment is avoided as it may become outdated. However the basic principle on which it was designed will remain valid. The basic design considerations of any one type of breathing equipment can therefore be directly related to any unit manufactured for commercial use.

The firm basic requirements of any commercial diving set are as follows:

1. It must have an unrestricted supply of oxygen within the defined oxygen partial pressure limits.
2. It must be capable of removing all expired carbon dioxide.
3. It must compensate for the ambient hydrostatic pressure.
4. It must be designed for comfort and for safe operation by the diver.

Compressed Air Breathing Apparatus

Although much greater effort and cost is directed to deep diving, the greatest amount of work is still carried out in the air diving range using open-circuit air breathing sets, either self-contained, i.e. scuba, or surface-supplied. Even with further off-shore development in the deeper depths the greater proportion of work carried out is within about 50 m and this will not significantly change. There is little improvement that can be made in the compressed air set and the advantages and disadvantages of the equipment cannot be affected by any further improvement in design. The fundamental advantage is that the use of air as a breathing medium is simple and inexpensive. The disadvantage of air is the restrictions it imposes on depth: theoretically diving to 90 m is possible but effectively in most commercial operations is limited to about 50 m. Between the two types of equipment the self-contained scuba set has the advantage of mobility but is severely restricted by the limited working times at

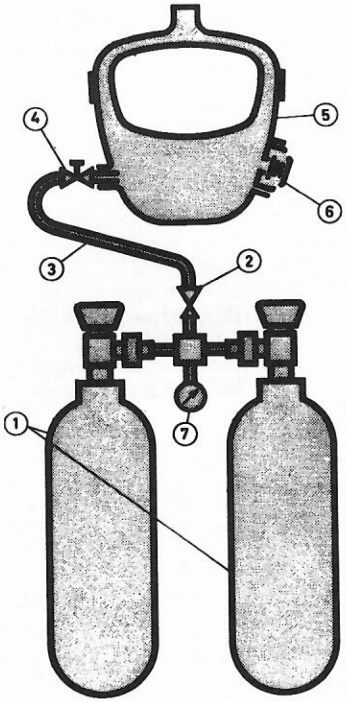


Fig. 10.18. Self-contained open-circuit breathing apparatus with constant air flow.

1 compressed air cylinders with cylinder valves
2 pressure regulator
3 supply hose
4 manually controlled air flow valve
5 full-face diving mask
6 air exhaust valve
7 pressure gauge

depth, directly related to the limited endurance of the air supply carried. This is overcome by the use of surface-supplied air breathing equipment and, because the surface-supplied operation is inherently a much safer method of diving, the scuba method of diving is becoming less used. Both systems are faced with the problem of increased breathing resistance with depth which will affect the working performance of the diver.

Scuba (self-contained air breathing apparatus)

The system works on open-circuit, as does surface supply, where the diver exhales into the surrounding atmosphere. The system cannot be considered really efficient when one considers that in normal breathing only 4% of the total volume is actually consumed by the body. Under pressure, with increased volumes, the rate of efficiency decreases even further. In spite of this it is a very simple, inexpensive and reliable method of diving, in general use more than any other design, but subject to the operational restraints of oxygen tolerance and nitrogen narcosis. There are basically only two types of regulator that deliver the air to the diver at the required pressure and volume, a constant mass regulator and a demand regulator.

Constant Mass Regulator. This regulator produces a constant supply of gas to the diver and is similar in this respect to the constant gas supply to a surface-supplied diver through a breathing hose or umbilical. The diver usually wears a full face mask with an adjustable supply valve allowing the right amount of air into the mask. The additional and surplus air supplied is vented out into the water and this very inefficient method precludes commercial use of this type of regulator. The air is supplied at this constant rate from the air cylinders and the system is illustrated in Fig. 10.18. The constant flow rate must be capable of supplying the diver during maximum exertion so that there is no restriction on breathing. During normal breathing the excess air is exhausted directly into the water. Although not commercially viable, the constant mass regulator does have naval or military advantages because the exhaled air is circulated through a breathing bag or counter lung and rebreathed. In this way the flow through the constant mass regulator can be reduced considerably, increasing the endurance.

Demand Regulator. On demand air supply, controlled by the demand regulator, is activated by the following:

1. The diver creating a slightly negative pressure in the air chamber of the regulator by inhaling.
2. Whilst the diver is descending the ambient water pressure creates an over-pressure in the wet side of the regulator.
3. Manually controlled supply mechanisms are sometimes incorporated in breathing sets to supply additional air.

The basic design and function is illustrated in Fig. 10.19. The design must allow the diver the required volume of air at the correct pressure

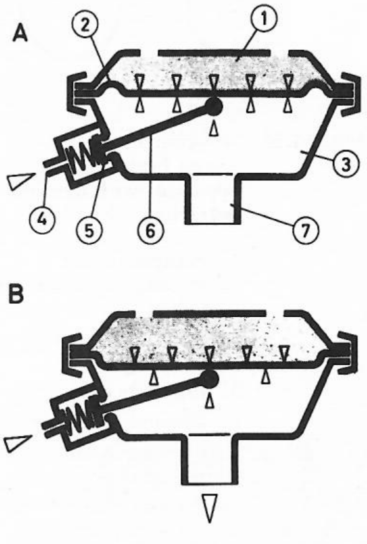


Fig. 10.19. Principle function of a demand regulator.

A Water chamber and air chamber at equal pressure

1 water chamber
2 diaphragm
3 air chamber
4 air supply
5 valve
6 tilt lever
7 air outlet

B Pressure difference between water and air chamber with automatic alterations to the volume as pressure varies with depth. In Fig. 10.19 the difference between a single stage and double stage is not considered. In A the water-filled chamber and air-filled chamber are at the same pressure and the diaphragm and lever are therefore in a closed position. No air is being delivered by the action of valve. During the inhalation stage the pressure in the air chamber drops below the pressure in the water chamber and the diaphragm moves downwards, as shown in B in Fig. 10.19, and opens the valve by moving the lever. Air flows out until the pressure on both sides of the diaphragm is equalized. A similar sequence of events takes place during descent when more air is needed as the ambient pressure increases in the chamber open to water. Fig. 10.20 shows the demand valve incorporated into a complete unit.

Whilst the simplest form of scuba diving equipment incorporates a single air cylinder and single-stage regulator to a simple demand valve, the development from this to improved designs has been considerable and varied. Fig. 10.21 illustrates the variations of air diving apparatus and the uses. The total endurance of each system is directly related to the amount of air that is carried in cylinders which can vary, depending on the pressure and capacity in the cylinders.

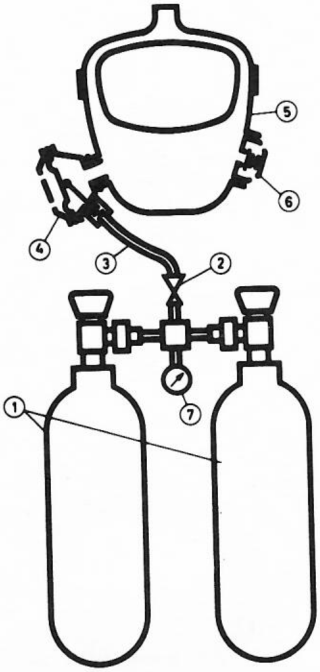


Fig. 10.20. Self-contained open-circuit breathing apparatus with demand regulator.

1 compressed air cylinder with shut-off valves
2 pressure reduction, first stage
3 supply hose
4 demand regulator
5 full-face mask
6 air exhaust valve frequently located in the regulator itself
7 pressure gauge

Single-stage Regulators. The normal pressure in HP air cylinder is between 200 and 300 bar, fully charged, depending on the safe working pressure of the cylinder. This pressure will naturally reduce during a working dive, as the diver consumes his air supply, to a minimum safety level. In any case the pressure needs to be reduced to safe low pressure suitable for inhalation into the lungs. This reduction in pressure takes place in one stage in the single-stage regulator, controlled effectively by the diaphragm/valve combination as illustrated in Fig. 10.23. There are two basic types:

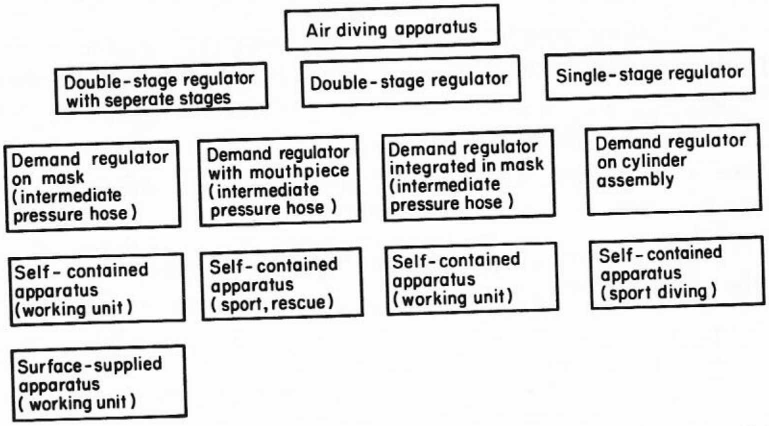


Fig. 10.21. Varieties of air diving apparatus. The first and second stages of the regulator may be designed with a venturi nozzle. Cylinder assemblies may comprise several cylinders.

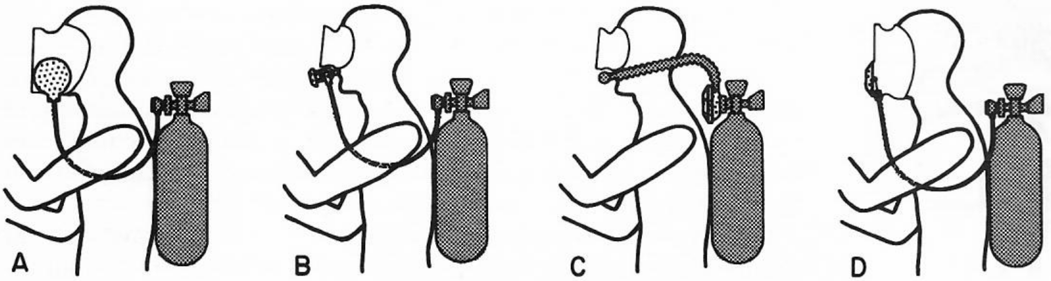


Fig. 10.22. Alternative methods of breathing from supply cylinders.

A Regulator mounted on a full-face mask, first and second stages separated
B Mouthpiece regulator, first and second stages separated
C Regulator mounted on cylinders, single- or double-stage
D Regular integrated in full-face mask or helmet, first and second stages separated

1. Upstream valve: single-stage regulator with valve stem opening against pressure and closing with pressure.
2. Downstream valve: single-stage regulator with valve opening in pressure direction and closing against pressure.

The breathing resistances of single-stage regulators are generally greater than those of double-stage regulators. In the upstream valve, a decreasing pressure in the supply cylinders will lead to decreased breathing resistance because the force to open the valve becomes less. The reverse is the case in the downstream valve, where the reduction in supply pressure will increase breathing resistance because a greater force is needed to activate the valve. The single tilt lever mechanism in this type of regulator cannot provide the same degree of efficiency as the double lever mechanisms although the degree of breathing resistance can be improved with the use of injectors.

Double-stage Regulators. By reducing the pressure from the HP supply cylinder to LP for inhalation in two separate stages the breathing resistance is reduced to a more comfortable and constant level. The layout of such a system is shown in Fig. 10.24 where the first and second stage is incorporated in one unit. In the first stage the combined action of the diaphragm and spring reduces the air supply to an intermediate pressure in the range of about 4–9 bar above ambient pressure. This can operate on the downstream principle or the upstream principle. The first stage in the reduction, often referred to as a pressure-reducer, allows the high pressure air from the storage cylinders into the second stage at the correct low pressure which the diver can inhale on demand. This first stage of transfer from high pressure to the diver working pressure is achieved by either of two methods shown in Fig. 10.23. A shows the downstream method

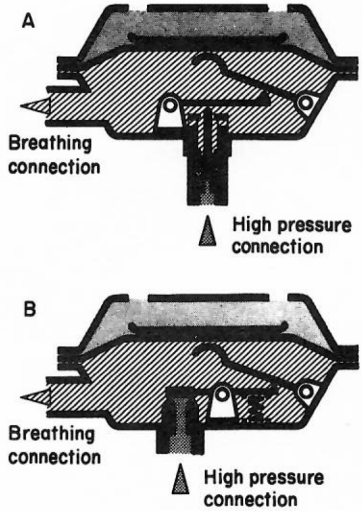


Fig. 10.23. Single-stage regulators.

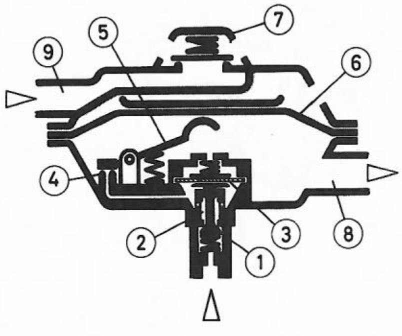


Fig. 10.24. Principles of a double-stage regulator.

1 valve
2 pressure-reducing valve, first stage
3 diaphragm, first stage
4 valve, second stage
5 lever, second stage
6 diaphragm, second stage
7 exhaust valve
8 inhalation connection
9 exhalation connection

where the valve opens against the pressure and B shows the upstream method where the valve opens with the pressure. Whichever system is used a balanced design must allow sufficient flow rate to allow for breathing resistance. In Fig. 10.24 the various parts of a double-stage regulator are shown with their various functions from first stage to second stage and the inhalation and exhalation to and from the diver's respiratory system.

Clearly, when designing a breathing system, the exhalation from the diver's lungs has to be considered as well. The human respiratory system is more comfortable when the exhalation resistance is lower than inhalation resistance. Fig. 10.25 shows the influence that the regulator position has on breathing resistance and the considerable effect hydrostatic water pressure has on this breathing resistance. As it is impossible to mount the regulator at the centre of the breathing cycle because the diver's attitude is constantly changing in the water, the most favourable position needs to be selected. Furthermore the exhaust valve needs to be close to the diaphragm of the second stage.

In Fig. 10.25, when the diver is in a face-down attitude there is a hydrostatic pressure differential of approx. +0.02 bar, due to the difference between the diaphragm and the diver's breathing centre when the regulator is mounted on the cylinder manifold. In addition the inhalation resistance has to be taken into account. In this position the exhalation resistance is less since the exhaust valve is higher than the lungs or breathing centre. If, however, with the second stage the diver is using a single hose regulator in the mouthpiece instead of the double hose, the situation is reversed because in a face-down attitude there is a greater exhalation resistance. Conversely in a face-up attitude the exhalation resistance is less as the second stage regulator is above and therefore at a lower pressure than the lungs. The extent of the exhalation resistance is to a great extent determined by the

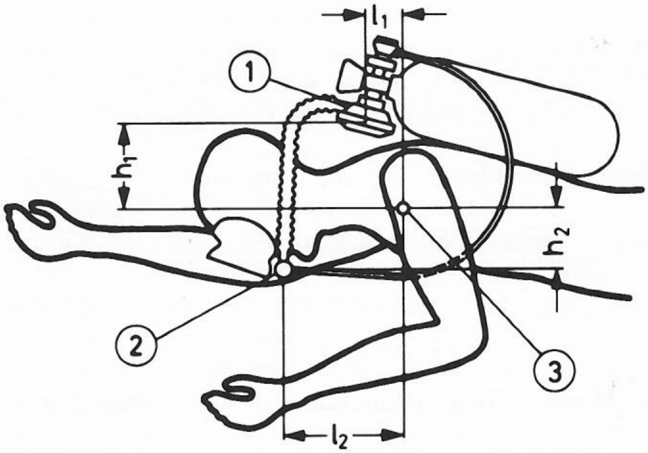


Fig. 10.25. Influence of the position of the regulator on breathing resistance.

1 double hose regulator mounted on cylinder valve
2 single hose regulator (second stage in mouthpiece)
3 respiratory breathing centre

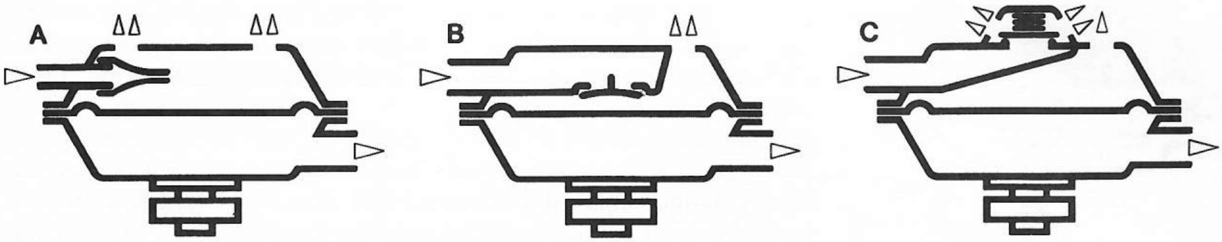


Fig. 10.26. Examples of the arrangement of exhaust valves in regulators.

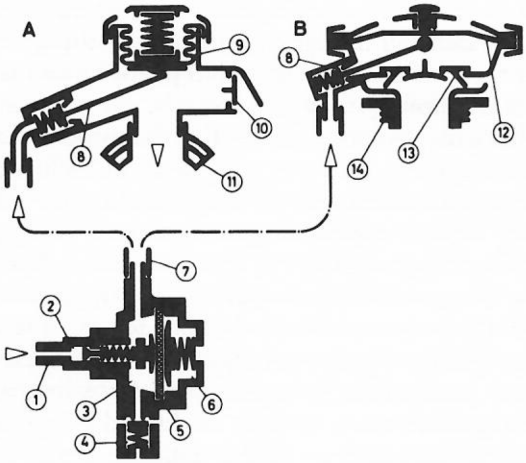


Fig. 10.27. Double-stage regulators with separate first and second stages.

A Mouthpiece regulator
B Regulator for connection to a mask

1 connection to HP storage cylinder
2 high-pressure section
3 intermediate pressure section
4 safety valve
5 diaphragm, first stage
6 regulating spring
7 connecting hose
8 tilt lever
9 bellows, second stage
10 exhaust valve
11 mouthpiece
12 diaphragm, second stage
13 exhaust valve
14 mask connection

position of the exhaust gas in relation to the centre of the body's respiratory system.

The other determining factor in an exhalation system is the design of the exhaust valve. Fig. 10.26 illustrates three principal designs. The most efficient design is one which requires the minimum displacement of water and is shown in C.

The diver breathes either from a mouthpiece or from a breathing mask with a free flow of gas circulating inside. Where the regulators are mounted on the HP storage cylinders the LP gas is passed to the diver through a LP hose, either a single hose in which case the diver exhales into the water from the mouthpiece, or a double hose where the exhaled air is exhausted at the regulator. For convenience, less maintenance and lower cost, the single breathing hose is generally used.

Double-stage Regulator System with Separate First and Second Stage. Rubber bellow hoses for inhalation and exhalation are not generally used in commercial diving as they are not rugged and are prone to damage. The use of the single hose with separate first and second stage, as illustrated in Fig. 10.27, is usual. The regulator can be fitted as a mouthpiece or integrated into an open face mask. In Fig. 10.27 the tilt valve is the basis of the whole operation, reacting to the pressure of sea water and to the respiratory requirements of the diver by opening and shutting the supply from the first stage. From a first stage reducer the gas is supplied to two types of second stage. In Fig. 10.27A a spring bellows is used to act on the tilt valve whilst in Fig. 10.27B a rubber diaphragm is used. The diaphragm is the normal method used to achieve pressure compensation. When the second-stage regulator is fitted to the mask this is the optimum position relative to the centre of breathing as illustrated in Fig. 10.25 and breathing resistance is minimized. There are a number of ways in which the regulator can be fitted to the mask. If fitted at the side near the cheek there is no need to design bubble deflectors which tend to increase the resistance. Single hose regulators will not normally free flow, whatever position the diver adopts in the water, whilst in the double hose regulator there is some likelihood of the air escaping when the mouthpiece is in a higher position than the regulator housing on the inlet to the HP supply.

When comparing the first stage of the combined double-stage regulator incorporating the first and second stage, as illustrated in Fig. 10.24, and the double-stage regulator with the first and second stages separated, as illustrated in Fig. 10.27, there is a need for an additional safety valve to be fitted between the separated first and second stages of the latter. The valve which connects the first and second stage functions on the upstream principle, where the valve closes with the pressure. If the first stage should be defective and a build-up of pressure occurs within the connecting hose between the first and second stage this would be dangerous, hence the need for a safety valve. However in the combined regulator shown in Fig. 10.24 which acts on the upstream principle, illustrated in Fig. 10.23B, there is no chance of a build-up of pressure as the valve seats against the pressure and the air would escape without the need of a safety valve.

The danger of freezing up in the first stage due to external water temperature is prevented by separating the water from the air cavity with a diaphragm whilst still allowing the hydrostatic pressure to be exerted.

Demand Regulator with Injector. Injector systems can produce large air flows with relatively small driving pressure; autonomous hard hat systems are an example of this. In the case of scuba equipment, where the air supply is restricted to the volume in the supply cylinders, a different type of injector can be used in the demand regulator. The principle is based on the fact that air moving through an injector will create a relatively large negative pressure behind the jet. Properly designed and sited, this jet can be applied to the diaphragm, thus increasing the air flow during inhalation but not increasing the inhalation resistance. Fig. 10.28 illustrates the principle of the injector as fitted to a single-stage regulator but it can also be applied to a double-stage regulator. A characteristic of the injector system is that, during the inhalation cycle, after a relatively high initial resistance is overcome, the resistance drops rapidly. If poorly designed or not functioning correctly, there can be a positive pressure which allows more air than the diver can inhale, even resulting in a continuous unchecked air flow. This can be controlled by placing an inhalation valve in the mouthpiece but this increases the initial resistance. Clearly if the injector principle is used the regulator has to be carefully designed and maintained to obtain the advantages.

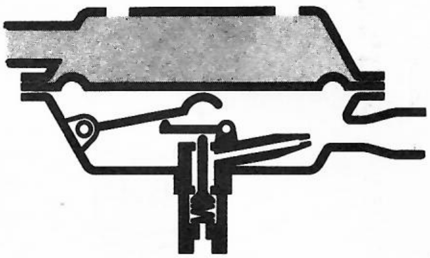


Fig. 10.28. A single-stage regulator with injector.

High Pressure Connection to First Stage. There are two standard fittings (Fig. 10.29) which connect the demand valve or regulator to the supply cylinders—an international fitting and a 5/8 inch screw connector with an O-ring seal. Both fittings can achieve a pressure seal by hand tightening, without tools, the pressure itself creating a seal. Whichever system is used for the connection, a compatible adaptor is needed to recharge the supply cylinders.

Breathing Connections. Fig. 10.30 illustrates the various types of regulator breathing connections. Five main types can be identified as follows:

1. Hood connection.
2. Full face-mask connection.

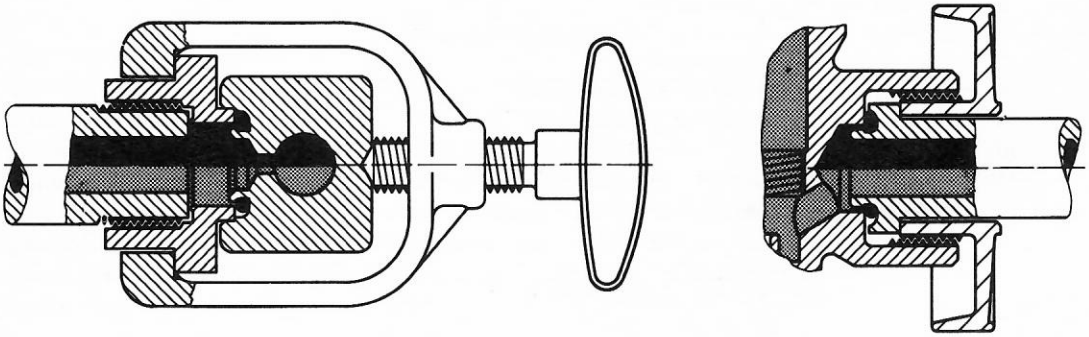


Fig. 10.29. High-pressure cylinder valve connections.

A ‘international’ connection

B 5/8 in screw connection

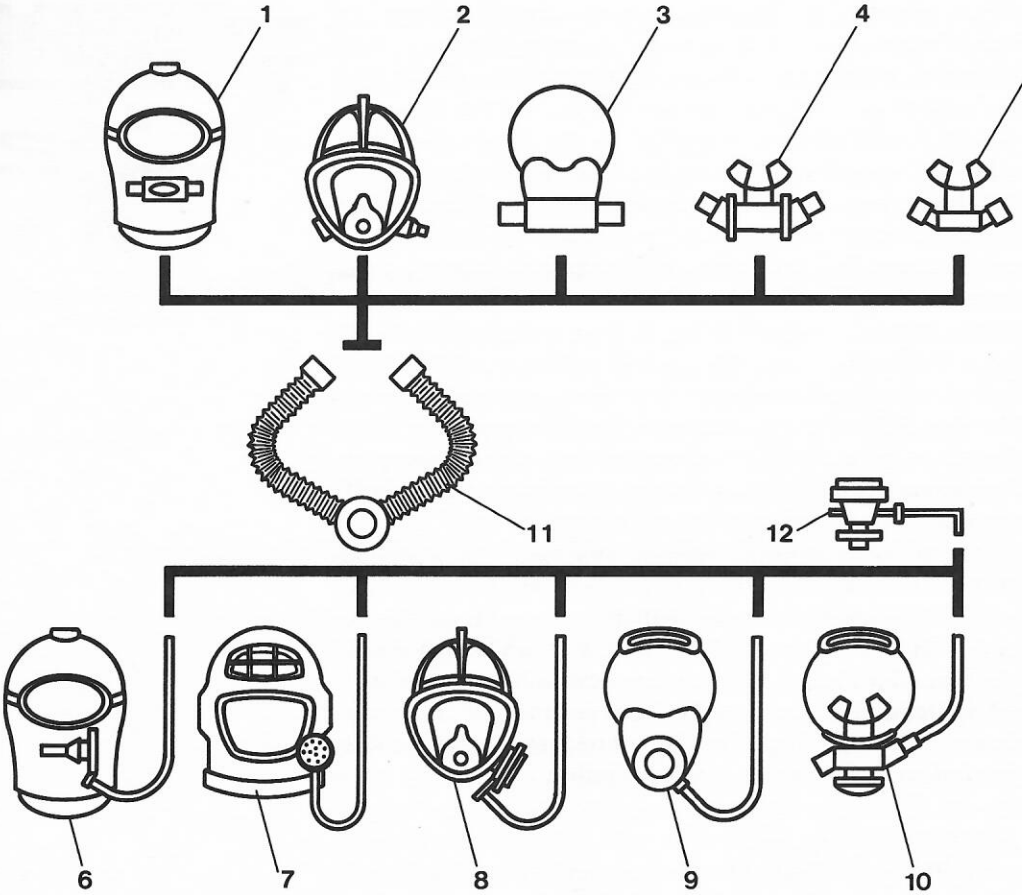


Fig. 10.30. Breathing connections for regulators.

1 hood for constant-volume suit (with mouthpiece or oral mask)
2 diving mask with internal mask
3 oral mask
4 mouthpiece with non-return valves
5 mouthpiece without check valves
6 hood for constant-volume suit with knuckle thread connection
7 helmet with integrated regulator
8 diving mask with knuckle thread connection
9 oral mask with knuckle thread connector
10 mouthpiece regulator
11 double-hose regulator
12 first stage of single-hose regulator

3. Helmet connection.
4. Oral–nasal connection.
5. Mouthpiece connection.

For commercial use only, the hood, face-mask and helmet are in general use. They offer the best protection against the cold and polluted water. With heavy duty constant volume suits an oral–nasal mask is more often used to facilitate communication. If wet suits are worn a full face-mask is considered more practicable.

A full face-mask fitted with an oral–nasal breathing system will have a purge valve to deflect breathing gas over the face plate. Purgers will demist the face plate, expel any water and flush through the dead spaces inside the mask. An oral–nasal mask will also reduce the internal volume of dead space where a build-up of CO_2 may occur. A well designed mask will have a rubber face expansion seal to fit comfortably around the diver's facial contours.

If a double hose regulator is used there is a considerable volume inside the hose which, if filled with water at some stage, will have to be blown out. This volume can be reduced by fitting non-return valves on each side of the mouthpiece and the amount of water can be reduced to a minimum. This is important if, in an emergency, two divers are using the same mouthpiece and supply as the water can be evacuated from the small area in the mouthpiece. The twin breathing hose tubes are made of rubber which is oil-resistant and, as far as is possible, durable in sea water (Neoprene).

To reduce the flow resistance of the internal breathing gas the inside of the tubes should be smooth. The breathing tubes, however, are naturally bulky and exposed to damage under water and, therefore, in commercial diving when breathing on demand from a regulator, the preferred method is to have a single hose which connects the first stage at the supply source on the cylinder to the second stage on a mask, helmet or hood. The connecting low-pressure hose is made as short as possible and is well protected close up to the diver's body.

In sport diving single hoses are more common for the same practical reasons as used for commercial diving. Mouthpieces are usually fitted instead of commercial hoods or full face-masks as there is no requirement for communication, which precludes the use of a mouthpiece, and also for convenience with the smallest possible sealing area around the mouthpiece.

Air storage cylinders

The diving time or endurance of a self-contained open-circuit scuba compressed air diving set is dependent on the volume and pressure of air in the supply cylinders, the depth of the diver and the air consumption of the diver. When the diver is swimming at medium speed near or on the surface the average consumption of air is 20–28 litres/min, increasing to 50–80 litres/min if working hard. These average figures will fluctuate with different divers. The volume of the lungs will remain the same with increase in pressure but the consumption will increase as the depth increases. The consumption will double from the surface to 10 m depth (2 bar) and treble at 20 m depth (3 bar). Assuming an air consumption rate of 22–24 litres/min on the surface, Table 10.7 shows diving time as a function of diving depth and air storage supply. Decompression is required for diving

Table 10.7 Diving time as a function of diving depth and air supply

Diving depth (m)	*Diving time* (min) *with air supply of* 1400 litres	1600 litres	2800 litres	4200 litres
0	60	70	120	180
5	40	47	80	120
10	30	35	60	90
15	24	28	48	72
20	20	23	40	60
25	17	20	34	51
30	15	17	30	45
35	13	15	27	40
40	12	13	24	36

exposures in the shaded area and furthermore the values do not take into account the time for descent and ascent. The values in Table 10.7 are shown graphically in Fig. 10.31. The no decompression limit is represented by a dotted line. Should this position lie to the left of the dotted curve, for any given depth and time, it will normally be possible to ascend to the surface without decompression. Should the depth time position lie to the right of the curve, decompression is needed and stops will have to be carried out according to the relevant decompression table. For example, from the graph it is possible to surface without stops from 40 m when 1400-litre air storage cylinders are used. It is therefore technically possible to select the optimum air storage cylinders in terms of volume to provide sufficient air for a preselected depth and time mission with an adequate reserve. Air storage cylinders carried by divers are normally filled to a pressure of between 200 and 300 bar. Cylinders vary in capacity and are manufactured in alloy steel or aluminium. The common range of capacity is between 7 and 10 litres but some cylinders have a capacity of 15–20 litres. Aluminium cylinders are generally more popular because they are lighter than steel and easier to maintain, but they are expensive. Steel cylinders are more prone to corrosion and need special preventive treatment, especially inside where the onset of corrosion is more difficult to detect. On the outside a zinc spray is applied and then a zinc-enriched paint. Any rusting should be removed. For the inside no entirely reliable method has been devised and generally prevention is the method used by ensuring that the charging air is dry and properly filtered, that the charging process is not too rapid causing excessive heat and that there is some residual pressure inside, when empty, to prevent any moisture entering.

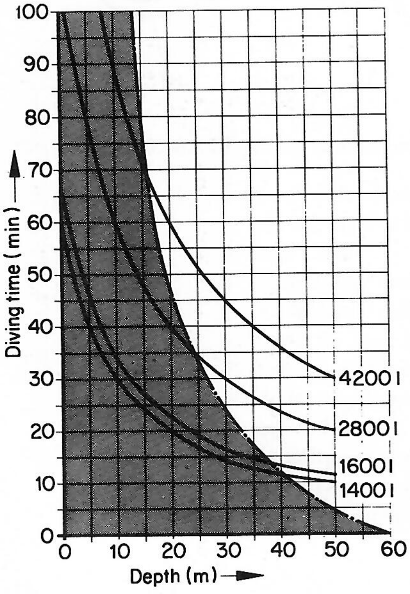


Fig. 10.31. Diving time as a function of diving depth for different air supplies (air consumption rate 22–24 litres/min), showing the no-decompression limit (dotted line).

Cylinders should be colour coded at the shoulder to conform to national regulations and are more easily recognizable under water if coloured orange or white. Cylinder valves should be made in brass or stainless steel to avoid seawater corrosion. Often the valves are protected against impact with rubber sleeves. In some designs the

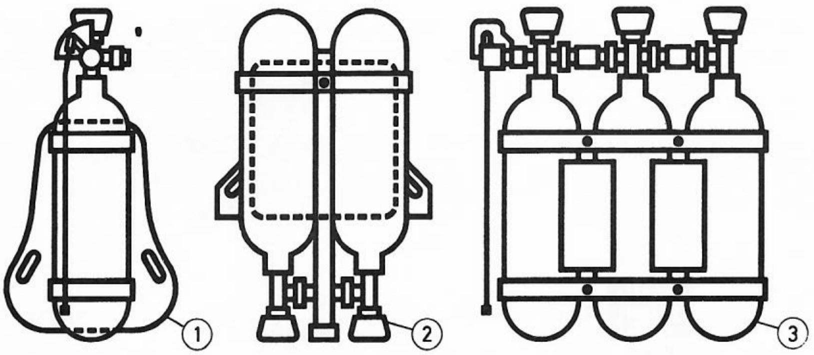


Fig. 10.32. Air cylinder assemblies.

1 Single tank with back pack
2 Double tanks with frame and back pack
3 Three tanks secured in a frame. This assembly is also produced in a triangular form

valves incorporate an air reserve valve if they are not fitted with a pressure contents gauge. To increase endurance two or sometimes three air cylinders are joined together with a cylinder block sometimes designed to allow for variatons in the number of cylinders.

Cylinder Backpack and Harness. The cylinders are secured to the body either directly with a canvas webbed harness or onto a plastic backpack which is moulded to fit the contours of the diver's back. Fig. 10.32 illustrates the backpack and the use of a frame to hold multiple cylinders and act as a shock absorber. The harness, with or without a backpack, must hold the cylinder stationary on the diver's back in the optimum position for breathing. The harness will be fitted with a quick release to discard the breathing equipment in an emergency. Fig. 10.33 illustrates an ideal harness to carry out these functions. The weight of the cylinder assembly is taken by the two shoulder straps, adjusted with D rings, and padded over the shoulders to distribute the weight. A waist belt stops the cylinders from moving and contains the quick release buckle in the centre. Ideally the release should be made with one movement. It should be carefully maintained and tested.

Air Reserve Valves and Pressure Gauges. Although not mandatory, some diving breathing cylinders are fitted with reserve valves which allow a residual volume of high-pressure gas to remain in the cylinder. This air reserve mechanism should serve two purposes: first, to give the diver warning that his air supply is getting low, and second, to provide sufficient air to enable him to surface. On a double cylinder one cylinder can be retained as the reserve, only opened by an air reserve pull rod which equalizes the pressure. The warning that the main supply is running low is given by a resistance in breathing which is caused by a spring-loaded check valve which will begin to close as the air pressure in the main cylinder drops. By pulling on the equalizing rod and equalizing the pressure the diver continues to

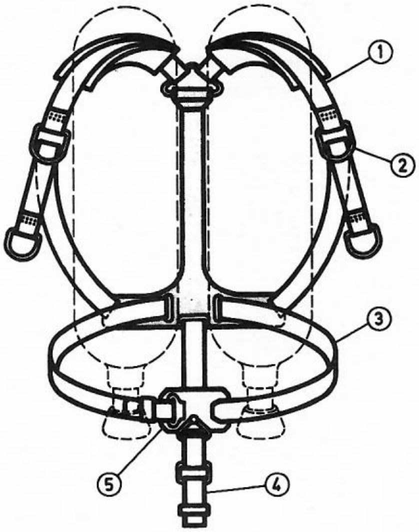


Fig. 10.33. Harness for an air scuba.

1 shoulder strap
2 double-D buckle
3 waist strap
4 battery strap
5 quick-release buckle

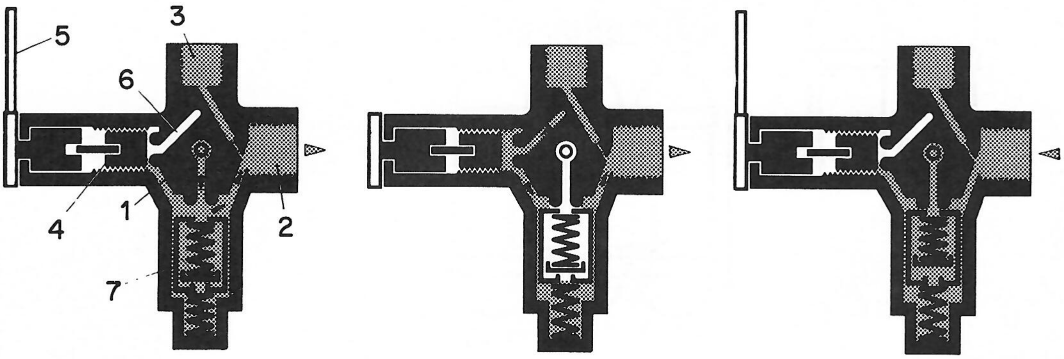


Fig. 10.34. Function of an air reserve system with manual cancelling installed in a cylinder shut-off valve.

A Air flow to regulator with pressure above 40 bar, valve stem lifted

1 cylinder valve seat
2 regulator filling connection
3 connection for pressure gauge
4 air reserve valve
5 lever for air reserve
6 bore directly to cylinder
7 valve stem

B Air flow to regulator with valve opened

C Air flow during recharge (air reserve valve closed), the check valve in the valve stem pushed open

breath normally. This process can, of course, be repeated but there is a danger that the diver may forget the number of times he has equalized, or leave the reserve valve open. Therefore the diver should never assume that the reserve cylinders will automatically provide additional air and should, when breathing resistance is felt, start the ascent to the surface and terminate the dive. Fig. 10.34 illustrates the action of the reserve valve. The design should ensure that the rod actuating the valve cannot be accidentally activated by the diver. An automatic device fitted as part of the regulator is becoming more widely used but it is not entirely acceptable as it may not give a positive warning to the diver.

A simple procedure is to insert a valve into the first stage of the regulator which progressively increases the breathing resistance for the remaining 30 bar of pressure in the supply cylinder. Although it gives a warning this system cannot provide additional reserves of air and for that reason is not entirely adequate.

Another method involves using optical warning signals projected onto the face mask but these are sophisticated electropneumatic systems which are only applicable to advanced closed-circuit, deep diving breathing systems where additional information on the partial pressure of oxygen may also be displayed.

Whatever system is used, a pressure gauge allowing the diver to read the residual pressure in the supply cylinder is essential. The most common arrangement for self-contained air diving equipment, as illustrated in Fig. 10.35, is two supply cylinders with the supply valve manifold facing downwards and a single-hose two-stage regulator with first stage on the air cylinder and second stage on the regulator. To provide reasonable endurance at depths of 30–40 m, extending to 50 m, the air cylinders will contain at least 2800 litres, with two cylinders each with a capacity of above 10 litres, connected to a face mask via the regulator and fitted with a pressure gauge.

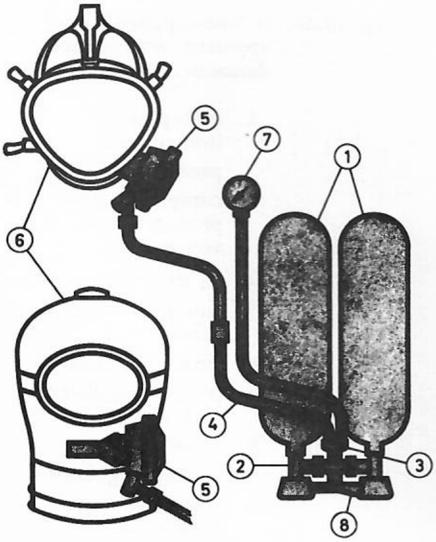


Fig. 10.35. A self-contained air breathing apparatus with cylinders facing downwards.

1 air cylinders
2 cylinder valves
3 pressure regulator
4 pressure hose
5 demand regulator
6 full-face diving mask or hood
7 pressure gauge
8 air reserve lever

Surface Demand Diving Equipment (SDDE)

The development of modern SDDE is an extension of standard diving where air is supplied from the surface, allowing greater endurance with a reduction in flexibility. Since, however, the diving depth will not normally exceed 50 m, with an 80 m umbilical, a wide area of about 1000 m² can be covered which is sufficient for most commercial operations. Early surface demand diving equipment comprised a demand regulator worn on the back and connected to a mouthpiece or face mask with a low-pressure hose. The regulator was supplied from the surface with air at 6–7 bar by an umbilical. In the event of a failure of the air supply, the diver made a rapid if not an emergency ascent to the surface. The present-day arrangement is shown in Fig. 10.36 where the air is supplied to the regulator and to the diver from either a bank of high-pressure cylinders or a low-pressure tank with compressor. In addition the diver carries an emergency supply on his back, sometimes referred to as bale-out bottles. The system is compatible for use from a diving bell, habitat or lock-out submersible. The components are identical to a self-contained breathing set except in the function of the reserve bale-out cylinder. The cylinder is fitted with a pressure regulator and an automatic shuttle valve which automatically switches to air reserve in the event of a surface air failure. The main functions of the automatic shuttle valve are as follows:

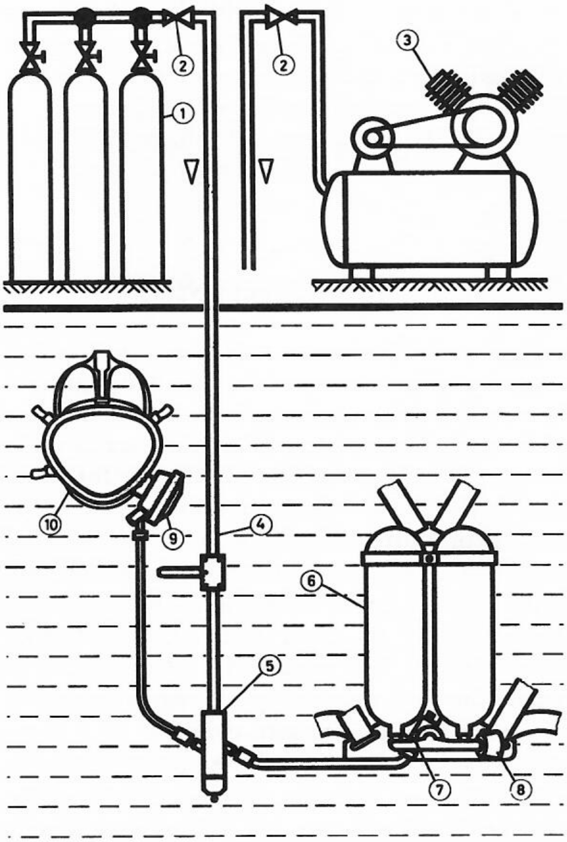
1. To supply air to the diver in the event of the failure of the main supply.
2. To indicate positively to the diver that he is switched to his reserve supply.
3. To provide an additional safety function by ensuring that the total breathing system cannot be operated unless the reserve cylinder is open ready for emergency use.

Diving suits

The development of diving suits for different situations has been as progressive as the development of the breathing systems to which they have to be compatible. Until 40 years ago the only suit used was the canvas standard diving dress, unaltered in design since its inception. Diving was limited to salvage, harbour works and naval operations, for which it was ideally suited. The introduction of the demand valve, high-pressure and closed and semi-closed breathing systems demanded variations to suit each and every need. The

Fig. 10.36. A hose-supplied diving apparatus with surface demand.

1 high-pressure storage bank
2 pressure regulator
3 compressor (low pressure) and volume tank
4 air supply hose
5 automatic shuttle valve
6 air reserve tanks
7 pressure regulator with manifold
8 cylinder valve
9 demand regulator
10 diving mask or hood



development of the light-weight helmeted diving suit in modern materials was a great improvement on the standard dress, as was the wet and dry suit.

Standard diving dress

The standard diving suit, relatively unchanged since the original Augustus Siebe suit in the 19th century, is based on a helmet and a diving suit joined as one part, allowing control of buoyancy by regulation of the amount of air inside the suit. The air is also the breathing gas. A 'hard hat' helmeted diver is illustrated in Fig. 10.37. The dress is made to fit closely around the body up to the chest but allows adequate clothing and thermal protection to be worn over the surface of the body. The dress therefore covers the body except for the hands and head. Whereas constant pressure corresponding to a water height of B_1 and B_2, shown in Fig. 10.37, acts on the upright diver from the head to the lower extremity of the air bubble, the pressure increases below that to a value which corresponds to H, i.e. the depth of the foot of the diver. The feet of the upright diver, the lowest part of the body, are therefore subject to a greater pressure, which is the difference between H and B. The size of the air pocket is adjusted by opening and closing the spring-loaded inlet valve.

In other attitudes, where the diver is bending, crawling or lying

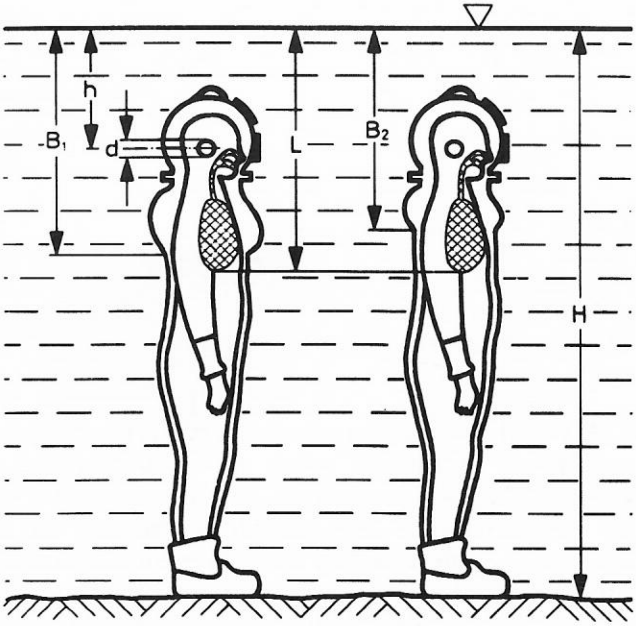


Fig. 10.37. Air cavity inside the diving dress for different settings of the air exhaust valve.

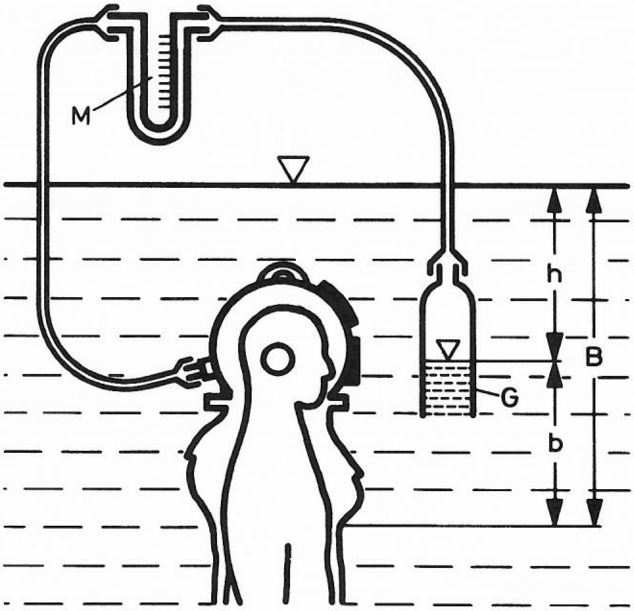


Fig. 10.38. Air pressure measurement in the helmet to determine the water height from the lower edge of the air bubble to the helmet valve.

down, the air may fill the upper parts of the corselet or diving dress before being vented out through the outlet valve. This will, if not checked, blow the diver to the surface and will be dangerous. To counter this the diver should keep the outlet valve open and remove the excess air by raising the helmet from time to time. To calculate the head of water from the bottom of the air bubble to the inlet valve, a mercury pressure gauge can be used as shown in Fig. 10.38. The container should be transparent so as to adjust for the correct height.

Table 10.8 Weight measurements directly beneath the surface of the water using standard diving dress

Variable air volume (litres)		*Absolute weight** (kg)	*Maximum inflated volume* (litres)
Neutral	41.5	173	217
Normal	15	173	217
Minimum	5	173	217

*Allowing 80 kg for the weight of the diver.

A very real danger whilst using this type of equipment is a fall, particularly in shallow water where the pressure variations are greater. A fall will increase the pressure which may not be balanced by the air pressure. It is possible to calculate the maximum safe increase in depth caused by an inadvertent fall, bearing in mind that the calculations will vary with different diving equipment due to the different internal air volumes. By weighing the diver in water the variable air volume inside the diving suit is calculated, known as V_A. To do this all air initially is vented out of the suit and then weighed. The suit is then inflated until neutral buoyancy is achieved. The difference in weight (kg) determines how many litres of air are required at that depth to maintain neutral buoyancy. For an average diving dress and helmet V_A is about 41.5 litres. Clearly the diver varies the volume of air V_A on the bottom to suit the working conditions. Table 10.8 lists the variable values of V_A when weight measurements are performed immediately below the surface of the water, the smallest value which still allows adequate respiration being 5 litres of air. In addition to V_A, the flexible volume, there is the enclosed volume, V_H, inside the helmet to which the corselet is attached. The volume V_H is the volume of the helmet less the displacement of the diver's head. Fig. 10.39 illustrates the value V_H based on an average standard diving helmet. From these values of V_A and V_H the maximum safe falling depth, h_2, can be calculated from the surface, by the formula:

$$(V_H + V_A)(h_1 + 10) = V_H(h_2 + 10)$$

Furthermore,

$$h_z = h_2 - h_1$$

which is more normally expressed as

$$h_z = \frac{V_A}{V_H}(h_1 + 10) \quad (m)$$

Therefore if $h_1 = 0$, i.e. the fall is from the surface,

$$h_z = \frac{V_A}{V_H} \times 10$$

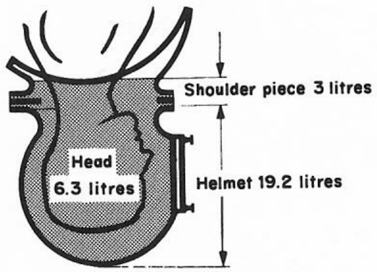


Fig. 10.39. Measuring the helmet volume with water.

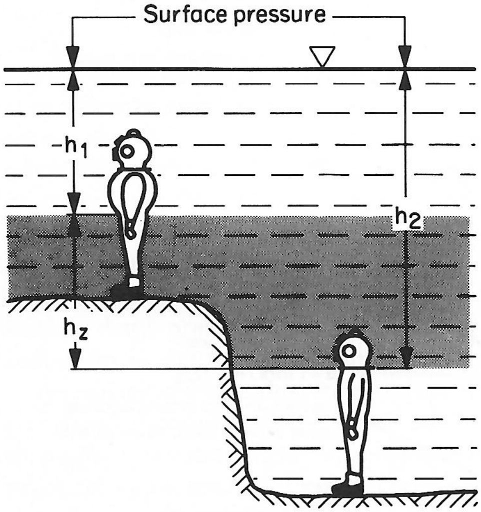


Fig. 10.40. Safe falling depth for a standard hard hat diver.

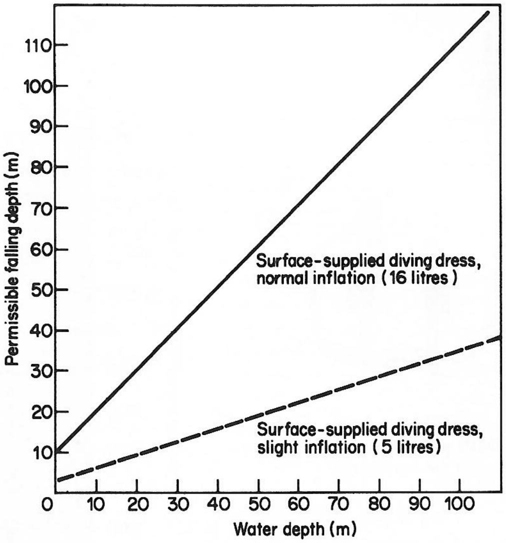


Fig. 10.41. Safe falling depth for normally and slightly inflated dress.

The figures from Table 10.9 apply in this situation. For falls from other depths, the situation will change, since the air volume in the dress and the enclosed air in the helmet will influence not only the maximum safe falling depth but also the working depth. The value of h_2 increases in direct proportion to that of h_1. Figs 10.40 and 10.41 show the safe falling depths for various types of suit.

An additional danger is that of the standard diver being blown up if he is working in a condition of neutral buoyancy and the outlet valve is restricted. If the diver is blown upwards with a positive buoyancy that cannot be controlled there is a danger of air embolism and rupture of the suit. It is possible to calculate the maximum depth that a diving suit will withstand whilst being blown to the surface. The maximum depth h_1 is calculated on the basis that the pressure inside the suit will not exceed 0.2 bar when surfaced, assuming that the suit is in a well maintained condition.

Table 10.9 Permissible falling depth from the surface

Degree of inflation	*Permissible falling depth* = h_z (m)
Neutral	26
Normal	10
Slight	3

The formula

$$h_1 = \frac{12 \times V_2}{V_1} - 10 \text{ (m)}$$

where V_1 is the volume of expandable air in a neutrally buoyant suit including helmet and suit and V_2 is the volume of air in the suit after being blown to the surface. Maximum safe depths for blowing up are given in Table 10.10 for two different sizes of suit.

Table 10.10. Maximum safe depth in the event of blowing up to the surface

	V_1 (litres)	V_2 (litres)	h_1 (m)
Medium suit	70	113	9.4
Large suit	70	122	10.8

Air Requirement for Standard Equipment. The air flow to the diver is determined by the working depth and the performance of the

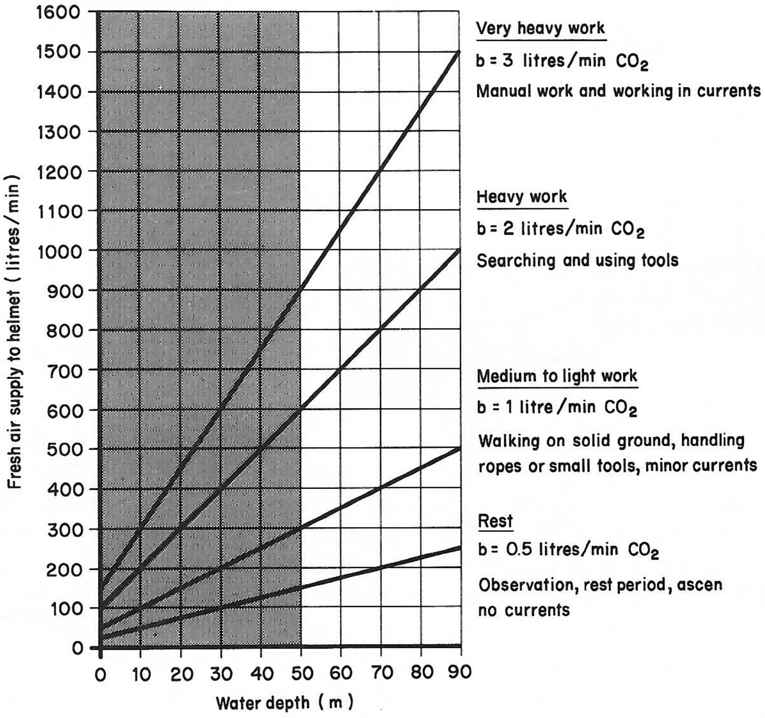


Fig. 10.42. Air requirement for a diver in standard dress for different levels of work effort, with a maximum CO_2 partial pressure of 0.02 bar at various water depths.

diver. The onset of CO_2 poisoning is a more immediate problem than lack of oxygen and although flushing the helmet will reduce the CO_2 it will not eliminate it to the same extent as breathing at atmospheric pressure. It is, however, sufficient if the partial pressure of CO_2 does not exceed 0.02 bar. Since CO_2 partial pressure is directly proportional to the absolute pressure at the respective diving depth, assuming constant CO_2 production, increased air flows are needed to flush the CO_2 out of the system. Fig. 10.42 shows the air requirement for a diver plotted with various degrees of exertion whilst working, on the basis that the CO_2 partial pressure does not exceed 0.02 bar in the helmet. Although the graph is calculated to diving depths of 90 m it is normal nowadays to limit air diving to 50 m.

Air Supply Systems for Standard Diving Equipment. Normally the air is supplied through an air hose or umbilical, sufficient to overcome the bottom pressure and the pressure losses through the hose and to ventilate the diver's helmet to maintain a non-toxic partial pressure of CO_2. An alternative arrangement is to carry the air supply in cylinders on the back, but this is rarely used as the amount of air needed and the very limited capacity of the cylinders will reduce the endurance to the extent that it becomes impractical.

In the past air was supplied by hand pumps but nowadays the air is supplied direct from LP volume or HP storage cylinders on the surface.

Fig. 10.43 shows the arrangement where the main inlet valve is controlled manually by the diver and Fig. 10.44 where the supply is automatically controlled by an air flow regulator. The main advantage of the automatic system is that in the event of a fall and lack of control the increased pressure can be compensated for. A further improvement on this design is shown in Fig. 10.45 where the automatic regulator is positioned on the diver's chest; this allows the diver fine control over his air supply. A further advantage is that the intermediate pressure to the regulator can be higher, allowing a reduction in the size of the air hose giving less drag.

A semi-closed-circuit system is shown in Fig. 10.46 where the air is circulated through a CO_2 absorbent cannister. The air is supplied through a constant mass injector system but, as stated, has little practical application due to severely limited endurance.

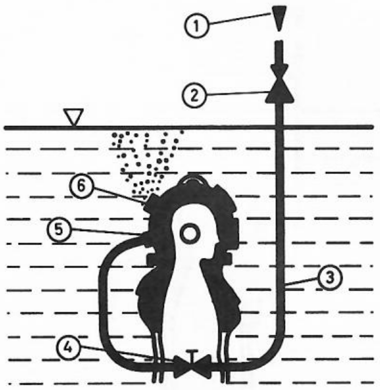


Fig. 10.43. Surface-supplied diving dress with a manually operated air supply.

1 air supply
2 pressure regulator
3 air hose
4 regulating valve
5 helmet connection
6 air exhaust valve

Standard diving dress equipment

The modern standard dress includes the equipment illustrated in Fig. 10.47. The helmet is still manufactured in copper or brass sheet and connected to the breast plate or corselet by an interrupted thread and locked. The diving dress, made of strong vulcanized material, has a heavy rubber collar with bolt holes which is attached to the corselet and secured with corselet brasses. The diving dress is strengthened in those parts which are subject to wear and tear, such as the elbows and knees. The seal around the wrists is achieved by using rubber cuffs. The diver enters the suit by expanding the rubber collar. The helmet will usually have two side windows and one front window and sometimes a top window. The front window with the largest area can be unscrewed and removed. The faceplates may have protective bars fitted on the outside and be made of safety glass. The air hose is connected to the non-return valve at the back of the helmet. The air is conducted around the inside of the helmet and through air ducts to give the best ventilation and prevent any build-up of moisture on the faceplates. The foul air escapes through an outlet valve, usually situated on the right side of the helmet near the diver's ear. A non-return valve is fitted, which works in the opposite way to the inlet valve, allowing the air to escape when at a slightly higher pressure than the surrounding water, and preventing the water from entering. The valve can be temporarily opened by pressing the protruding spindle with the movement of the diver's head inside the helmet or manually from outside. This allows the diver to control his buoyancy. Additionally there is a spitcock which is sometimes fitted in the front of the helmet to act as an outlet valve for further control or to draw water into the helmet to clear the front faceplate. A line telephone is fitted to the helmet. Additional safety features will

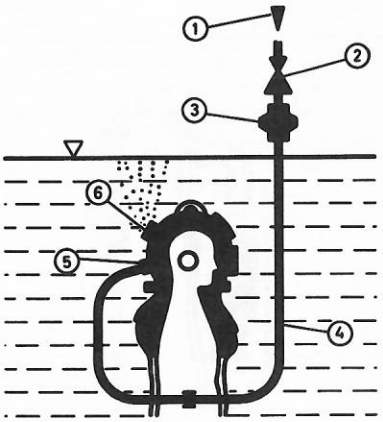


Fig. 10.44. Surface supplied diving dress with gas flow automatically regulated.

1 air supply
2 pressure regulator
3 diver regulator
4 air hose
5 helmet connection
6 air exhaust valve

include welding visors and the insulation of the helmet during welding.

To counteract the large volume and buoyancy in the upper part of the standard dress, weights need to be distributed around the lower portion of the body to give good stability. In Fig. 10.48A the weights are distributed in such a way that maximum relief and stability is achieved when working in the bent position. By wearing a crotch weight vertically below the air cavity around the chest and helmet the diver's boots can be made lighter. In this arrangement the front weights can also be used as air storage with 400 litres at a pressure of 200 bar, although this is an unusual design. Fig. 10.48B shows the weighted belt favoured by the US Navy and Fig. 10.48C a front and back weight used mainly by British and Russian divers.

The boots are made of stout leather with brass toecaps and wooden soles onto which are attached lead soles. Alternatively they may be of cast iron with leather straps.

The airpipe or umbilical is designed not to kink, buckle or be squeezed. It may be positively or negatively buoyant, although it is usually the latter to withstand currents.

Fig. 10.49 shows a manual air regulator for use where no automatic regulator is fitted. This arrangement, where the valve is on the left side of the chest and easily operated with the diver's right hand, is favoured by British and American divers. A short hose leads from the valve to the helmet and a fine control of the air is achieved by using a needle valve. The pressure is adjusted on the surface to about 6–7 bar above the ambient pressure of the diver. During the ascent it is reduced to 3–4 bar above the ambient pressure.

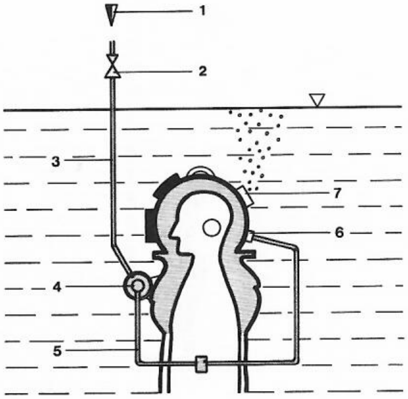


Fig. 10.45. Surface supplied diving dress with gas flow automatically regulated by a regulator on the diver's breast plate.

1 air supply
2 pressure regulator
3 intermediate pressure hose
4 diver regulator
5 air hose
6 helmet connection
7 air exhaust valve

Standard deep diving dress

Before semi-closed, mixed gas, self-contained breathing apparatus and light-weight deep diving helmet systems were introduced, within the last twenty years, almost all deep diving was carried out using the standard diving suit, with oxy-helium gas. In order to keep the carbon dioxide levels within acceptable limits the flow rates of the breathing gases had to be very high and therefore also the cost. To conserve gas, circulation systems were developed which led to the further development and the introduction of the oxy-helium lightweight helmet (Fig. 10.50). The CO_2 absorbent unit is carried on the back. An injector system supplies a metered quantity of fresh gas which is then circulated around the helmet and passed through the CO_2 absorbent cannister. At depths of more than 60 m the supply would be about 7 bar above ambient pressure, reducing with lesser depths to about 3.5 bar. By introducing a circulation system, only about one-fifth of the fresh gas is needed to ensure a sufficiently low CO_2 content in the helmet. A deflector plate is fitted in the absorber to prevent channelling. Normally the CO_2 absorbent unit is active for about three hours, with an additional reserve. The circulatory system can be by-passed so as to revert to an open demand system.

Although standard equipment is rarely used for deep diving nowadays, particularly in north-west Europe where common

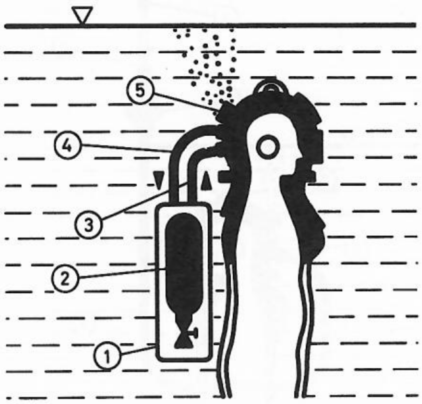


Fig. 10.46. Autonomous semi-closed diving dress with back unit and without air hose.

1 back unit with CO_2 absorbent
2 high-pressure tanks
3 circulating hose, gas input
4 circulating hose, gas output
5 air exhaust valve

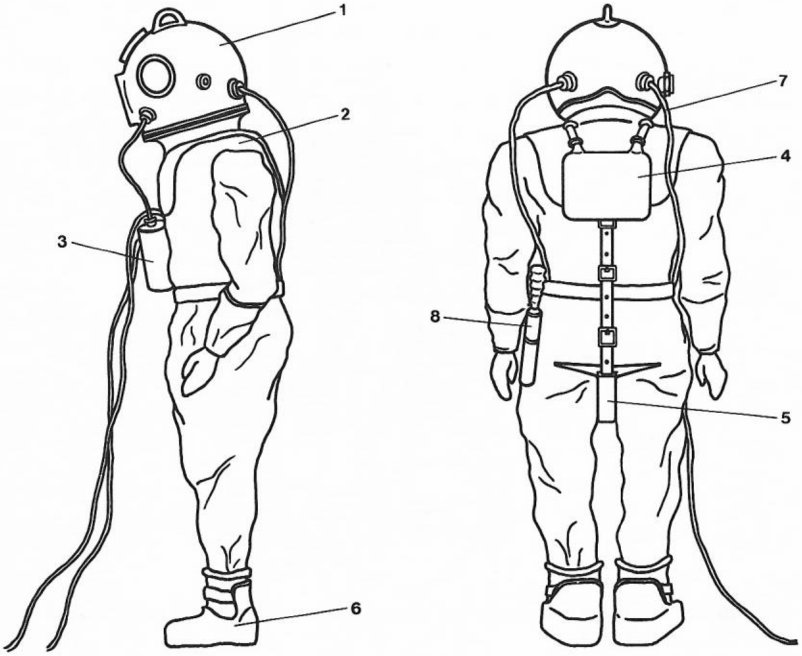


Fig. 10.47. Diver with surface-supplied standard diving dress.

1 helmet with breastplate
2 diving dress
3 front weight with compressed air tanks and connecting hose
4 back weight
5 crotch weight
6 boots
7 helmet air supply hose
8 knife and belt

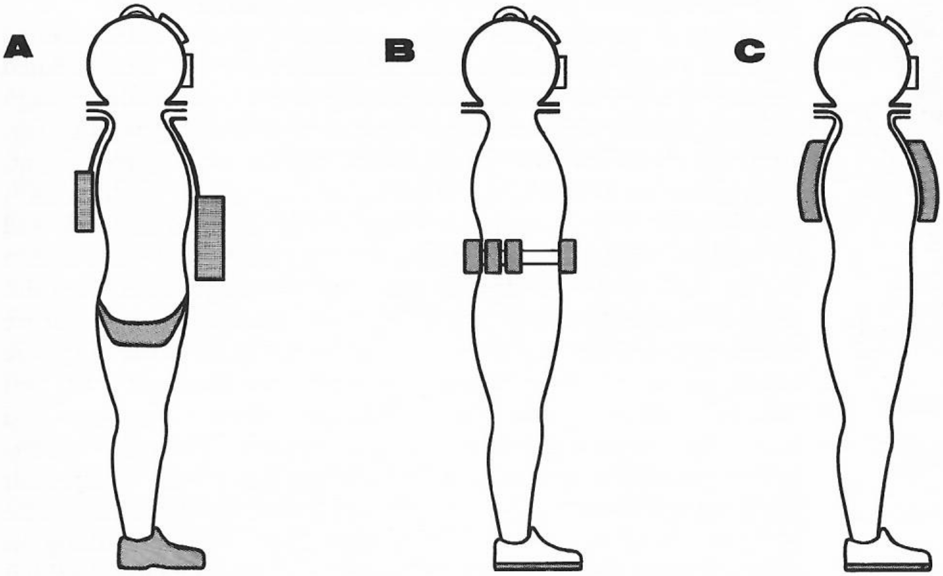


Fig. 10.48. Weight distribution in different standard diving dress.

A German diving dress
B American diving dress
C British diving dress

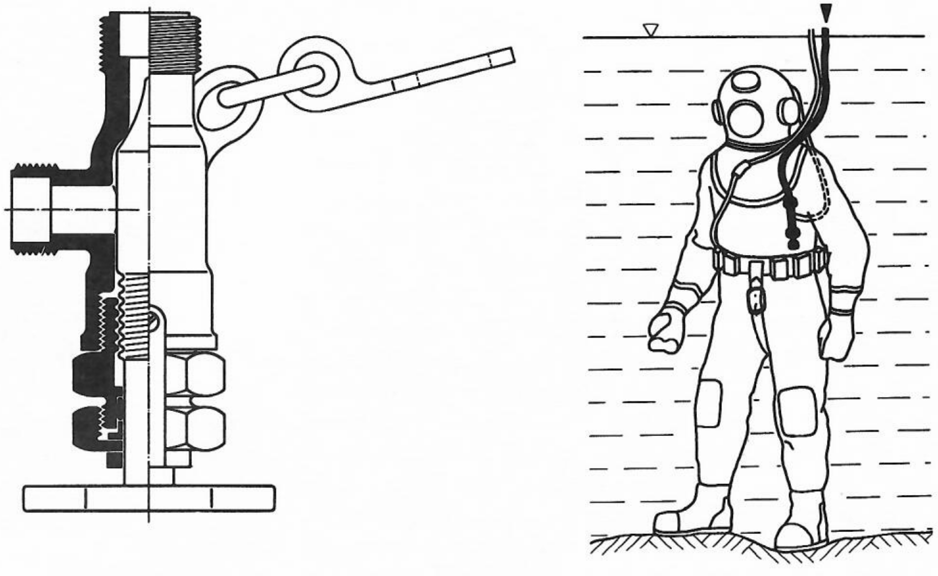


Fig. 10.49. Position and cross-section of an air control valve on a standard diving dress.

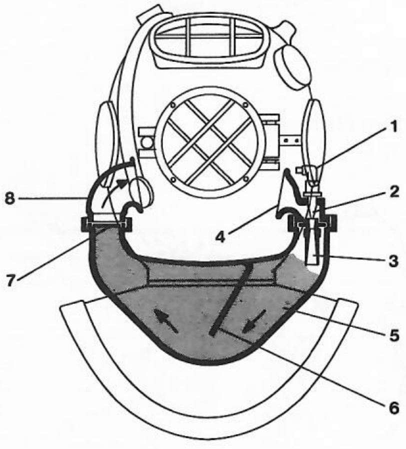


Fig. 10.50. Injector and carbon dioxide absorbent canister for deep diving dress.

1 helium-oxygen supply
2 flow regulator
3 injector
4 intake connection to helmet
5 CO_2 absorbent canister
6 baffle
7 wire mesh strainer
8 exhaust union to helmet

practice is to limit surface demand equipment, whether air or mixed gas, to 50 m, it is still used in various parts of the world and is popular with commercial divers in the States and the US Navy where it may be used to depths of 90 m.

Self-contained standard mixed gas breathing set

There are certain, but not many, conditions when a self-contained standard diving set can offer some advantages over a surface-oriented standard gear, in particular where strong currents can produce a high drag effect on the air-breathing air hose or when entering wrecks. Fig. 10.51 shows a back view of the standard self-contained equipment, designed to operate effectively to depths of about 40 m. The CO_2 absorbent cannister is located between the compressed air bottle and the oxygen bottle. The breathing cycle through the helmet is shown in Fig. 10.50, with fresh oxygen replacing the oxygen consumed and an absorbent unit removing the CO_2. Oxygen and compressed air are discharged simultaneously from two cylinders and a desired mixture can be obtained. The mixture may vary from about 60% O_2 and 40% N_2 to 40% O_2 and 60% N_2. The use of these oxygen-enriched breathing mixtures will additionally increase the endurance on the bottom, not only because of the recirculation and reuse of gases but also because bottom times are increased without decompression as the body tissues are absorbing less nitrogen. Open-circuit breathing on air is not practicable as the flow requirements would be in the region of 160 litres/min. In the system illustrated in Fig. 10.51 the pressure of the breathing gases is initially reduced to about 10 bar and, since the diaphragm of the reducer is exposed to the surrounding ambient pressure, the additional pressure is compensated for and the gas flow is

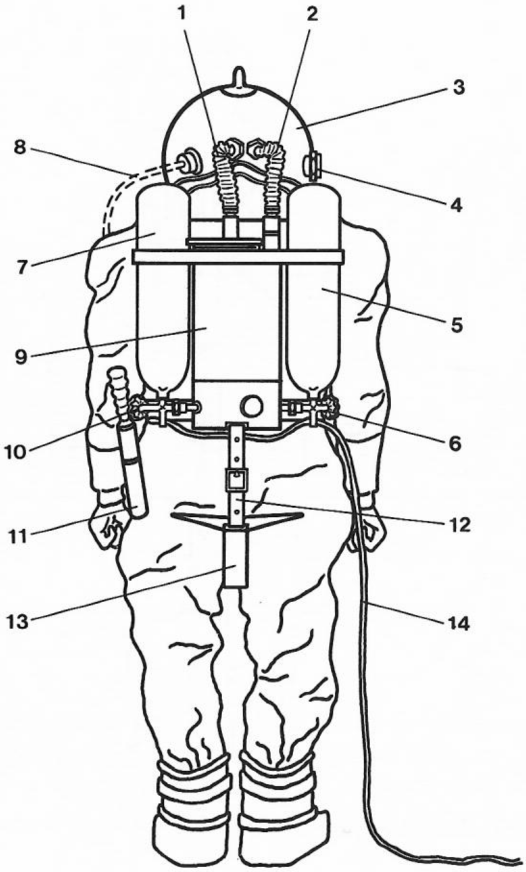


Fig. 10.51. Self-contained mixed gas standard dress.

1	mixed gas intake
2	mixed gas exhaust
3	helmet
4	gas exhaust valve
5	compressed air cylinder
6	compressed air cylinder valve
7	compressed oxygen cylinder
8	telephone cable
9	CO_2 absorbent cannister
10	compressed O_2 cylinder valve
11	diving knife
12	weight harness
13	weight
14	communications and signal line

increased as the depth increases. The gas flow passes from the regulator, through the injector nozzle. With a driving gas flow of 3.6 litres/min the air circulates at about 100 litres/min. The system incorporates a safety valve and a pressure contents gauge. The CO_2 absorbent cannister is interchangeable. The oxygen content of the mixture can be varied within the limits of oxygen partial pressure, at least 0.2 bar with an upper limit dependent on exposure. Although oxygen-enriched mixtures are more economical in terms of endurance, in terms of cost air breathing is more economical as the oxy-nitrogen mixtures have to be prepared and need to be pre-mixed and tested.

The rigid helmet

The improvement in design of the rigid helmet has been very rapid over the last ten years. Now designed to fit onto a light-weight dry suit, the system retains some of the advantages of the heavy standard equipment and some of light-weight self-contained equipment. By using glass-reinforced plastic a very light helmet can be moulded in many designs which would be impossible working with copper or other metals. Rigid helmets can be made smaller and more comfortable. Fig. 10.52 illustrates a modern rigid helmet which

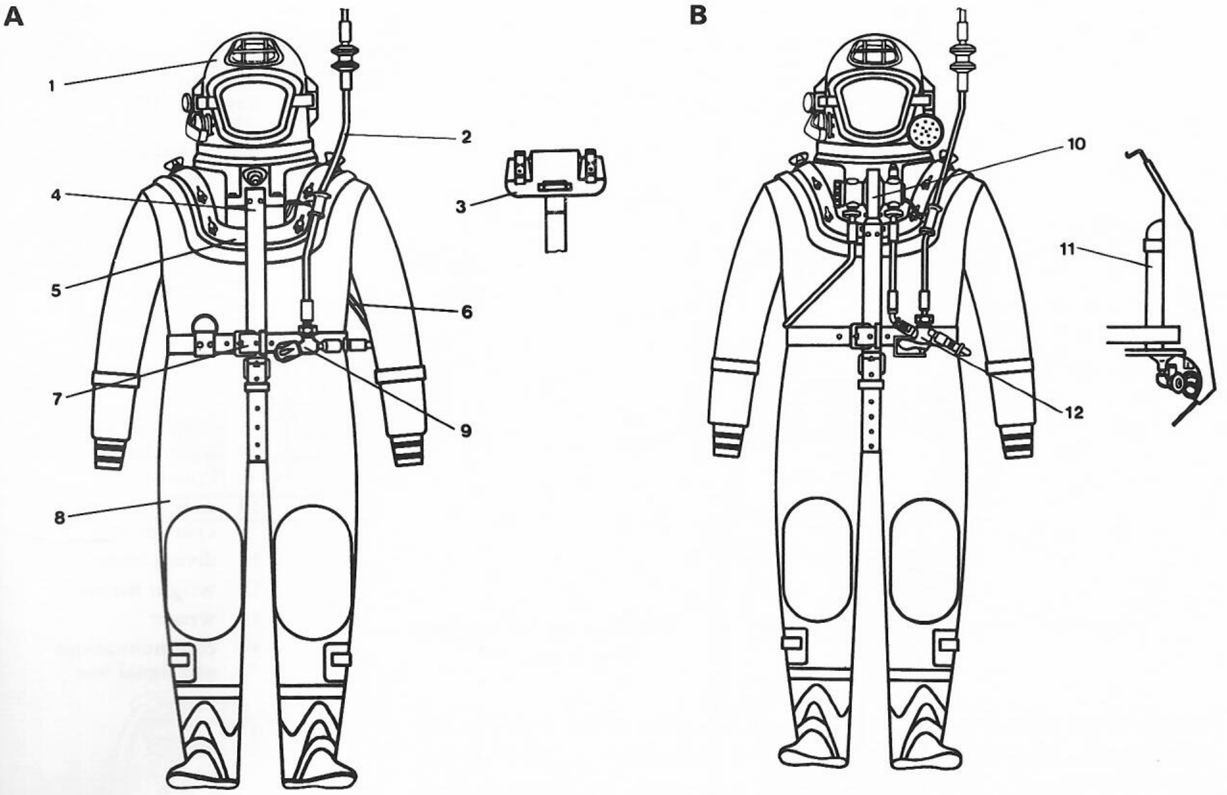


Fig. 10.52. Compact helmet systems

A Manual air control

B Diver regulator and air reserve unit

1 diving helmet
2 supply hose
3 back weight
4 front weight
5 collar
6 connecting hose
7 belt
8 heavy diving suit
9 manual control valve
10 automatic supply control
11 reserve air supply
12 emergency switch-over valve

seals onto a light diving suit, giving the diver the flexibility of free swimming with flappers in any attitude or a more rigid upright stance wearing boots. This light-weight equipment is nowadays accepted for diving off-shore.

The helmet, although usually designed with a locking seal which makes a waterproof seal with the collar of a dry suit, can be used with a wet suit. The seal is made around the neck of the diver; although uncomfortable, this is preferable in warm waters where a dry suit would be unbearably hot. The use of these compact, smaller helmets or band masks is now accepted for general use in all but very shallow water, used with a wet suit, a dry suit or a heavy diving suit adapted to fit the helmet. In all but the latter, the equipment can be used for operations from a diving bell.

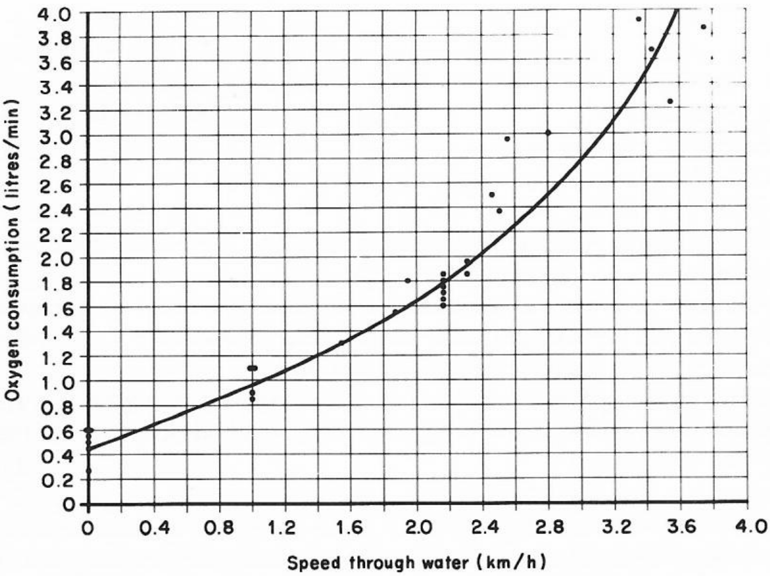


Fig. 10.53. Oxygen consumption during distance swimming.

Fig. 10.69 shows a system of supplying gas on a closed-circuit principle, circulating around the helmet and being returned to the bell. Most modern diving practices use an open-circuit system, supplying gas to the helmet and expelling the air to the surrounding water.

Calculation of Gas Mixtures

Although oxy-nitrogen gas mixtures are not normally used in commercial diving in shallow waters because of the simplicity of compressed air and passing it through the air hose to the working diver, they are used in certain situations in self-contained equipment where endurance is the prime objective. In deeper waters below about 50 m the introduction of helium as an inert gas and the selection of the correct composition of oxygen and the inert gas, nitrogen/helium, and the flow rate required to provide sufficient oxygen to the diver is essential. This is particularly important in semi-closed- or closed-circuit systems where much of the gas is being reused.

Oxygen content of a gas mixture

For the calculation of the total oxygen flow rate in a mixed gas flow the following formula can be applied:

$$O_{2\,\text{tot}} = Q \times O_{2\,\text{per}} \times 0.01 \text{ (litres/min)}$$

with $O_{2\,\text{tot}}$ = oxygen component of total gas flow (litres/min)
Q = total gas flow rate (litres/min)
$O_{2\,\text{per}}$ = oxygen in mixture (%)

Oxygen partial pressure

The oxygen partial pressure in an apparatus depends on various factors. For an oxygen rebreather with $O_{2per} = 100\%$ only the diving depth has an effect on the oxygen partial pressure. In this case the partial pressure is found by the formula:

$$P o_2 = P_D \text{ (bar)}$$

The situation is different for diving equipment which is supplied with mixed gas.

For open-circuit systems, with gas supplied by a demand regulator, for example, the oxygen percentage in the gas mixture has an effect on the Po_2, in addition to the diving depth.

The consumption of oxygen in the body is not relevant as the system is open-circuit and the gas is not rebreathed. Po_2 is calculated by the formula:

$$P o_2 = O_{2\,\text{per}} \times 0.01 \times P_D \text{ (bar)}$$

In a semi-closed circuit, with a pre-set flow, the consumption of oxygen has to be taken into account, too. For the calculation of Po_2 a formula is obtained as follows:

$$P o_2 = \frac{(Q \times O_{2\,\text{per}} \times 0.01 - C)}{Q - C} P_D \text{ (bar)}$$

or

$$P o_2 = \frac{O_{2\text{tot}} - C}{Q - C} P_D \text{ (bar)}$$

From this important basic formula and before obtaining the O_2 flow formula in a mixed gas flow an equation can be deduced which is used for calculations of the flow rate when the gas mixture and the diving depth range are known. The formula is:

$$Q = \frac{(O_{2\text{tot}} - C) P_D}{P o_2} + C \text{ (litres/min)}$$

where Po_2 = oxygen partial pressure (bar)
C = oxygen consumption rate (litres/min)
P_D = pressure at diving depth (bar)

By rearranging the formulas and computing P_D for a given gas composition and total flow rate, the maximum and minimum permissible diving depth can be determined by assuming a minimum and maximum oxygen consumption rate. For short dives, 1.8 bar and 0.2 bar can be assumed as permissible upper and lower limit of the oxygen partial pressure. For saturation diving, 0.4 bar is a reasonable limit.

Oxygen consumption and mixture calculation

The oxygen consumption of a diver depends in the first place on his working effort. The diving depth does not affect the oxygen consumption if the increased respiratory work due to the higher density of the breathing medium is disregarded.

Table 10.2 shows the oxygen consumption for different kinds of work. The values are average figures and in practice there may be tolerances, as for all physiological data.

Fig. 10.53 shows the consumption of oxygen whilst distance swimming, for periods of 30 min at a depth of 1.5 m in a water temperature of 25°C. Consumption rates of more than 3 litres/min of oxygen were recorded. Table 10.11 shows the maximum possible oxygen consumption related to time. For working purposes it would be reasonable to accept a maximum oxygen consumption of 2.5 litres/min and a minimum consumption of 0.5 litres/min with the average oxygen consumption being 1.3 litres/min. Fig. 10.54 shows the oxygen content required in a gas mixture for a given depth and partial pressure.

Table 10.11 Maximum possible consumption of oxygen related to time

Oxygen consumption (litres/min)	*Time*
0.25	constantly
1	several hours
2	1–2 hours
4	15–30 minutes
5	1–2 minutes

By using the following formulae it is possible to calculate the gas mixtures needed for given rates of oxygen consumption and for maximum diving depths using a semi-closed mixed gas rebreathing system with a counterlung or inhalation bag.

1. At first the maximum and minimum oxygen percentage in the counterlung is determined for the respective depth range. With the pressure $P_{\mathrm{D\,max}}$ at the maximum diving depth and the permissible oxygen partial pressure $P\mathrm{O}_{2\,\mathrm{max}}$, the maximum oxygen percentage $\mathrm{O}_{2\,\mathrm{per\,max}}$ in the counterlung is calculated according to the formula

$$\mathrm{O}_{2\,\mathrm{per\,max}} = \frac{P\mathrm{O}_{2\,\mathrm{max}} \times 100}{P_{\mathrm{D\,max}}} \, (\mathrm{vol\%})$$

and the minimum oxygen percentage $\mathrm{O}_{2\,\mathrm{per\,min}}$ in the counterlung according to formula

$$\mathrm{O}_{2\,\mathrm{per\,min}} = \frac{P\mathrm{O}_{2\,\mathrm{min}} \times 100}{P_{\mathrm{D\,min}}} \, (\mathrm{vol\%})$$

2. To calculate the necessary total gas flow Q, the following two equations are arrived at:

$$\mathrm{O}_{2\,\mathrm{tot}} = C_{\mathrm{min}} + \frac{\mathrm{O}_{2\,\mathrm{per\,max}}}{100}(Q - C_{\mathrm{min}}) \text{ (litres/min)}$$

$$\mathrm{O}_{2\,\mathrm{tot}} = C_{\mathrm{max}} + \frac{\mathrm{O}_{2\,\mathrm{per\,min}}}{100}(Q - C_{\mathrm{max}}) \text{ (litres/min)}$$

from which the following formula is arrived at:

$$Q = \frac{C_{\mathrm{max}}(100 - \mathrm{O}_{2\,\mathrm{per\,min}}) - C_{\mathrm{min}}(100 - \mathrm{O}_{2\,\mathrm{per\,max}})}{\mathrm{O}_{2\,\mathrm{per\,max}} - \mathrm{O}_{2\,\mathrm{per\,min}}} \text{ (litres/min)}$$

3. To determine the oxygen component $\mathrm{O}_{2\mathrm{tot}}$ of the mixed gas flow, the total flow rate Q is inserted in the two equations.
4. The oxygen percentage in the mixture is at last calculated from the following formula:

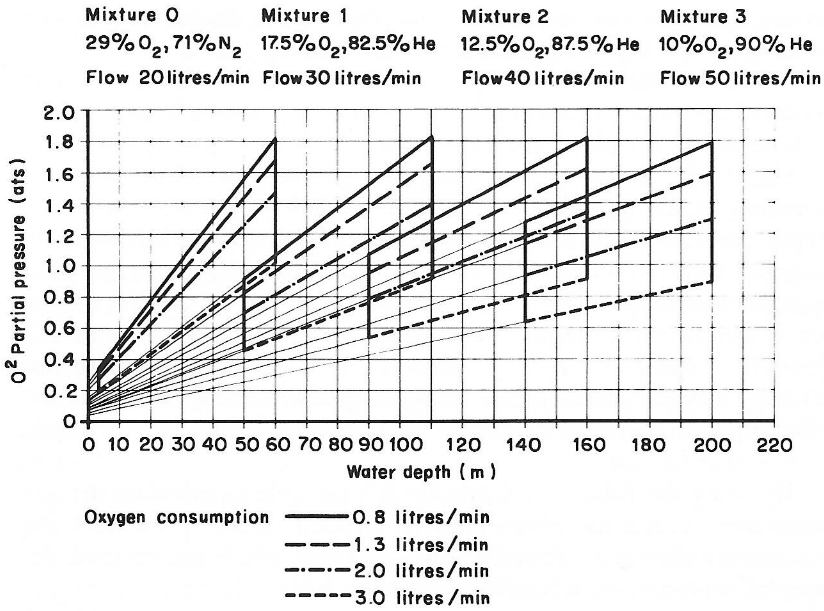


Fig. 10.54. Oxygen partial pressure as a function of oxygen consumption for a deep-diving apparatus with semi-closed circuit and pre-mixed gas supply.

$$O_{2\ \mathrm{per}} = \frac{O_{2\ \mathrm{tot}} \times 100}{Q} (\%)$$

A series of oxygen partial pressure graphs (Fig. 10.54) of a deep diving semi-closed mixed gas set are shown using these formulas.

Deep Diving Techniques (Breathing Equipment)

The methods used to operate divers today have undergone a rapid change within the last decade with experimental dives in the region of 500–700 m. Whilst many of the tasks at the greater depths will need to be carried out by submersibles and remote-controlled vehicles, there will always be a need for divers. Whereas divers can freely descend to about 50 m, beyond this depth the diver is nowadays usually transported either in a diving bell or a submersible or from a habitat. The actual breathing systems will not vary as the same basic life-support principles apply to all, whereas the methods of transportation will vary considerably as discussed in other chapters.

The different types of deep diving equipment are shown in Fig. 10.55. All systems are based on the use of oxygen helium mixtures or trimix, a combination of oxygen, helium and nitrogen. The oxygen content in both mixtures and the nitrogen content in the trimix are relatively low because of the need for a low partial pressure and a high helium content of about 90–95% is normal.

With the very high cost of helium gas it might be assumed that the use of closed circuit, or at least semi-closed breathing systems, would

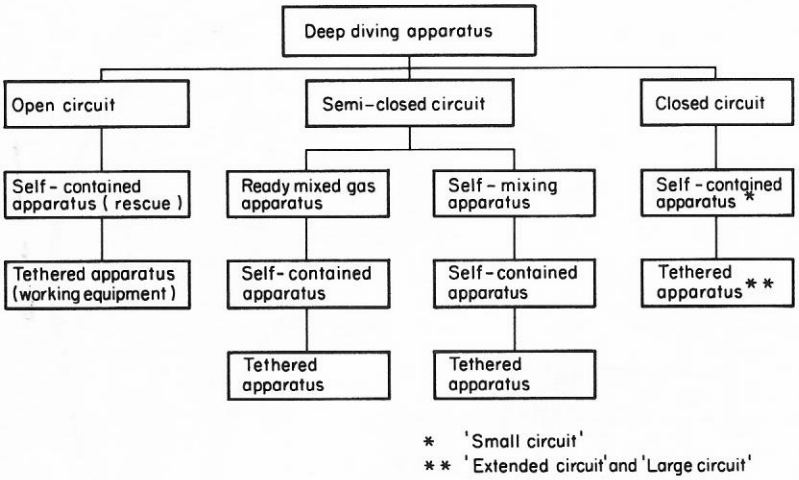


Fig. 10.55. Various options for deep diving equipment.

be preferred so as to economise on gas. So far this has not been the case, largely due to simplicity and reliability of the open-circuit system which overrides the high expenditure on gas. It is not feasable to provide a self-contained open-circuit system at other than shallow air diving depths where, at a depth of 150 m, the gas consumption is about 480 litres/min, in comparison to 30 litres/min on the surface. An external supply is to have a cylinder, or bale-out bottle as it is sometimes called, which can supply sufficient gas, on the same principle as a scuba set, in an emergency if the main supply fails so that the diver can return to the diving bell, submersible or habitat.

Although open-circuit deep diving systems are preferred, systems which work on the semi-closed principle are being introduced and as the reliability and efficiency improves, they will become generally accepted. In this kind of apparatus, a specific helium–oxygen mixture flow is supplied into the circuit with a flow rate and a gas composition which are adjusted in such a way that the permissible oxygen partial pressure limits are safely maintained independent of changing oxygen consumption in the depth range of that mixture. By partial recovery of the gas and simultaneous carbon dioxide elimination, gas consumption is within acceptable limits and hardly exceeds more than 50 litres/minute even at diving depths of 200 m.

The gas supply of a semi-closed circuit apparatus can be either premixed gas or a self-mixing system. Systems with automatic mixing are possible but the design is so complicated that the practical application has to be considered very carefully. When two separate gas components are processed, not only is correct mixing a relatively involved procedure but the necessary monitoring sensors need to function with the minimum of maintenance. The design is much simpler for systems with a ready mixed gas supply. With a constant mass flow of premixed gas only certain depth ranges can be covered but they are great enough to be satisfactory for practical applications.

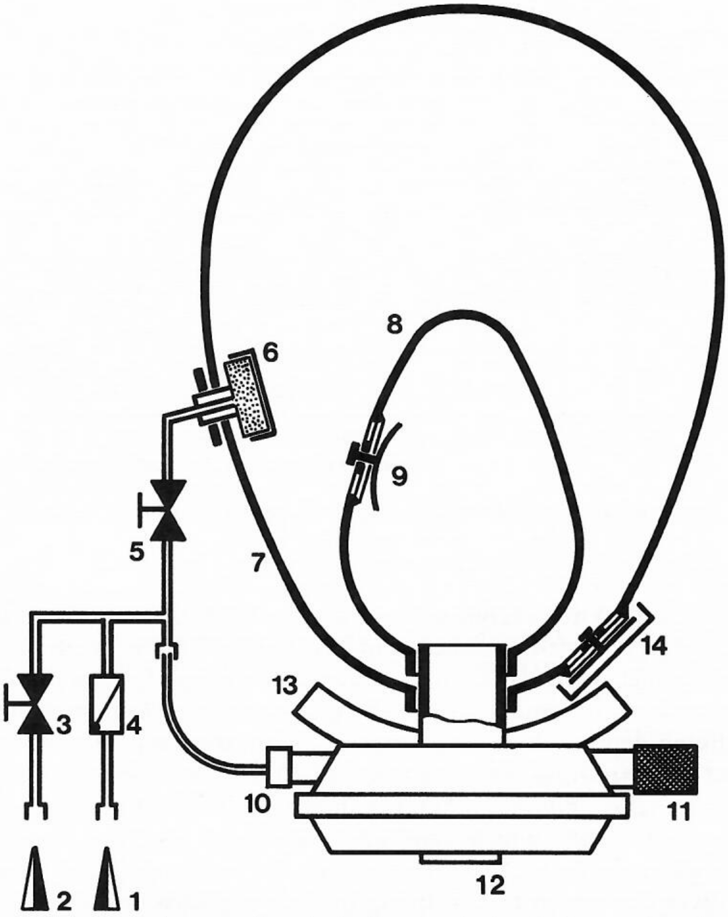


Fig. 10.56. A diving helmet (band mask) for deep diving (open circuit).

1	gas inlet, hose supply
2	gas inlet, emergency supply
3	valve
4	non-return valve
5	valve
6	silencer
7	outer mask (helmet)
8	oral-nasal mask
9	non-return valve
10	gas inlet to regulator
11	adjusting spindle
12	purge valve
13	gas exhaust
14	outlet valve

The diving equipment is relatively simple in design and a further advantage is in the use of different gas mixtures. Depending on the specific application and the desired diving time, gas may be supplied from the mixed-gas cylinders on the apparatus or through a supply hose from a diving bell. The gas umbilical must be small allowing the diver to exit and re-enter through the chamber hatch. The radius of action, given by the length of the umbilical, will rarely inhibit the diver's work. Semi-closed breathing systems can be successfully used to diving depths of at least 200 m with gas consumption a deciding factor. At greater depths the closed circuit is the most desirable diving system if a high percentage of the gas can be recovered. At the same time the desired respiratory balance can be maintained, with the oxygen partial pressure kept constant by an oxygen sensor which measures the partial pressure and controls the oxygen input. The extended closed-circuit system which is designed to be installed in the diving bell or submersible, thereby reducing the surface element, will in future be used more in the deeper depths although the large surface circuit is in current use. For example a DDC on the surface is in the same gas circuit as the SDC and the gas mixture is circulated from the diving bell through a CO_2 absorbent unit into the chamber with additional oxygen to make up the deficiency and

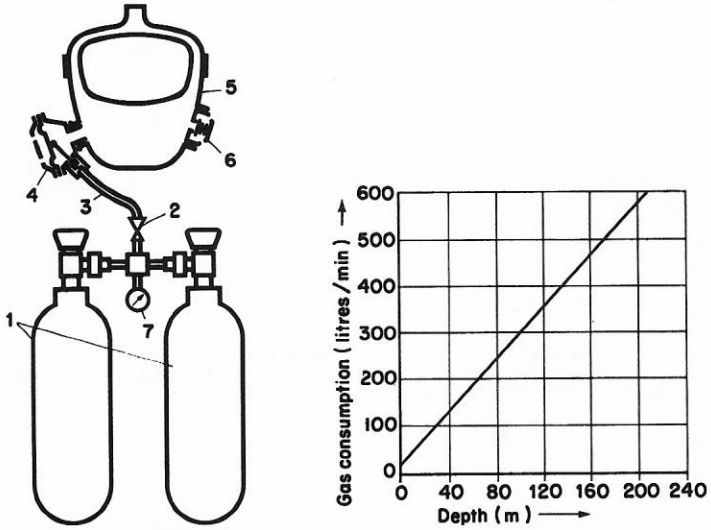


Fig. 10.57. An open-circuit system and its average gas consumption.

1 storage cylinders with shut-off valves
2 pressure regulator
3 connection hose
4 demand regulator
5 face mask
6 air exhaust valve
7 pressure gauge

recirculated down to the bell. This complete closed-circuit saturation system is illustrated in Fig. 10.00. All monitoring is done on the surface but, although pressure changes are slow, large volumes can be circulated. Another extended circuit is shown in Fig. 10.60 and these systems are described later in the chapter.

Deep diving, open circuit

Fig. 10.56 shows a gas circuit for a helmet working on open circuit. Fig. 10.57 illustrates the proportional increase of gas consumption with diving depth.

Deep diving apparatus with semi-closed circuit, pre-mixed gas

The normal operating range of deep diving with semi-closed circuit is currently betwen 50 and 200 m where the economy in gas will apply. As stated, the partial pressure of oxygen should not exceed 1.8 bar and be less than 0.2 bar.

Semi-closed diving, self-contained mixed gas

Originally designed for military use, the equipment was adapted for commercial use for deep diving without surface supply or support from a diving bell. Nowadays this type of free diving is limited to about 50 m. At deeper depths the equipment is fitted with a gas umbilical which allows for greater endurance and safety and is suitable for operations from submersibles and habitats where gas supplies are limited.

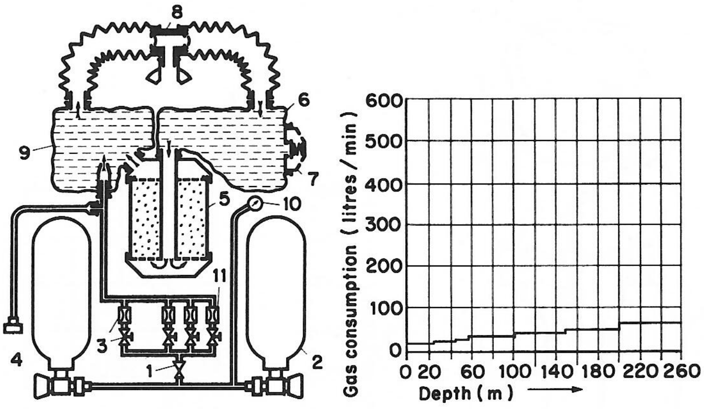


Fig. 10.58. A semi-closed circuit and its average gas consumption.

1	pressure regulator
2	mixed gas storage cylinder
3	bypass valve
4	connecting hose for external gas supply
5	carbon dioxide absorbent canister
6	exhalation bag
7	outlet valve
8	valve with mouthpiece
9	inhalation bag
10	pressure gauge
11	constant mass flow regulator

A self-contained unit is shown in Fig. 10.58 which can be used for deeper dives allowing three separate flow rates to be selected. The mixture in the gas cylinder is selected for the depth and passes to one of the three constant mass flow regulators which can be selected by the diver. The gas passes into the inhalation bag, or counter lung, and is then inhaled by the diver through the inhalation tube and exhaled back into the bag after passing through a CO_2 absorbent unit. Non-return valves are fitted in the mouthpiece.

Semi-closed diving, umbilical-supplied mixed gas

The adaptation of the self-contained semi-closed system to be supplied through an umbilical is shown in Fig. 10.59. The system is designed to allow a diver wearing the apparatus to pass through a hatch with a minimum diameter of 600 mm; the diving time will only be limited by the capacity of the CO_2 absorbent, usually about two or three hours, and by the physical exertion of the diver himself. Fig. 10.59 illustrates a system identical to the self-contained semi-closed system (Fig. 10.58) with the umbilical supply passing directly into the inhalation bag. A flow monitor will register a supply failure and warn the diver either visually or acoustically; in this event the diver opens the supply from the bale-out emergency bottle which, through a reducer, will supply the bag and give sufficient gas for return to the chamber.

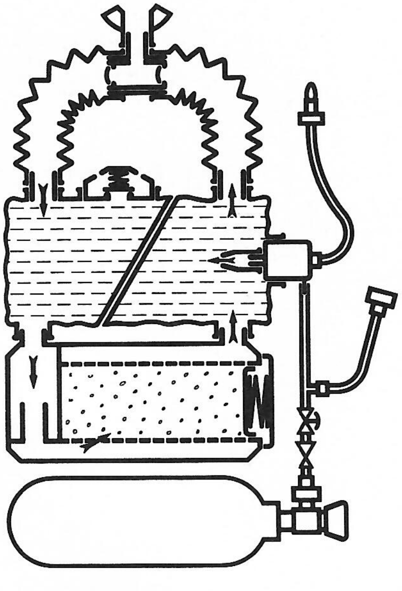


Fig. 10.59. Mixed gas apparatus with a semi-closed circuit and umbilical.

Gas supply to the diver from the surface

A surface-supplied system is illustrated in Fig. 10.60. Although surface-supplied systems are generally not used below about 50 m this

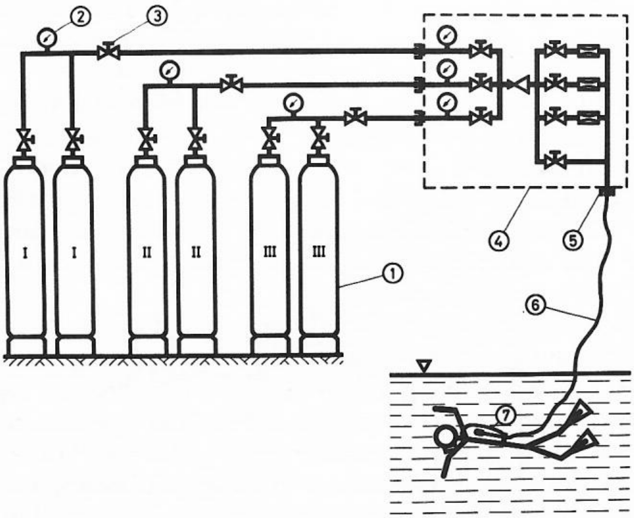


Fig. 10.60. Surface-supplied pre-mix gas supply system.

1	mixed gas cylinders I–III	5	umbilical connection
2	storage bank pressure gauge	6	umbilical
3	storage bank supply valve	7	diving apparatus
4	control panel with gauges, valves, pressure regulators		

is a common practice in the Gulf of Mexico and other warmer areas. Also in an emergency, where a diving bell is not available, this may be the only means of providing assistance to a trapped diver or underwater vehicle in distress. A system shown in Fig. 10.60 has ready-mixed gas, possibly subdivided into up to three separate mixtures for different depths. These are separated with shut-off valves and the selected gas mixture passes through a flow regulator, with a predetermined flow rate for the depth and mixture, and then through the umbilical to the diver's breathing bag. The change-over from different mixtures at the correct depth demands accurate depth recording by pneumogauge on the surface control panel.

Gas supplies to the diver from a diving bell (SCC)

The supply of gas through an umbilical is equally relevant from a submersible or a habitat. The correct flow can either be set within the SCC or other under-water chamber or passed at an intermediate pressure and through a flow regulator on the breathing set where it is finally adjusted to the correct working pressure of the diver.

Self-mixing systems

Much of this type of apparatus has not been developed for operational use with the same degree of reliability and ease of maintenance that is generally reflected in other systems. Fig. 10.61 illustrates the self-contained semi-closed self-mixing unit which has been used. Helium and oxygen are stored separately, with a larger helium supply because of the greater quantity needed. With a selected 3 litres/min of oxygen which will be adequate for the maximum oxygen consumption, only one regulator is required for the injection of O_2 and supplies it at a constant overpressure to the flow metering device.

On the helium side the output has to be increased as the depth increases and the second stage of a two stage reduction, exposed to ambient pressure, will achieve this. Bypass valves are fitted. The flow control mechanism is designed to produce a correct mixture for any depth within the limits of the apparatus. If the flow rate should fail a signal can be actuated. Similarly if the gas supply is below a preset level this will also be indicated.

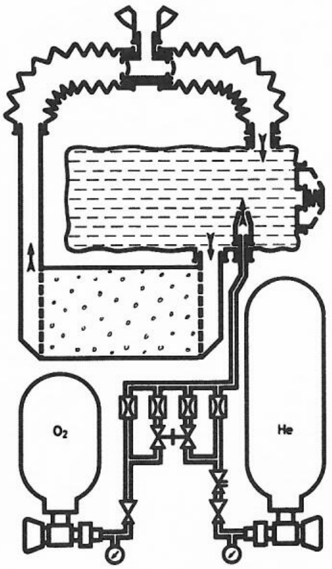


Fig. 10.61. Self-contained self-mixing deep diving apparatus.

When the self-mixing system is not required to be self-contained and can be supplied through an umbilical, the mixing unit will be mounted inside the diving bell or chamber. The pressure regulator, flow control and bypass unit shown in Fig. 10.61 are thus inside this SCC. An oxygen sensor measuring Po_2 can be fitted on the breathing apparatus and so indicate to the diver the correctness of his breathing mixture relative to oxygen content. The actual breathing set can therefore be very small.

Fig. 10.62 shows a completely closed circuit system with an automatic oxygen input control and in Fig. 10.63 a closed circuit system with average gas consumption. In general however operators still prefer to use the less complicated systems using premix gases which are more reliable and easier to handle.

Closed-circuit systems

A perfect closed-circuit breathing system would require only the addition of small quantities of oxygen to replace the metabolic consumption. This ultimate ideal is not likely to be achieved and present systems fall well short of it. These systems are only partially in operational use and they are not favoured because of their complexity and cost. Not until they achieve total reliability, easy maintenance, are rugged and the cost is reasonable will they be generally used.

A small circuit system is illustrated in Fig. 10.62. In this system an oxygen sensor is installed in the breathing circuit to record the partial pressure of oxygen before or inside the inhalation bag, preferably in the bag. The sensor activates the oxygen input through an amplifier depending on the required Po_2 and the consumption of O_2 in the body. The sensor and injection system is very precise. As a safety feature up to three sensors can be fitted so failure of one will bring another into operation. The breathing bag with the carbon dioxide absorbent cartridge is connected to the facemask (or diving helmet) by the exhalation hose and the inhalation hose. In this closed system the circulation of the breathing medium is in the direction of the arrows. The gas storage cylinder supplies inert gas into the circuit through a self-acting pressure controlled valve when the pressure difference between breathing bag and environment is enlarged due to increasing ambient pressure as, for example, during descent. The oxygen cylinder delivers oxygen through the pressure regulator, a regulating valve and line into the breathing bag. Inside this breathing bag a sensor is installed which produces a different electric values

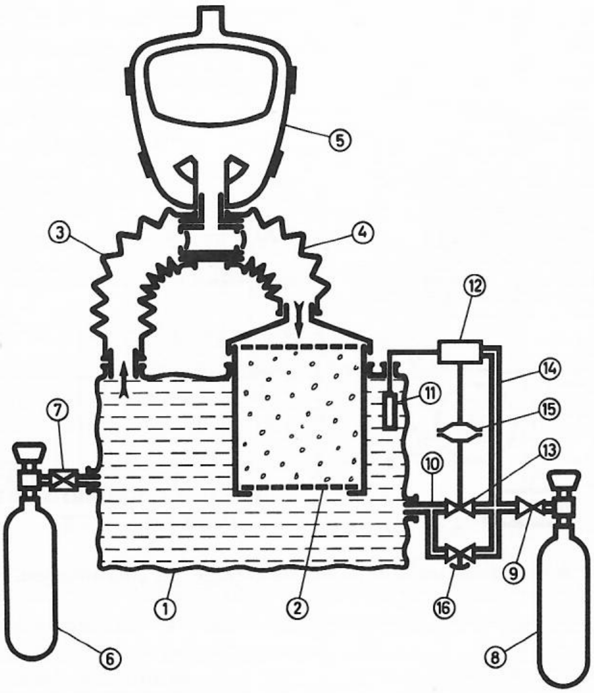


Fig. 10.62. A completely closed circuit with automatic oxygen input control.

1	breathing bag	9	pressure regulator
2	carbon dioxide absorbent	10	line
3	inhalation hose	11	sensor (oxygen partial pressure)
4	exhalation hose	12	amplifier
5	face mask	13	oxygen input valve
6	inert gas cylinder	14	oxygen branch line
7	demand valve	15	servomotor
8	oxygen cylinder	16	oxygen bypass valve

according to changing oxygen partial pressure. The sensor is connected to the amplifier by which the measured electric values are amplified and used to control auxiliary valves which are inserted in an oxygen branch line. This oxygen branch line ends in a solenoid which controls the oxygen input valve. As soon as the oxygen partial pressure drops below a certain value, the oxygen input valve is opened. As soon as the desired partial pressure is reached again, the valve is closed, again by the solenoid. An oxygen bypass valve is connected in parallel to the oxygen input valve which is designed as push-button valve and which can be used by the bearer of the apparatus to fill the circuit with pure oxygen.

Fig. 10.63 illustrates an American system using several O_2 sensors simultaneously to give a mean value of the actual Po_2.

A closed-circuit system as fitted to a diving bell is illustrated in Fig. 10.64. The bell is filled with the required oxy-helium mixture for the depth and the type of dive envisaged. The oxygen partial pressure is regulated by a sensor and the working of the system is shown in Fig. 10.65. The recirculation of the gas applies both to the breathing

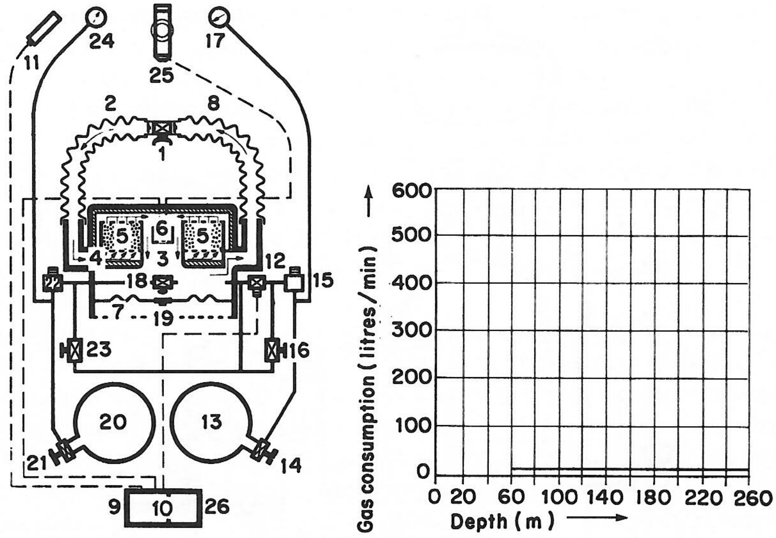


Fig. 10.63. A closed-circuit system and its average gas consumption.

1	mouthpiece non-return valve	13	inert gas container
2	exhalation hose	14	valve
3	breathing bag	15	pressure regulator
4	connection	16	valve
5	carbon dioxide absorbent	17	pressure gauge, inert gas
6	oxygen sensor	18	demand valve
7	diaphragm	19	sieve
8	inhalation hose	20	oxygen container
9	electronic unit	21	valve
10	electronic unit	22	pressure regulator
11	warning signal	23	valve
12	solenoid	24	pressure gauge, oxygen
		25	read-out for Po_2
		26	batteries

apparatus in the water and the chamber environment. The procedure is as follows. The mixed gas is drawn through the compressor and a regulator into a chamber. The regulator can lower the pressure inside the chamber by 2–3 bar below ambient. The suction hose to the diver is connected to this chamber. The CO_2 absorbent unit is connected to the high-pressure side of the compressor and from here gas passes to the overpressure chamber. An overpressure of about 3 bar, with respect to the ambient pressure, is maintained in this tank by a regulator. The gas supply line to the diver is connected to this point, as is the exhaust valve, to supply the bell with regenerated clean gas. The diver has a gas control valve and, since overpressure and suction can be kept very constant, low inhalation resistances can be achieved. There is no danger of the system being subjected to external damage.

Another version is where only oxygen is supplied from the bell, illustrated in Fig. 10.66. The diver carries a helium supply cylinder only and a semi-closed breathing system as previously described. An O_2 sensor in the inhalation hose transmits the partial pressure of oxygen to the bell and through an amplification circuit and solenoid oxygen is injected into the system.

Another example of an extended circuit is for a delivery pump and a suction pump to be sited outside, but attached to, the diving bell and enclosed in a pressure chamber. The push-pull pump pressure vessel supplies gas from the bell to one diver. One such system is illustrated in Fig. 10.69 designed by Normalair Garrett.

Breathing gas for divers is circulated by a push–pull pump contained in a steel pressure vessel attached externally to a bell. One pump/pressure vessel combination supplies gas, from the bell, to one diver. The pressure vessel, designed to withstand external pressure when the bell is used as a one-atmosphere observation chamber, comprises lower and upper housings, divided by a diaphragm to which are attached both the pump and the motor.

A gas control panel, situated within the bell, contains the following: A differential pressure gauge which measures the difference between supply and return gas pressures, which indicates whether the system is functioning correctly; a pressure/vacuum gauge which indicates how far the diver is above or below the bell, i.e. his vertical location; a filter to remove particles in the gas supply line to the diver; an inlet strainer to protect the delivery pump inlet; a non-return valve to prevent emergency gas from passing into the delivery pump; a change-over valve to direct emergency gas (from the emergency bell supply) to the diver; and a water trap to trap slugs of water and prevent them entering the suction pump.

Gas is drawn into the bell penetration through the inlet pipe, containing the inlet strainer; from there it passes to the pressure vessel through a flexible hose. The gas is then routed by pipe to the delivery pump where it is compressed and passed back into the bell. Delivery

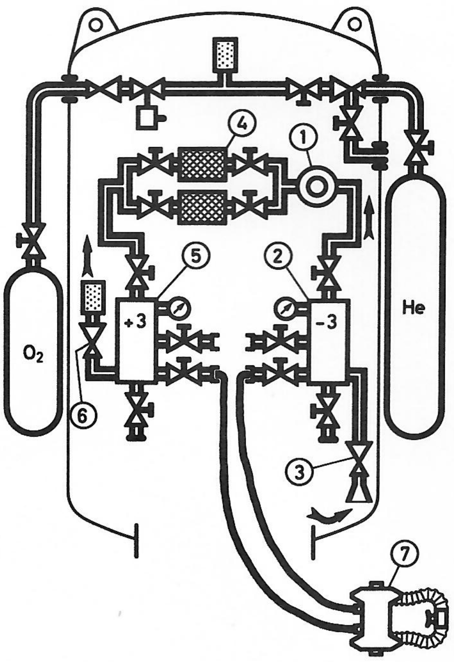


Fig. 10.64. A closed-circuit demand system for diving bell and diving apparatus (extended circuit).

1 pump
2 compensator cylinder
3 supression regulator
4 carbon dioxide regeneration unit
5 overpressure compensation cylinder
6 pressure regulator
7 mixed gas control valve

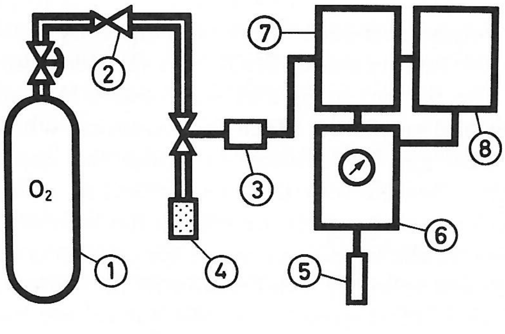


Fig. 10.65. Principles of an oxygen sensor and supply system.

1 oxygen cylinder
2 pressure regulator
3 control valve (solenoid)
4 silencer
5 sensor
6 oxygen meter
7 amplifier
8 energy supply

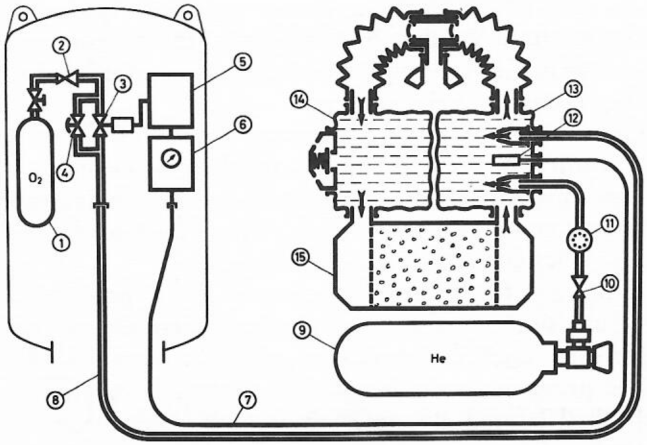


Fig. 10.66. Closed breathing circuit with oxygen supply from the diving bell through a hose.

1	oxygen cylinder	9	helium cylinder
2	pressure regulator	10	pressure regulator
3	solenoid valve	11	helium demand valve
4	oxygen bypass valve	12	oxygen sensor
5	amplifier	13	inhalation bag
6	oxygen meter	14	exhalation bag
7	sensor data line	15	carbon dioxide scrubber
8	oxygen supply hose		

gas is supplied to the diver via the non-return valve delivery filter and an excursion umbilical and returns to the inlet connection of the suction pump via the return umbilical hose, a water trap and the pressure vessel. The suction pump delivers the gas back to the bell where it is released into the intake of the bell scrubber.

In an emergency a manual valve on the control panel within the bell connects the bell emergency gas supply to the diver's hose. A non-return valve prevents the emergency gas entering the delivery pump (which could be defective and allow the gas to pass back into the bell). A robust anti-suck valve, having only one element, is connected to the helmet outlet fitted by a flexible hose. Should the element fail, the return pump can suck water but not the diver. Between inlet and outlet an island is positioned which effectively forms a gap in the gas flow system. To bridge this gap, the gas must partially inflate a flexible tube that is subjected to ambient pressure. This tube also controls gas pressure within the helmet. Should there be a breakdown in the supply system or for any other reason the gas return should tend to apply a depression to the helmet, the flexible valve will close. The depression in the gas return line cannot be transmitted to the helmet interior.

An emergency bale-out bottle attached to the diver's back is connected to a distributing tube within the helmet by a diver-operated valve. In the event of complete failure of the gas supply this valve must be opened. The gas will then pass through the helmet to

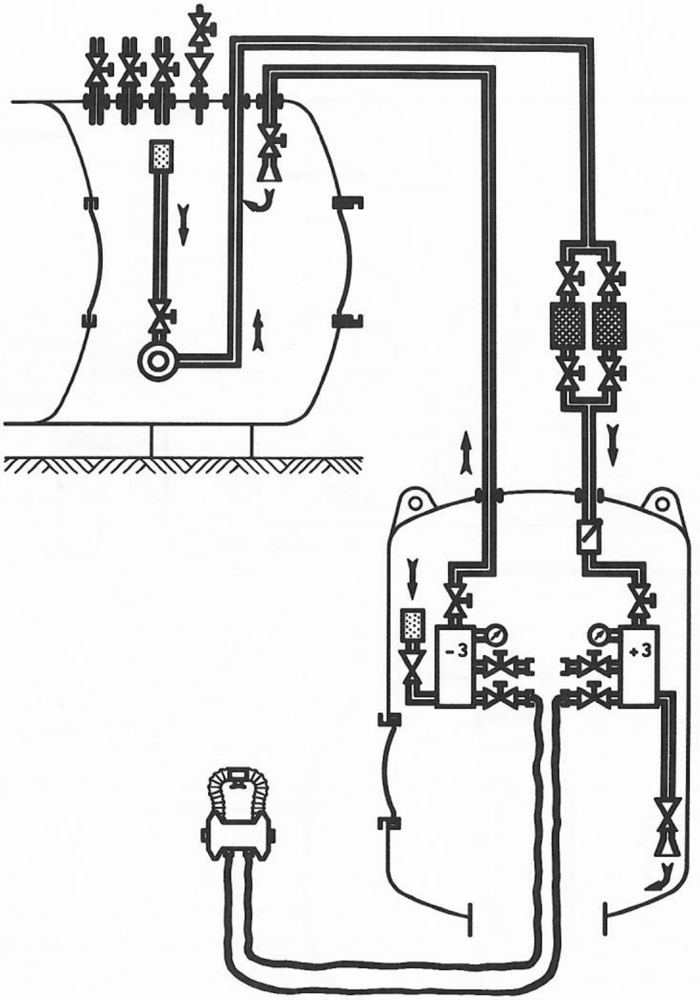


Fig. 10.67. Closed-circuit breathing demand system with surface chamber in the circuit.

the sea via the relief valve. At maximum depth it has a duration of only 2.5 minutes and the diver must return immediately to the bell. During both emergency and bale-out conditions the breathing gas will open the relief valve in the diver's helmet and pass into the sea.

The push–pull system requires a number of self-adjusting valves on or near the diver's helmet to control the gas pressure within the helmet to cover the complete diving spectrum. The diver can then concentrate on his work confident that his gas supply will stay within operational limits. An essential feature of any push–pull system is that the interior of the helmet should never be subjected to a dangerous negative pressure and to ensure that the internal pressure does not become excessive a safety valve must be fitted.

Large closed-circuit systems, where the gases are recirculated from and back to the surface, have also been developed. Figs 10.67 and 10.68 show the different systems. In Fig. 10.67 the recirculating pump

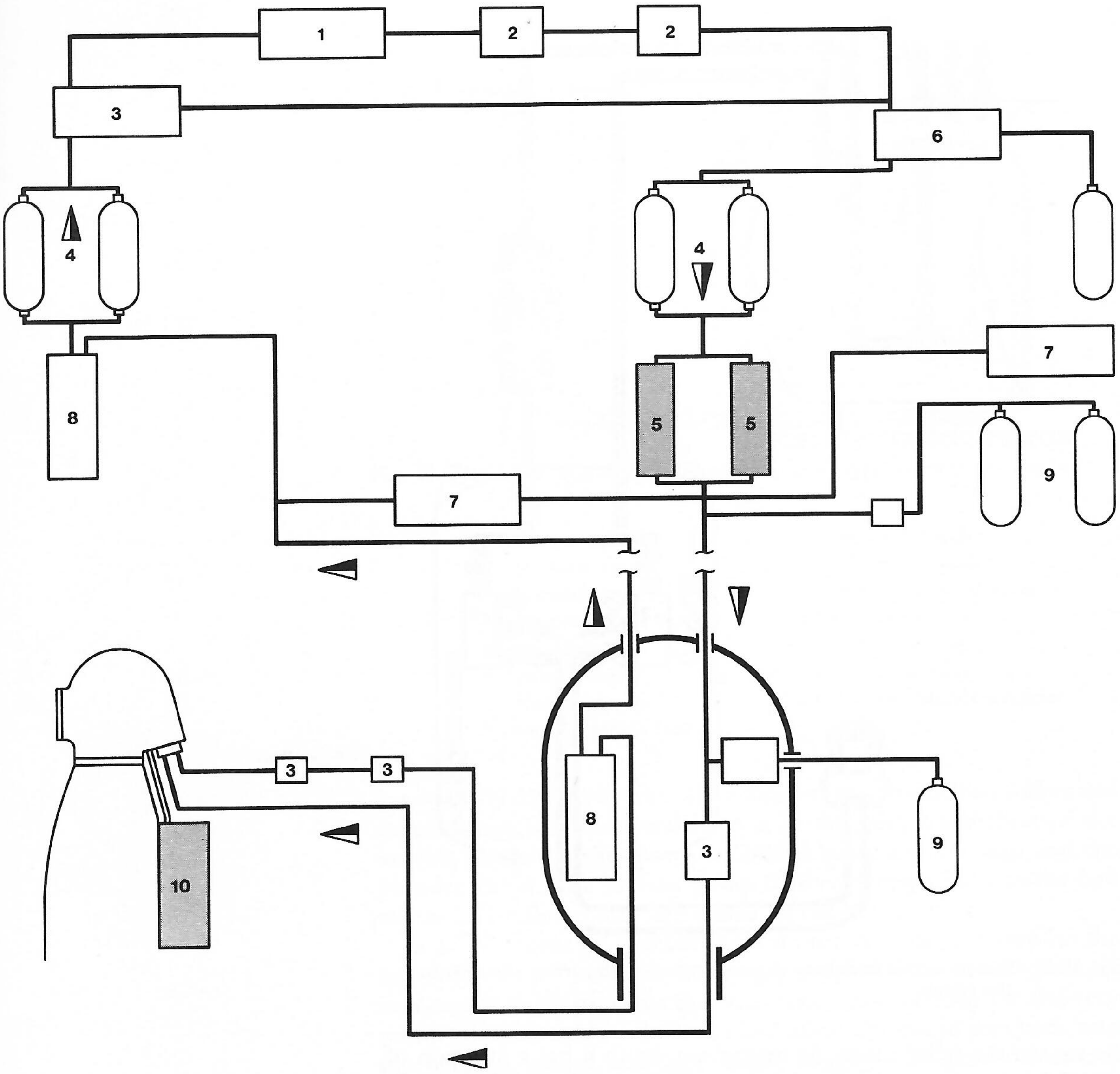


Fig. 10.68. Closed-circuit breathing demand system.

1	compressor	6	O_2 regulating system
2	filter	7	O_2–CO_2 control systems
3	pressure regulating devices	8	water separator
4	buffer	9	emergency supply
5	CO_2 scrubber	10	emergency breathing system

is sited inside a surface chamber. The breathing gas is pumped from the chamber through CO_2 scrubbers to the bell and the divers and returned back to the surface chamber. The surface chamber is at the same pressure as the diving bell and both will vary equally with descent and ascent.

An alternative design is the pressure vessel and pump as illustrated in Fig. 10.69; the bell mounted system can be detached and sited on

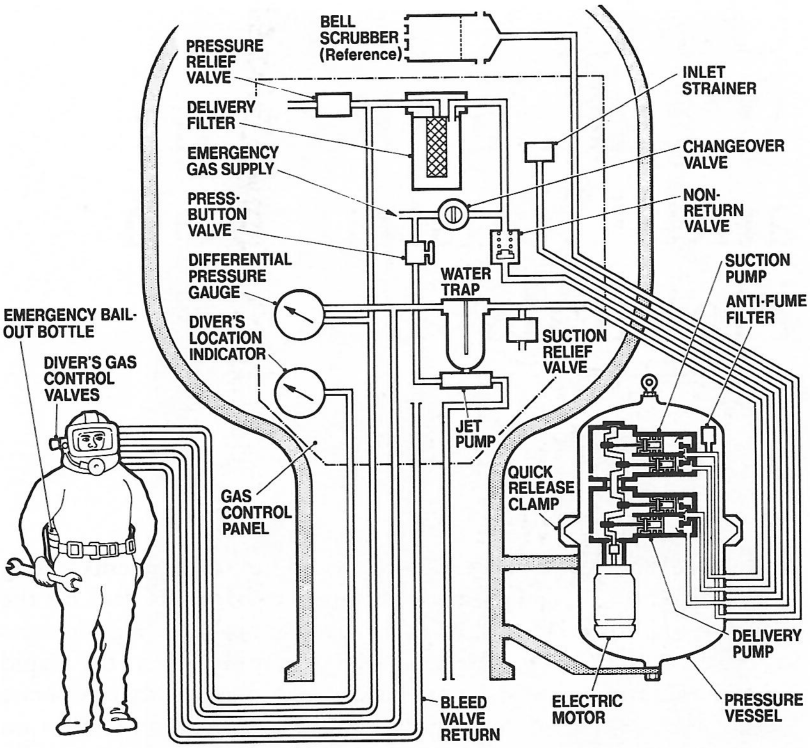


Fig. 10.69. Closed-circuit breathing demand system, bell mounted.

the surface. A circulation compressor which is installed under ambient pressure on the surface, supplies the diver with breathing gas. The gas flows through the diver's helmet on a free-flow principle and by means of a feedback line to the compressor. All devices which are necessary for the preparation of the breathing gas are included in this circuit. A measuring device checks the CO_2 content of the gas inhaled. Simple operating valves and regulators serve to adjust the diver's breathing gas pressure to the water pressure surrounding him. A back pressure control system automatically controls the pressure in the helmet and adjusts it to the surrounding water pressure. A relief valve in the helmet prevents a pressure build-up. The system has an emergency stand-by gas supply which can be used for open-circuit breathing should the primary circuit fail. In all systems the diver continues to carry the emergency bale-out cylinder on his back which allows him to return to the diving bell.