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Life Support Systems

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The term 'life support system' has been adopted from the new jargon of space technology. In fact, the concept goes back a century and more to the realization that man is a homeostatic animal. He can live only within narrow limits of oxygen partial pressure, is poorly tolerant to raised levels of carbon dioxide, has a narrow range of thermal stability, is required to maintain a very stable osmotic equilibrium, is prone to atmosphere-borne infection and is readily intoxicated by many chemical compounds and elements, some of which are formed by his own metabolic processes. In principle, therefore, the whole raison d'être of a life support system is to maintain the standard of life both quantitatively and qualitatively that was present before the life support system was required. This broad concept has applications ranging from environmental pollution in the widest sense through to diving as a more narrow application. It is with diving applications that this chapter is concerned.

Compressed air work of relatively short duration in diving and tunnel construction represents by far the greatest proportion of exposure to increased pressure that man currently encounters; and in such work the main life support requirement is merely to ensure a sufficient flow of fresh air to maintain adequate blood oxygenation and low levels of carbon dioxide. By such simple means men have been able to work under pressure for considerable periods.

With the engineering advances that made manned space flight possible, a new technology of life support engineering and physiology developed and spilled over into the diving and submarine fields. New chemical processes are available which simultaneously reduce carbon dioxide and produce oxygen; cryogenic and even thermonuclear processes have been employed in atmosphere control. Over the same period, gas analysis equipment to monitor closed compartment atmospheres has changed from simple volumetric apparatus to highly sophisticated mass spectrometry and gas chromatography. With more extensive and more efficient methods of maintaining a stable atmosphere, and with more effective equipment to monitor the atmosphere, man has stayed in space for a few weeks, submarines now patrol submerged for several months, and divers can live at depth for many weeks.

Life support requirements for diving depend very much upon the duration of the exposure to increased pressure. Deep dives require prolonged decompression and the logistics of maintaining a stable respirable atmosphere by simple ventilation alone are frequently not feasible in terms of gas storage or cost, especially if special gas mixtures or expensive gases, such as helium or neon are employed. Carbon dioxide is usually removed chemically and oxygen added as required by the metabolic demands of the diver. In saturation diving, where the exposure to increased pressure may last from several days to many weeks, not only must carbon dioxide be removed and oxygen added but thermal equilibrium must be maintained, humidity carefully controlled, and other noxious gases produced by metabolism eliminated. With such requirements has grown the need for more specialized and more sophisticated gas analytical techniques. Such diving procedures are indeed a far cry from the open circuit ventilation methods employed most commonly, but despite the complexity and the expense they are now dominating the field of commercial diving.

CARBON DIOXIDE REMOVAL

Carbon dioxide in solution is weakly acidic, and as such is readily neutralized by strong alkalis to form a carbonate salt and water. When potassium or sodium hydroxide are used by themselves to absorb CO_2, the reaction is strongly exothermic, and the heat generated may become a hazard in itself. Both materials are also highly deliquescent and are prone to deterioration during storage. They are so highly caustic and unstable that it is usual for them to be mixed with other less caustic alkalis such as hydrated barium hydroxide and calcium hydroxide.

Traditionally, a mixture of barium hydroxide, calcium hydroxide and potassium hydroxide, known as 'baralyme', has been favoured by the US Navy; while 'soda lime', a mixture of sodium hydroxide, potassium hydroxide and calcium hydroxide, has been favoured by the Royal Navy. In addition, particularly in space vehicles where weight considerations play a major role, lithium hydroxide (LiOH) is used. It has approximately half the weight for the same volume as the others at 8 to 10 times the cost. All three absorbent materials are packaged in granular form and provide little difficulty in handling in operational circumstances. The primary disadvantage with these materials is that they can be used once only. They are heavy to transport and bulky to store. Soda lime and baralyme particularly, are in general use throughout the diving industry, being the primary means of CO_2 absorption in high pressure chambers, saturation diving systems, underwater habitats and many types of underwater breathing apparatus. Their efficiency increases as the partial pressure of CO_2 rises, being quite inefficient at partial pressures below about 10 mm Hg. In addition, their efficiency diminishes at decreased relative humidities.

Passive absorption systems

Provided sufficient gas convection can be maintained within a closed compartment there is no strict necessity to maintain forced ventilation through chemical CO_2 absorbent beds. Open boxes of baralyme or soda lime placed on the deck plates of a high pressure chamber have been used quite successfully in relatively short duration oxy-helium dives. Specially fabricated panels containing CO_2 absorbent material placed in position to catch convective air currents have themselves provided the sole means of carbon dioxide removal for 2 months during the voyage of the *Ben Franklin* (Haigh 1971). A similar panel can readily be constructed from two blankets sown together to form a number of small pockets containing soda lime or baralyme.

Active absorbing systems

In general, forced ventilation scrubbing systems used with high pressure chambers are either internal or external. Each type has its advantages and disadvantages. At the present time all systems in use employ chemical absorbent material—soda lime, baralyme or lithium hydroxide—through which chamber air is either drawn or forced by a fan. Numerous means have been used over the years to drive the fan: electricity, hydraulics, pneumatics and magnetically coupled drive units.

Power systems used depend very much upon prevailing conditions. At sea, for example, in a diving bell, electricity may be the most suitable power source, despite the inherent danger of fire from sparking in atmospheres containing high partial pressures of oxygen, or the risk of electrocution in the water. Non-sparking, brushless motors encased in metal and purged with nitrogen venting to the outside of the bell are the type of choice.

Within static chambers, particularly where there is no shortage of low pressure compressed air, a pneumatically powered system is extremely effective. Such an internal CO_2 scrubbing system is in use in the high pressure chambers at the Royal Naval Physiological Laboratory (Eaton 1970) and is shown in Fig. 6.1. It employs standard submarine soda lime canisters through which chamber gas is drawn by a 'squirrel cage' fan powered via a magnetic coupling by a compressed air motor venting outside the chamber. Noise is minimized and the efficiency of the motor is regulated by the compressed air pressure outside the chamber. Gas flow through the scrubber decreases with increasing gas density, but this can be offset to some degree by increasing the fan speed. In practice, this system has proved extremely reliable and the changing of soda lime canisters has been reduced to a single rapid operation. Replenishment of canisters during a very long exposure can be made via the medical lock as it is large enough to take the standard submarine canister. Each submarine canister has been found to provide efficient CO_2 removal for two men for a minimum period of 12 hours.

Another method for providing power to drive a scrubber fan has been developed (Canty et al. 1972; see Fig. 6.2). This employs a magnetic coupling passing directly through the chamber wall in such a way that the non-ferrous cup between the inner and outer magnets forms in effect a part of the chamber wall. The outer magnet is rotated by a belt drive from an electric motor outside the chamber, and the drive is transmitted magnetically through the cup to the inner magnet inside the chamber. Either a direct drive shaft or a flexible shaft from the inner magnet is used to rotate the scrubber fan.

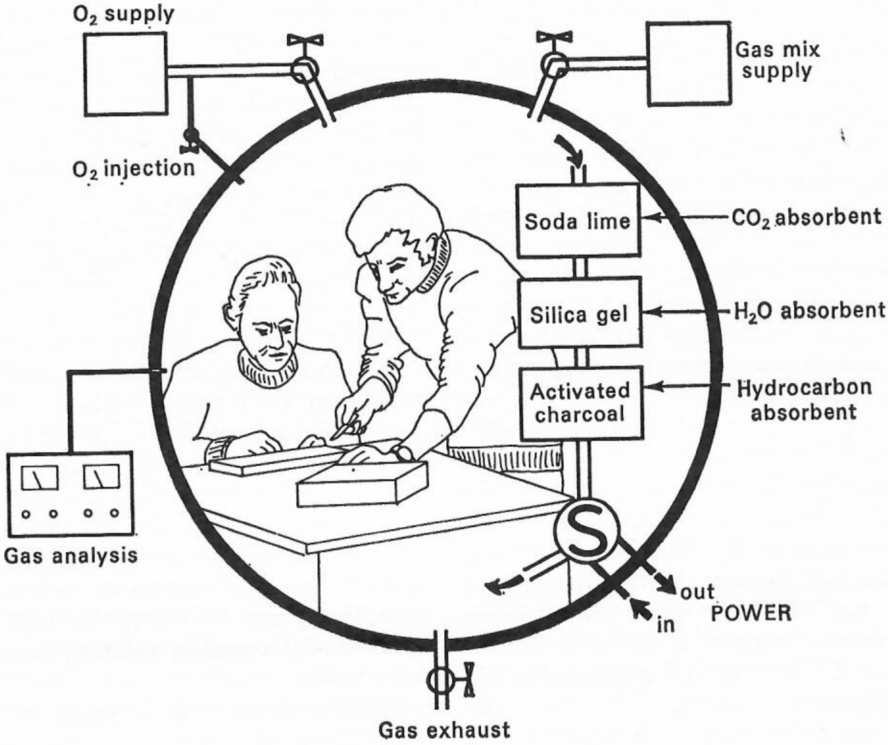

FIG. 6.1. Diagram of an internal scrubbing system of the type used at RNPL. In practice, power transmission to the blower is mediated via a magnetic coupling driven by a sealed compressed air motor, vented externally. Chamber air is drawn through the appropriate absorption beds

Other attempts to provide abundant non-electrical power inside high pressure chambers have included hydraulic systems. Vane-type pumps have been used effectively at low pressures, but are relatively inefficient, being prone to leaks at the shaft seal while under pressure and to

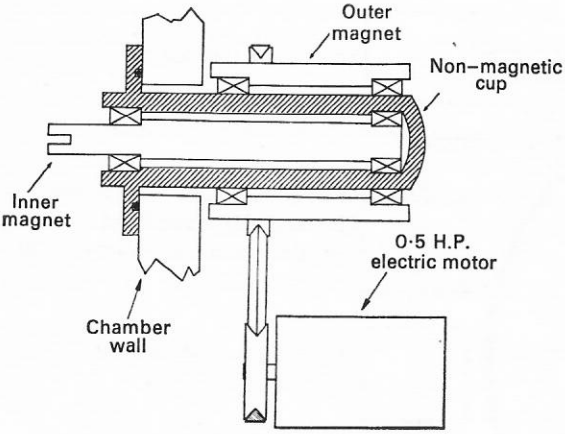

FIG. 6.2. Diagram of magnetically coupled power unit designed to transfer high-torque power drive directly through the wall of a pressure vessel. The outer magnet is driven via a 'V' belt from a suitable electric motor, and transfers its energy across a non-magnetic cup, the interior of which is at chamber pressure, to the inner magnet which, itself, acts as a rotary drive shaft to power tools and equipment such as scrubber motors

corrosion in cast-iron pump housings. Positive displacement hydraulic pumps are effective alternatives to other hydraulic systems, but require a driven impellor to impart rotary movement to a fan.

A low resistance liquid potassium hydroxide CO_2 scrubbing system was developed by Margaria, Galente and Cerretelli (1959), for physiological experiments. The system (Fig. 6.3) is basically a miniature adaptation of a large scale industrial scrubbing unit. In this system liquid KOH is sprayed from a reservoir over ceramic rashig rings in a glass fibre tower. Air is pumped through the tower near the bottom, passes up through the wet rashig rings and loses its carbon dioxide. The method could certainly be adapted for use in a high pressure chamber, especially where the application required a very low resistance to gas flow.

The main disadvantage with internal CO_2 scrubbing systems is the requirement for the men at pressure to replenish the absorbent. If a chamber environment became contaminated at extreme depth, access to the scrubbing system could be denied to fresh personnel from the outside. Thus, there is the ever present risk of irretrievable loss

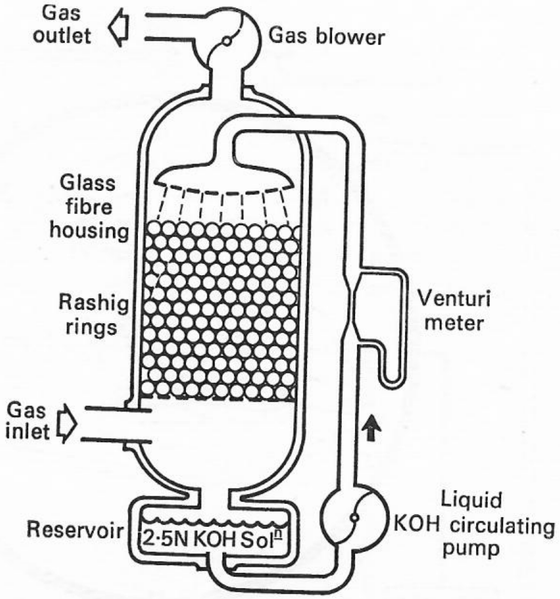

FIG. 6.3. Liquid potassium hydroxide scrubbing system (after Margaria, Galente & Cerretelli 1959). Liquid 2·5 N KOH is continuously pumped over a vertical bed of ceramic rashig rings of appropriate size at a flow rate sufficient to keep the bed wet. At the same time, CO_2-containing air is drawn up through the moistened bed, losing its CO_2 in passage

of control of the chamber atmosphere. With an external scrubbing system, control of chamber atmosphere is assured at all times.

External scrubbing systems operate on a closed loop with piping attached to the chamber (Fig. 6.4). Gas is drawn from one or more dependent places in the chamber, and is passed through the absorbent bed and pumped back to the chamber near the overhead. Replenishment of the absorbent is relatively simple as the loop can be closed off and decompressed. The canisters are then exchanged at surface pressure and the whole system repressurized.

With an external system provision can readily be made for scrubbing other noxious gases, for example carbon monoxide, methane and hydrogen sulphide, which build up during long exposures in closed atmospheres. Appropriate absorbent beds, for example silica gel for water vapour, activated charcoal for the removal of hydrogen sulphide and ammonia, can replace soda lime canisters. In addition, appropriate catalytic

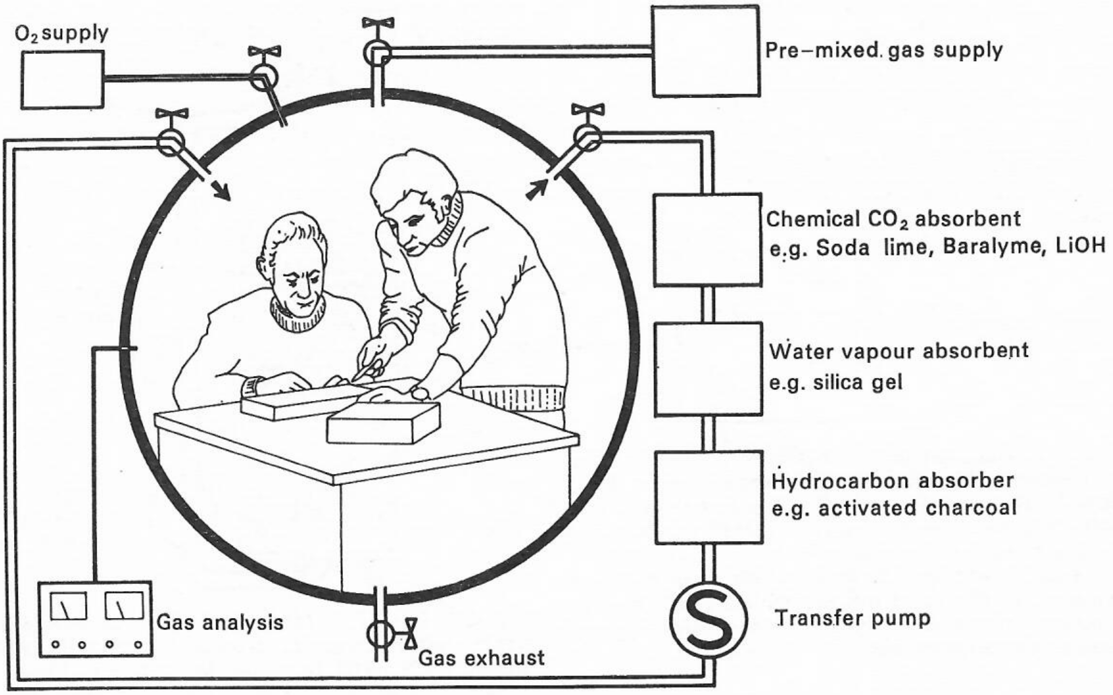

FIG. 6.4. Diagram of an external scrubbing system employing conventional absorption methods, of the type in use at the US Naval Experimental Diving Unit. Each absorption unit is separately housed in an external pressure vessel coupled to the chamber and to each other by high pressure piping and valves. In addition, to facilitate rapid replacement of absorption beds, two systems in parallel are commonly used: one shut down for replacement of chemicals and cleaning, while the other is in use. Not only is the system bulky and expensive, considerable problems have occurred in maintaining effective shaft seals on the transfer pumps against the persistently high head of pressure

burners can also be placed in series within the loop. Certainly it is true that the internal system in use at the Royal Naval Physiological Laboratory (RNPL) can also employ absorbent beds other than soda lime packed in appropriate canisters, but there is no effective internal way of removing hydrocarbons, carbon monoxide or other trace contaminants.

The disadvantages with external scrubbing systems are that they tend to be bulky, as the components are exposed to full chamber pressure. Difficulties in practice have been noted with drive-shaft seals failing to hold pressure in the system. With the recent development of suitable magnetic couplings this latter disadvantage may well disappear. A third disadvantage is one of cost. External systems are very much more expensive to build and install than their internal counterparts. Separate pressure vessels are required to house the absorbent canisters and wide bore high pressure piping is required to close the loop. Expensive chamber modifications may have to be undertaken if provision for such a system has not been included in the design stage.

OXYGEN ADDITION

Just as carbon dioxide is produced by the men under pressure, oxygen is consumed. The tolerable limits of oxygen partial pressure to which divers may be exposed depends very much upon the duration of the exposures. Obviously, the lower limit is that partial pressure which is sufficient to support life, about 0·1 ATS (70 mm Hg Po_2). but a more reasonable lower limit for general use should lie between 0·18 and 0·2 ATA. The upper limit for Po_2 is exposure-dependent, and for prolonged exposure, that is days to weeks, should probably not exceed 0·5 ATS. A recent report from the Institute for Environmental Medicine at the University of Pennsylvania (Clark & Lambertsen 1971) presents basic information on the tolerance of the lungs to increased partial pressures of oxygen in normal men. Fig. 6.5 depicts one of the pulmonary oxygen tolerance curves presented in the report, and represents the upper limit of oxygen exposure as a function of duration sufficient to cause some detectable effect of pulmonary oxygen toxicity in 50% of normal subjects. It must always be remembered that the effect of increased oxygen partial pressures upon lung tissue is cumulative, and if a high Po_2 has been used during the dive itself the pulmonary tolerance limits may easily be exceeded during decompression, particularly if the oxygen partial pressure is increased still more, for example, with the use of pure oxygen inhaled intermittently between 15 m (2·5 ATA) and the surface.

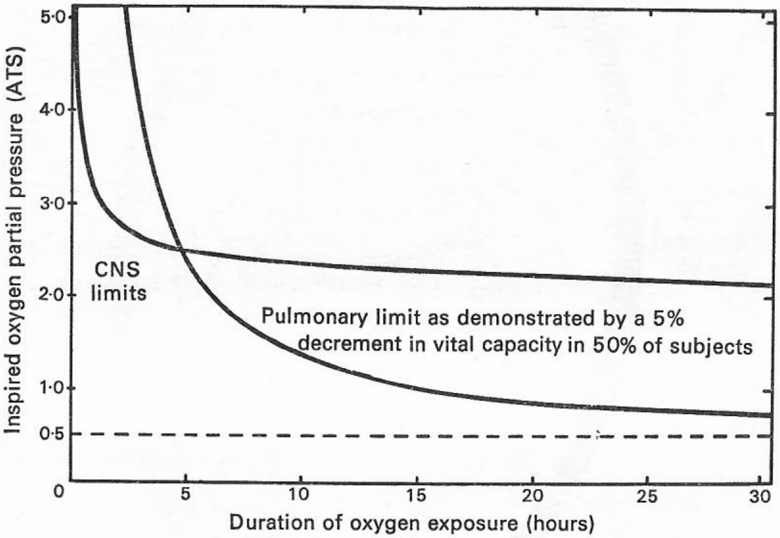

FIG. 6.5. A practical tolerance limit in normal man to pulmonary oxygen toxicity (after Clark & Lambertsen 1971)

Oxygen supply to make up for metabolic consumption during saturation diving must only be made under conditions of strict control. Perhaps the best system in use at the present time employs the injection of small quantities of oxygen into the chamber at high pressure through a venturi, thus ensuring adequate mixing of the oxygen with chamber gas. Intermittent injections are made when the oxygen partial pressure falls below a predetermined minimum level established during the planning of the dive. Provided calibration procedures are available, and a triple electrode system is used, a temperature-compensated polarographic method may be employed, the current-flow suitably amplified, and used both to give a meter read-out and to power a solenoid valve system governing the injection. During the 1500 ft (46 ATA) simulated dive at RNPL in 1970, chamber Po_2 was thus maintained within 0·43 and 0·45 ATA (Eaton 1971).

The addition of large volumes of oxygen while at pressure and without effective means of instantaneous gas mixing should never be employed. If no suitable injection system is available, then the chamber gas should be replaced with fresh premixed gas.

OXYGEN REMOVAL (OXYGEN DUMPING)

Pure oxygen breathing is frequently used during decompression to facilitate the elimination of inert gas. Oxygen also is frequently used as a breathing medium during therapeutic recompression in the treatment of decompression sickness. Exhaled oxygen contaminates the chamber atmosphere unless arrangements have been made for its removal. Most commonly, frequent flushing of the chamber atmosphere with fresh air is used to reduce the oxygen levels, but by such means it is not practicable to reduce the level of oxygen much below 0·25 ATS. A fully effective, automatic, inexpensive and reliable method for dumping exhaled gas has yet to be devised, but several workable compromises are available.

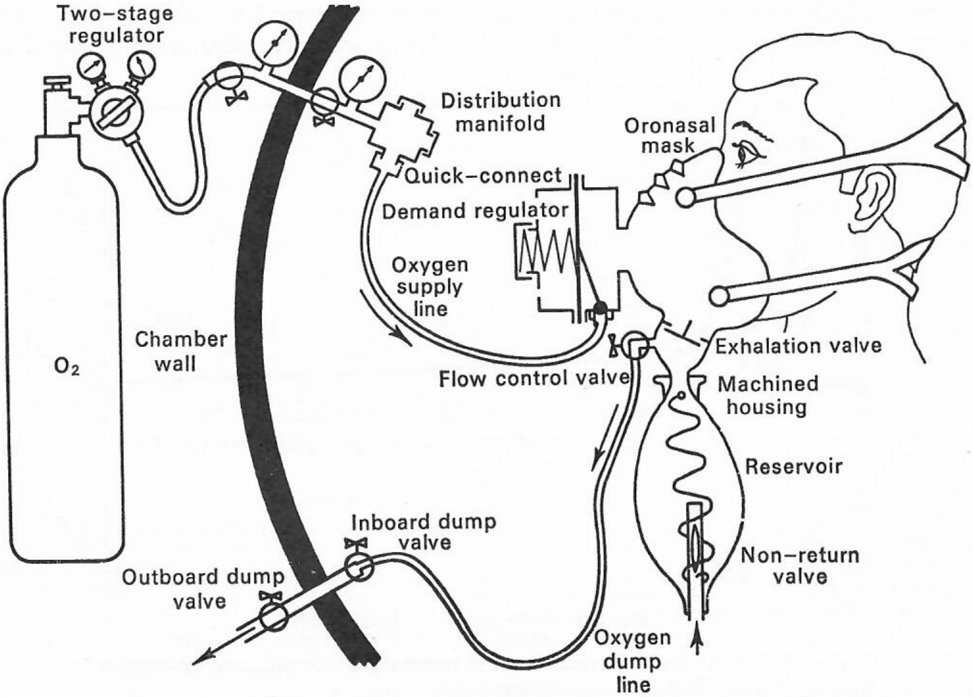

FIG. 6.6. Richard A. Morin's oxygen dump system. Oxygen is delivered via a demand regulator and exhaled gas is collected for dumping in a reservoir bag attached to the exhaust port of an oronasal mask. Exhaust flow in the oxygen dump line is controlled manually in such a way that the reservoir bag is kept partially filled. With moment to moment changes in pulmonary ventilation, constant adjustment of the exhaust flow control valve is required

The system currently in use at RNPL is similar to that designed by Richard A. Morin of the State University of New York at Buffalo (Fig. 6.6). Oxygen is delivered via a single-hose regulator from the built-in breathing system through a comfortable, well-fitting oronasal mask. Exhaled gas passes out through a non-return valve and thence is 'dumped' through a length of lightweight tubing connected to the chamber wall via a needle valve. The needle valve is used to control the degree of inflation of a four litre anaesthetic bag connected to the fitting immediately downstream from the dump line. The bottom end of the bag is open to chamber atmosphere via a non-return valve so that if the needle valve is open too wide, the bag deflates and chamber gas is drawn up through the non-return valve in the bag, thereby preventing the lungs from being exposed accidentally to any large pressure gradient. A coiled spring held inside the bag prevents its collapse when fully deflated. The main disadvantage with the system is the need for frequent adjustment of the needle valve to cater for changes in ventilation rate, which soon becomes irritating. The system in use at the Deep Trials Unit of the Admiralty Experimental Diving Unit is similar, except that a much larger bag is employed, obviating the necessity of having the safety relief valve at the bottom of the bag.

A third system available (Fig. 6.7) is in use at the Virginia Mason Research Center, and depends upon the use of a large high gas-flow pressure regulator mounted inside the chamber and operating at differential pressures of 5 to 7 psi. Small-bore pressure hose is used to couple the exhalation valve of the breathing system to the in-flow side of the regulator, and the gas is vented externally through the chamber wall. Such a system has the advantage of being automatic once the regulator has been set. Moreover, variable ventilation rates are automatically catered for by the regulator itself, and several divers can be accommodated simultaneously. Its disadvantages are that the exhalation tubing tends to be bulky and may cause difficulty in maintaining an adequate face-seal of the oronasal mask. Furthermore, it is expensive, primarily because of the cost of a large precision-built regulator capable of simultaneously handling the exhaled gas from several divers.

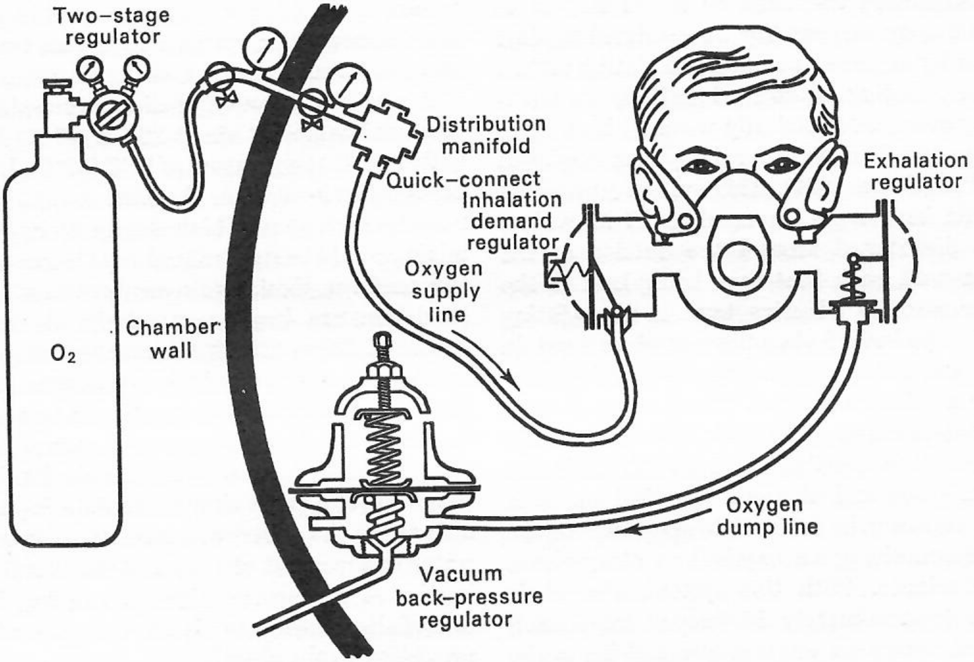

FIG. 6.7. Automatic oxygen dumping system of the type in use at the Virginia Mason Research Center, Seattle. Oxygen is delivered via a demand regulator and exhaled gas passes to the oxygen dump line via a special exhalation regulator and thence to the outside via a large vacuum back-pressure regulator set to maintain a constant pressure-drop of 5 to 7 psi across its diaphragm. Variations in pulmonary ventilation have little effect on the system

CONTROL OF TEMPERATURE

As discussed in a later chapter (16), inadequate control of thermal balance is one of the prime contributory factors in many diving accidents. In saturation oxy-helium diving, particularly in the open sea, the problem is a prime limiting factor to the performance of the divers. In general, cold is the more important factor in operational diving, but excessive overheating can also become a problem.

The range of temperatures covering a zone of comfort at 1 ATS in an air environment is quite wide, particularly if the subjects are allowed a free selection of clothing. In oxy-helium atmospheres under pressure, however, the zone of comfort becomes progressively narrower as the pressure increases. From 20°C ± 10°C at 1 ATS in air, the comfort zone narrows to about 29°C ± 1°C at about 500 m (50 ATA) in an oxy-helium atmosphere, regardless of the choice of clothing. The problem, then, is to maintain an internal temperature inside a steel shell weighing several tons within such a narrow range, with the shell perhaps suspended in an aqueous environment representing an infinite heat sink at a temperature as much as 26°C lower than the internal temperature.

Deck-mounted chambers on board ship or in the laboratory can readily be insulated against heat loss by means of a suitable insulating jacket. Moreover, heating of the steel shell can be facilitated by means of electrically powered heat tapes encircling the chamber as for the system employed at RNPL (Eaton 1971). This system utilizes 24 1000 watt heat tapes arranged in 12 individual circuits distributed around the outside of the chamber wall, each heat tape being held to the chamber wall by adhesive tape. A close-fitting insulation jacket of glass-fibre wool encased in woven glass cloth, manufactured in sections, lies exterior to the heat tapes. The arrangement is such that sections of the jacket are readily removable, thus allowing cooling. With the jacket firmly in place and all tapes switched on, it is possible to raise the internal temperature of the chamber containing an oxy-helium atmosphere, 1°C per minute. With this system, the whole chamber (approximately 16 tons of mild steel) reaches the required temperature and heats the gas simultaneously by conduction, radiation, and convection. The divers, therefore, live in an atmosphere of even temperature distribution.

Evaporative heat loss from the divers depends upon the level of water vapour in the atmosphere. It has been found, however, that at about 500 m (51 ATA) the range of comfort was so narrow that one diver performing light work became uncomfortably hot while the attendant was feeling chilled (Broussolle et al. 1975). Although Webb (1975) has made an attempt to solve this problem with an automatically regulated suit controlled by sensors attached to the subject, the solution is cumbersome. However, without some individually tailored personal micro-environment, such as Webb suggests, working dives to extreme depths may not be practicable.

With ship-board systems, operating in the sea, an account of the heating and insulation system employed in the US Navy Mk I Deep Diving System Personnel Transfer Capsule has been published by Majendie (1970) and by Riegel and Glasgow (1970). Basically, the system employs a number of heating elements distributed around the external shell of the capsule and cemented closely to its surface in a manner rather similar to that employed at RNPL. Insulation is provided externally by a 1 inch thick layer of thin syntactic foam cemented in sections to the surface of the capsule. By such means, constant internal temperatures of 35°C in an oxy-helium atmosphere have been maintained at about 260 m (27 ATA) depth with a water temperature of 13°C (55°F). However, despite the insulation, the heat loss at the shell may be such that a high degree of internal gas mixing would be required to keep the gas temperature uniform. Heat requirements even with heavy insulation are large, particularly at depths in excess of 200 m (21 ATA) in water temperatures below 10°C where oxy-helium mixtures are used. With external heating elements used on a chamber in the water, it is necessary to ensure that the elements are adequately electrically insulated in the event of a short circuit. No data is yet available about the electrical hazard to a diver underwater in the event of such a short circuit, but it is wise at the present time to assume that the risk of electrocution is high for any diver in close proximity to the chamber.

Hot water and even steam circulating systems either internally or externally placed have been used effectively over the years, but seem to have been superseded recently by the development of better forms of electrically heated elements. Internal heating systems have several disadvantages; they tend to be bulky, are localized sources of heat by radiation and conduction, and distribute heat poorly by passive convection. Apart from the power requirements of internal electrical, hot water, or steam heating systems an efficient forced convection system must also be provided, requiring in its turn a further source of power. In oxy-helium conditions, the heating elements of such an internal system are too hot to touch and, therefore, present the possible hazard of burns. Non-insulated, electrically resistive heating elements should be avoided at all times, on account of their attendant fire hazard, potential source of electric shock and risk of causing burns. They have been used, however, during quite deep dives where the oxygen content of the atmosphere was below fire risk threshold.

CONTROL OF WATER VAPOUR

Only in dives of long duration, i.e. in excess of 48 hours, does the control of humidity become important. Especially during decompression, the main problems seem to arise from the condensation of water vapour within the chamber so that the chamber walls, items of equipment, utensils, clothing and blankets become damp. Apart from the discomfort of living in a damp and sometimes dripping environment, the skin of the divers themselves becomes more than usually prone to infection. Fungal infections of the skin, and infections of the external ear are common, particularly in chambers containing a water-filled compartment.

Because of the large quantity of water contained in the chamber atmosphere its removal poses a significant problem with certain types of scrubbing systems. Just as large quantities of CO_2 can choke the system by freezing out at relatively high temperatures in cryogenic scrubbing systems, so too may the system be choked by frozen water vapour. In scrubbing systems relying upon molecular sieve material, moisture drastically reduces the efficiency of the material. It is therefore usual to interpose between the moist gas of the chamber and the scrubbing system a replenishable canister of silica gel to remove a large proportion of the water before the gas passes into the scrubbing system. It is possible by frequent replacement of the silica gel to maintain humidity levels within the chamber of between 50 and 70% of the saturated water vapour pressure at the particular chamber temperature.

Accurate analysis of water vapour content has proved in practice to be extremely difficult, but in most circumstances is fortunately not really necessary. In general, within shore-based facilities it has not been found too difficult to maintain a satisfactory relative humidity and, of course, temperature, within the narrow band of comfort required by the divers. Excessive evaporative cooling at constant chamber temperature, particularly in oxy-helium atmospheres, is soon brought to the attention of the chamber operating staff and is readily controlled by an increase in chamber temperature accompanied by the removal of silica gel from the scrubbing system.

OTHER GASES

In the course of digestion, particularly in the large intestine, small quantities of toxic gases may be produced by bacterial fermentation. Of these, the two most common are methane (CH_4) and hydrogen sulphide (H_2S), the actual quantities produced being a function of the diet. Many carbohydrates, particularly those with high bulk content, such as cereals, are responsible for the production of CH_4, whereas highly spiced proteins and egg materials may lead to production of H_2S. Over a considerable period of time, which may be regarded as weeks rather than days in an entirely closed environment, concentrations of these gases may approach maximal permissible levels.

Methane itself is non-toxic but highly inflammable in the presence of oxygen. In addition, small quantities of hydrogen are produced, which further contribute to a fire potential, although concentrations in excess of 4% by volume would be required.

Hydrogen sulphide is a highly toxic gas, even in low concentrations, acting as a central nervous system poison at concentrations of 700 p.p.m. at 1 ATS or greater, and as a pulmonary irritant in concentrations as low as 70 p.p.m. with prolonged exposure. The maximal permissible concentration for prolonged exposure is the surface equivalent of 10 p.p.m. or less.

Bacterial action on nitrogenous material in the bowel and particularly in urine may produce *ammonia*, a highly toxic gas which is irritant to the lungs and mucous membranes in low concentrations. The maximal concentration of ammonia should not exceed the surface equivalent of 50 p.p.m. *Acetone* and some volatile compounds are eluted from urine, but only very small amounts actually contaminate the chamber atmosphere.

Red blood cells have a mean life of approximately 120 days with a constant input of new cells balancing the destruction of the old. As a by-product of the degradation of haemoglobin from these destroyed cells, small quantities of *carbon monoxide* are produced each day and over a lengthy period may exceed the maximal permissible concentration of 50 p.p.m.

The production of CH_4 and, to a greater extent, H_2S can largely be controlled by appropriate choice of diet for the divers. The production of NH_3 can be reduced to a minimum by adequate daily cleanliness, which includes not only personal hygiene, but daily changing of underclothing, and meticulous attention to the handling and removal from the chamber of collected urine and faecal material. Toilet buckets, their seats, canisters and also the area around the toilets should be scrubbed daily to prevent the build-up of NH_3. It should also be remembered that if such material is spilt some may seep beneath the deck plates where an ideal environment always exists for a high level of bacterial activity.

In general, the majority of noxious gases produced by metabolic breakdown in the gut and urine can largely be removed by activated charcoal, frozen out of the gas by a cryogenic system, or readily removed by molecular sieve material. Provision should therefore be made in each type of scrubbing system for their removal. In this respect a catalytic furnace has proved extremely effective. Carbon monoxide, on the other hand, is poorly absorbed by activated charcoal, but is readily removed cryogenically by molecular sieve material or by catalytic furnace.

Traditionally, hopcalite has been used as the reagent in such catalytic furnaces, and is a mixture of 50% manganese dioxide, 30% copper oxide, 15% cobalt oxide and 5% silver oxide. It is most frequently used as a catalyst to oxidize the carbon monoxide in air. However, finely divided platinum is now superseding hopcalite as the catalyst in such furnaces, as it is more efficient and can deal with a wider range of contaminants.

Further breakdown products of faecal materials include indole compounds and other complex combinations of hydrocarbons and nitrogen, some of which may be halogenated with chlorine. In addition, chemicals used in many sanitary pans as oxidants or cleansing agents may also contain chlorine. For example, buffered solutions of hypochlorite evolve small quantities of chlorine gas. The maximal permissible concentration of chlorine at 1 ATS is 1 p.p.m.

Many of the materials used in the construction of diving chambers (paints, lagging, electrical insulation materials, lubricants on door hinges, and even materials such as synthetic clothing and some toilet articles) are subject to out-gassing of noxious materials. Most out-gassing products tend to consist of carbon dioxide and volatile hydrocarbons, many of which, being aromatic in nature, are quite toxic to liver, bone marrow and central nervous tissue. The most hazardous hydrocarbons belong to the halogenated groups, particularly those containing fluorine, and when oxidized in the presence of sulphur-containing compounds may form highly toxic by-products indeed. Such a compound is sulphur tetrafluoride, lethal at 10 p.p.m.

In normal circumstances, provided time has been allowed, for example, for new paint work to cure thoroughly, little problem from such materials may be expected in diving conditions. They do, however, represent a potential problem in nuclear submarines where crews may be required to live in a totally closed environment for periods in excess of 3 months, or perhaps, in long-term underwater habitat experiments. Some such materials may be absorbed onto active charcoal, but all may be removed cryogenically or by molecular sieve material. In the event of a dive continuing longer than several weeks, it would perhaps be advisable to exchange the chamber gas completely at least once during the dive.

The greatest potential hazard from out-gassed solvent materials is by their accidental introduction to the chamber environment. Noxious solvent chemicals such as trichlorethylene and petroleum by-products such as kerosene (paraffin) have been introduced at different times by accident into high pressure chamber environments. High pressure valves with Teflon or nylon seats pose a potential hazard. Such a valve may be opened inadvertently so that supersonic gas-flow is permitted across a critical orifice with an attendant rise in temperature at the edge of the valve seat in excess of the vapourizing temperature of the material forming the seat (approximately 450°C in the case of nylon, 600°C in the case of Teflon). The vapour given off is highly toxic even in low concentrations. The presence of any such materials in high concentration would, of course, constitute a major chamber accident. Indeed, the removal of the products in very low concentration presents difficulties if some oxidative process such as a high temperature catalytic furnace is used. Cryogenic and molecular sieve systems handle such materials adequately.

GAS ANALYSIS

Clearly, the requirement for gas analysis varies with the type of work being undertaken at pressure. During long-term experimental saturation dives within the high pressure laboratory, fully detailed knowledge of all components of the chamber atmosphere is required. Whereas, for short-term oxy-helium dives to 200 m (21 ATA) or less, using a submersible decompression chamber locking onto a deck decompression chamber, the main gas analysis requirements are merely for oxygen and carbon dioxide. Moreover, relatively simple but robust equipment will suffice in such cases. In the laboratory, however, highly sophisticated analytical equipment is necessary.

As it is not always possible to be certain of the components within the chamber atmosphere during a prolonged laboratory experiment, mass spectrometry, covering a wide mass range is advisable, in order to obtain an indication of the range of compounds present, either from their mass numbers directly or by their cracking patterns. In addition, such analysis should give an order of magnitude of the concentration of the compounds present. For more detailed analysis of the components of the chamber gas, the most accurate method available is by gas chromatography. Such instruments are expensive but must ultimately be the arbiters of the concentrations of all gases present. With the advent of the quadrupole non-magnetic mass spectrometer, greater flexibility of use for a lower capital cost can be achieved than with previous types. Some models can be used both as a chamber gas analyser of high resolution and accuracy, covering mass ranges from 2 to 200 overall, and by switching modes can rapidly be employed as fast-responding respiratory gas analysers.

Under routine operating conditions, the primary monitoring requirements are for oxygen and carbon dioxide. For continuous oxygen analysis two methods are principally in use, paramagnetic analysis and polarography.

The paramagnetic method exploits the fact that the oxygen molecule, consisting as it does of two atoms each with an unpaired electron in its outer shell, has strong magnetic susceptibility. Instruments operating on this principle are accurate, linear, though until recently were relatively slow responding.

The polarographic method depends on the reduction of oxygen at the cathode of an electrochemical cell, the output of which is proportional to the oxygen partial pressure of the gas surrounding the cell.

While paramagnetic systems are inherently more accurate, the operating mechanism is fragile and therefore subject to damage in transit. Polarographic systems on the other hand, are extremely robust and highly portable, but require frequent calibration to ensure accuracy. They are, perhaps, better employed as sensors of relative changes in oxygen concentration, rather than as arbiters of absolute concentration and, as such, lend themselves to the sensor side of an oxygen injection system, as described above.

The most common means employed to analyse carbon dioxide content is by infra-red absorption analysis, which is adequate for most operational circumstances. The accuracy of such analysers is inversely proportional to the rate of response: fast response instruments, i.e. 95% response in less than 1 second, are somewhat less accurate than slower responding instruments.

In addition, spot checks on carbon dioxide and oxygen content can be made by a chemical absorption method, used in such instruments as the Lloyd–Haldane or micro-Scholander apparatus. These techniques, however, require considerable skill on the part of the operator.

The more exotic gases encountered are for the most part better left to mass spectrometry and gas chromatographic analysis, with the possible exception of carbon monoxide which is difficult to detect by mass spectrometry. However, many such gases can be detected, although not necessarily positively quantified, by the use of appropriate chemical detector tubes. For instance, a large range of specific Draeger tubes is available to detect specific volatile compounds ranging from carbon monoxide to various types of mineral oil.

HELIUM RECLAMATION

The bulk of the helium used in the western world is produced in the United States of America and Canada, and the cost to the user in different parts of the world varies but is relatively expensive. Therefore, depending upon the quantity used, it is often advantageous to avoid wasting the helium vented during decompression. After the removal of carbon dioxide, water vapour, carbon monoxide, micro-organisms and other trace contaminants, the remaining components of the gas mixture are helium, oxygen and some nitrogen, usually 1% or less. The partial pressure of oxygen present tends to depend upon the depth of the dive.

The simplest means of re-using the gas collected is to accept a small degree of nitrogen contamination and either to add more oxygen to the mixture to make up a given higher Po_2 oxygen–helium mix, or to add fresh helium to the mixture to make up a given lower Po_2 oxygen–helium mix. With each transfer of gas in such a cascade method some will be lost, but the method is quite cost effective if extremely large volumes of gas are not required over the year.

If the cost-effectiveness of the cascade method is outweighed either by the cost of helium lost or the time taken to reconstitute mixtures within the cascade, the impure helium mixture may be scrubbed of both oxygen and nitrogen. Industrially, two methods are employed: cryogenic freezing-out of O_2 and N_2 by passing the gas

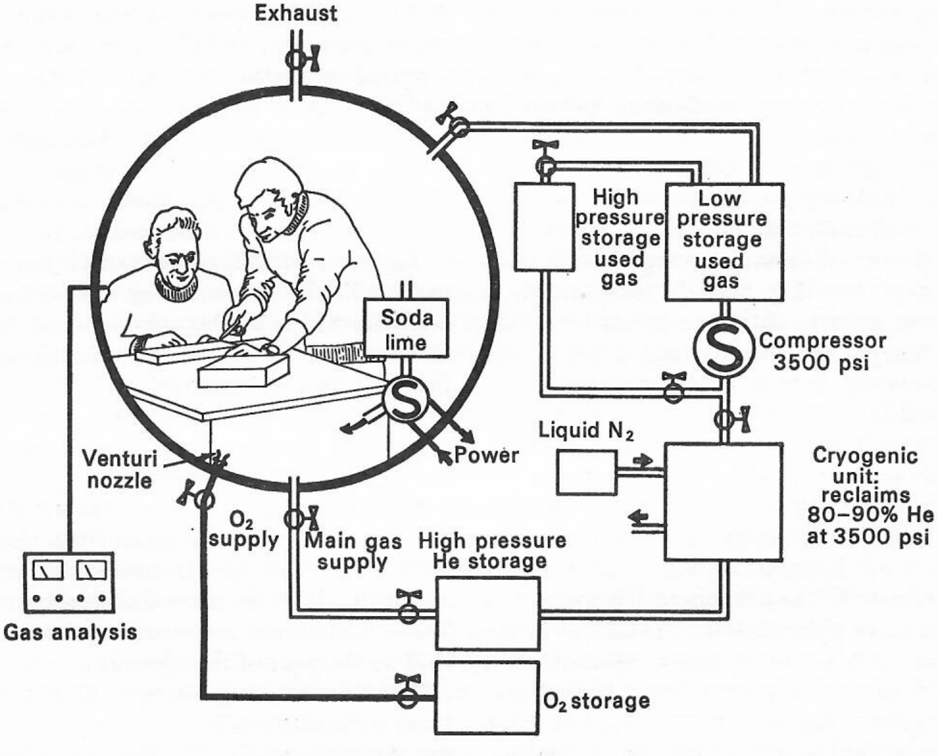

FIG. 6.8. Diagram of a cryogenic scrubbing and helium reclamation system of the type at present in use at the Deep Trials Unit, Admiralty Experimental Diving Unit. To avoid choking the cryogenic unit with solid CO_2, the CO_2 is scrubbed separately by an internal system. The bulk of water vapour condenses out during transfer stages. Helium and oxygen mixtures are produced within the chamber, mixing being by venturi nozzle

mixture through heat exchanger coils cooled with liquid nitrogen, or multiple molecular sieve columns. In both methods, some helium is again lost.

Fig. 6.8 represents schematically the cryogenic helium reclamation system in use at the Deep Trials Unit of the Admiralty Experimental Diving Unit. Carbon dioxide, water vapour and some other noxious materials are scrubbed out of the chamber atmosphere first and then the gas is bled down to large, helium-tight bags, from which it is pumped through the cryogenic unit into the high pressure helium storage bank. Although 90 to 95% recovery by the unit is claimed, some additional helium is lost in the storage bags and pipework, making the overall recovery somewhat lower. The capital costs of such units are high and require a constant drain on expenditure due to the usage of liquid nitrogen. In addition, the need to rely upon a ready supply of liquid nitrogen reduces the general usefulness of such equipment to shore-based facilities within reasonable transporting distance of a supplier of the bulk gas in liquid form.

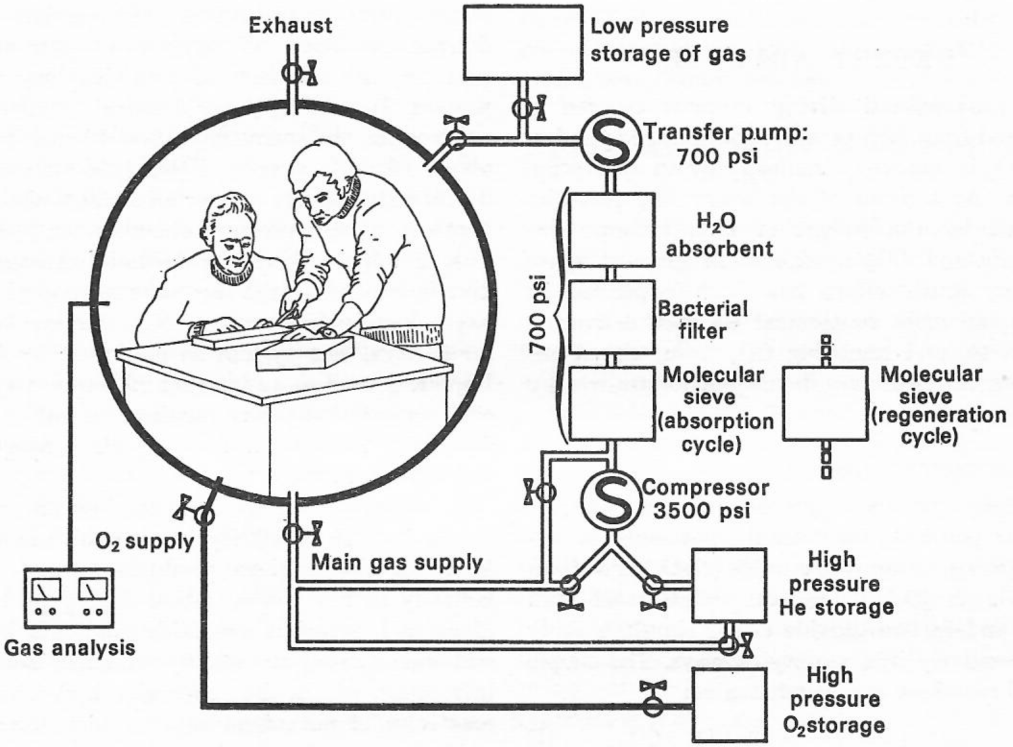

FIG. 6.9. Diagram of a molecular sieve scrubbing and reclamation system. No internal CO_2 scrubber is required, although provision must be made for water vapour removal before gas enters the molecular sieve bed to prevent caking of the bed. At the end of a given scrubbing cycle, the bed material is regenerated simply by back-flushing with scrubbed gas, and the impure flushed gas from the regenerated sieve material can either be dumped or passed back through the bed at its next scrubbing cycle

Molecular sieve reclamation appears, at least superficially, to be more attractive in terms of lower overall capital cost and of reducing running costs. The columns of sieve material may be regenerated, and require replacement at infrequent intervals. Fig. 6.9 shows schematically the type of system that could be applied to a diving context. A positive benefit is the ability of the system to scrub out of the chamber atmosphere all contaminants except water, which should be removed independently to prevent choking of the bed with wet, caked, molecular sieve material. It is true that some helium is lost when the beds are reverse-flushed with pure helium to regenerate the molecular sieve material, and, in addition, some is lost in pipework and storage vessels. In normal industrial practice, however, better than 80 to 85% recovery of helium may be expected.

RECENT ADVANCES

In conventional diving systems oxygen is delivered from high pressure gas storage cylinders and CO_2 is removed chemically by an absorption system. As a result of the heavy fuel penalties imposed by the weight of high pressure gas cylinders and CO_2 absorbent in manned space vehicles, much effort has been expended in developing more economical ways of delivering oxygen to, and removing CO_2 from, closed environments. Two main developments are worthy of note.

Peroxide/superoxide systems

In these systems oxygen is carried as a superoxide or peroxide, for example, potassium superoxide (KO_2), sodium superoxide (NaO_2) or sodium peroxide (Na_2O_2). These compounds react with water and carbon dioxide either simultaneously or successively in a variety of ways. The simple overall reactions can be written as:

$$8KO_2 + 4CO_2 \longrightarrow 4K_2CO_3 + 6O_2 \qquad (1)$$

$$8NaO_2 + 4CO_2 \longrightarrow 4Na_2CO_3 + 6O_2 \qquad (2)$$

$$2Na_2O_2 + 2CO_2 \longrightarrow 2Na_2CO_3 + O_2 \qquad (3)$$

Broken down into its component parts, the superoxide reacts in the presence of moisture, e.g. water vapour from the breath or in the chamber:

$$4KO_2 + 2H_2O \longrightarrow 4KOH + 3\ O_2$$

The potassium hydroxide thus formed, absorbs the carbon dioxide by the reaction:

$$CO_2 + 2KOH \longrightarrow K_2CO_3 + H_2O$$

Thus there is absorption of the carbon dioxide and generation of oxygen. In theory at least, the quantity of oxygen produced by the reaction should be a direct function of the concentration of CO_2.

Such a system has been produced commercially by L'Air-Liquide in France who claim that under normal conditions of relative humidity between 50 and 70% at 20°C, the potassium superoxide system keeps the composition of the atmosphere constant at the initial composition of oxygen and CO_2 and, furthermore, adjusts the rate of the reactions to correspond with the level of activity of the divers. Quantitatively, the reaction should deliver 190 litres of oxygen at atmospheric pressure, per kilogram of potassium superoxide present. In addition, the chemical reactions are exothermic, the quantity of heat liberated being about 1 kcal/L oxygen. Using this system, two divers were entirely supported at 30 m simulated depth in a high pressure chamber for $1\frac{1}{2}$ hours. This dive was followed by a simulated saturation dive in which three divers were supported in an oxy-helium environment at 100 m simulated depth for 3 days. The system as marketed by L'Air-Liquide is used as an internal life support system with an external power requirement sufficient to drive the blower fan drawing air through the superoxide reactor.

A further advantage of potassium superoxide lies in its high reactivity as an oxidizing agent. Many of the noxious products formed metabolically in low concentration during prolonged dives, such as carbon monoxide, ammonia, indoles and mercaptans, are readily oxidized, and held in solution within the superoxide bed. The very reactivity of potassium superoxide is, however, a disadvantage in that it is extremely caustic to human tissue, which creates a potential hazard, particularly in handling and storage of the material. Moreover, within such an internal life support system, efficient filtration must be provided for gas on the outflow side, to prevent such caustic materials from entering the chamber atmosphere and being deposited on skin, clothing, bedding or equipment, or being inhaled by the divers. The end product formed, potassium carbonate (K_2CO_3), tends to be deliquescent, which may cause the granular bed of KO_2 to cake and solidify at its most reactive parts, thereby reducing the overall activity of the bed and decreasing the efficiency of the gas circulation blower.

For larger volume oxygen production and CO_2

absorption, sodium peroxide (Na_2O_2) and sodium superoxide (NaO_2) react with moisture to form caustic soda (NaOH) and hydrogen peroxide (H_2O_2), which itself decomposes to oxygen and water. The caustic soda solution thus produced is transferred to a second reactor where it absorbs the carbon dioxide from the atmosphere, with the formation of sodium carbonate. Although a more complex system than the potassium superoxide one described above, the reactions are more readily controlled to match oxygen consumption requirements within the environment, and can handle large volumes of gas. This system is, perhaps, more applicable as a life support system in a submarine, submersible or underwater habitat than in conventional diving operations.

The prime disadvantage with such systems is that a non-regenerable carbonate salt is formed, and, like soda lime, the superoxides and peroxides have a once-only capability. L'Air-Liquide claim durations for their system of 24 hours per man per 3·75 kg of potassium superoxide; 16 hours per man per 3·2 kg, and 8 hours per man per 2 kg, thus relying upon average oxygen consumptions between 0·5 L/min for the 24-hour duration, and 0·8 L/min for the 8-hour duration.

High temperature solid electrolyte systems

In these systems (Weissbart, Smart & Wydeven 1969) a doped zirconia ceramic membrane is employed at a temperature of 1000°C. If a potential is applied to the two faces of the membrane by the use of suitable electrodes, oxygen ions pass across the membrane from anode to cathode. The reactions are: at the anode, $CO_2 \rightarrow CO + O_{(S)}$, at the cathode, $2O_{(S)} \rightarrow O_2$. At a lower temperature, and using a suitable catalyst, carbon monoxide disproportionates into carbon dioxide with the deposition of graphitic carbon: $2CO \rightarrow CO_2 + C$. On recirculation of the gas, the carbon dioxide is reduced by the zirconia electrolytic cell into oxygen and carbon. The Faradaic efficiency of the system is claimed to be high, particularly if small amounts of water are present with the carbon dioxide, enough to decrease the reduction of the electrolyte itself. Such a system is largely self regenerating, but has the grave disadvantage in the diving situation of operating at very high temperatures.

Photosynthetic systems

In the presence of appropriate ultra-violet light intensity and a suitably nutrient environment, green algae convert carbon dioxide into oxygen. Within the marine environment such purely biological systems may find a place in the future. In addition, by slight alteration in the nutrient medium and level of ultra-violet light, specialized forms of algal growth can be encouraged which are in themselves highly nutritious, if perhaps monotonous, sources of food.

APPLICATIONS OF LIFE SUPPORT AT SEA

The limitations of ship-board isolation impose restrictions upon the type and size of the life support system used, and perhaps upon the level of sophistication attainable in the analysis of chamber gas. There is clearly a limit to the bulk and weight of the life support system employed.

With the advent of effective designs for an efficient, compact, molecular sieve life support system, the problems of conventional external systems may be overcome. The bulky pipework and massive canister housings right next to the chamber can be replaced by a self-contained unit including, if necessary, its own power supply and compressor, housed remotely from the chamber area and coupled to it by narrow bore pipes and small valves. In addition, the molecular sieve material is regenerated and has an overall life in excess of 6 months. Moreover, the molecular sieve system enables a better than 80% recovery when used for helium reclamation. The combined capabilities of life support and helium reclamation built into a readily transportable modular unit make the design extremely attractive for both ship-board and shore-based use. It is envisaged that the external molecular sieve life support system would be supported by a small scrubbing system inside the chamber capable of removing CO_2, water vapour and perhaps some of the hydrocarbons. This system would be used in an emergency where the molecular sieve system was not functioning for some hours.

In the meantime, the choice of life support system for ship-board use centres around the advantages and disadvantages of internal versus external systems. Both are based upon the chemical removal of CO_2 by a granular alkaline bed, the removal of water vapour by silica gel and by the scrubbing of other noxious compounds by activated charcoal. The advantages of the internal system are primarily ones of cost and of saving in space in the region immediately around the chamber, coupled with some enhancement to gas circulation within the chamber. As such, it is a very useful system, particularly on dives of relatively short duration to depths shallower than 200 m, where access to the interior of the chamber by external control staff is a practical proposition in an emergency.

In general, for greater safety and flexibility in operation an external system is to be preferred. With an external loop it is possible to include a catalytic furnace to remove carbon monoxide and other noxious products, thus allowing significantly prolonged durations of bottom time and decompression. The main disadvantages are the bulk and the cost. The bulk encroaches upon useful deck space within the ship, and, as in the case of some diving ships where the chambers are mounted relatively high in the superstructure, the increased mass may significantly raise the centre of gravity of the ship. In addition, a bulky external life support system, mounted next to the chamber and coupled to it by wide bore high pressure steel piping, increases the problems should the chamber need to be moved as it is virtually an integral part of the chamber structure.

Shore-based facilities generally do not have a major problem with space and unless geographically isolated, provide no great logistical problem for the supply of fresh soda lime, silica gel, activated charcoal, liquid nitrogen, or, for that matter, replenishment of molecular sieve material. In addition, the electrical requirements for a shore-based facility can be virtually limitless, whereas, at sea, the use of electrical power may be restricted. Moreover, the power supplies to shore-based facilities are in general mains voltage, whereas at sea electrical voltages on-line may differ greatly.

FIRE HAZARDS

Three factors combine to cause any fire: the partial pressure of oxygen must be sufficiently high to support both ignition and combustion, some form of inflammable material must be present, and there must be an active source of ignition. For obvious reasons, matches and cigarette lighters must not be allowed in high pressure chambers.

As a general rule, it is wise to prevent equipment or lighting operated from mains voltages from being exposed to high pressure chamber atmospheres. Although methods for encasing electrical equipment in an explosion-proof housing purged with an inert gas such as nitrogen are in common use, a potential hazard nonetheless exists. It is worthwhile, as far as possible, to exclude combustible materials such as paper, loose clothing, and excess bedding, but not to the detriment of the diver's welfare. It is now well known that despite somewhat increased partial pressures of oxygen, a sufficiently high partial pressure of inert gas provides a significant blanketing effect to ignition and propagation of a fire (Dorr & Schreiner 1969). In deep oxy-helium dives where the oxygen partial pressure is maintained at 0·5 ATS or lower, the fire hazard is insignificant. Only during the shallow phases of a decompression where oxygen partial pressures are raised does the risk increase. Therefore, it is advisable to employ some form of exhaled gas dumping outside the chamber, particularly when the divers are breathing pure oxygen either during a normal decompression or during recompression therapy.

Although much discussion has centred upon the best ways of combating fires in high pressure chambers, one of the simplest and most effective ways of handling the situation is simply to repressurize the chamber with an appropriate inert gas thus reducing the oxygen concentration. It is fortunate that the intensity of a fire will diminish to manageable levels, or even be extinguished, with oxygen partial pressures remaining sufficient to maintain life. The resultant increase in total pressure will, of course, add somewhat to the decompression time, but the problems so caused are relatively minor.

Once the fire has been extinguished, the major hazard is from smoke and fumes generated by combustion. A damp cloth held over the nose and mouth can act as a very efficient filter screening the lungs and mucous membranes from heavy contamination. As soon as possible the divers should breathe a respirable gas mixture delivered via the built-in breathing system, thus allowing adequate ventilation of the chamber and subsequent restitution of an internal respirable mixture. In competent hands all this could be done very quickly, allowing early assessment of the damage and, hopefully, an early return to a stable state. In chambers lacking a considerable margin for pressurization above the pressure at which the fire breaks out the same method could be employed, with judicious simultaneous venting of chamber atmosphere through the exhaust valve, the controlling factor being the P_{O_2} inside the chamber as judged by the activity of the fire. Again, a built-in breathing system with a respirable gas mixture on-line must be readily available to the divers.

On the other hand, emergency decompression of the chamber may prove catastrophic for the divers, without necessarily diminishing the problems of extinguishing the blaze.

Water sprinkler systems have, in the main, proved ineffective. However, a weak (100:1) solution of high grade household detergent in water forced under pressure across a fine mesh screen placed in front of a high volume air blower has proved very effective in putting out test fires in chambers (Dorr & Schreiner 1969). Smoke and other solid particles adhere to the surface of the bubbles formed leaving a respirable, if soapy, gas mixture in the chamber.

The majority of fires in high pressure chambers have involved some fault in electrical equipment operated either from mains supply, or drawing a relatively large current—the energy for ignition being volts × amperes. If such equipment must be used inside a high pressure chamber then, apart from internal protection of the equipment by a housing purged with inert gas, the active power line should be fitted outside the chamber with a circuit-breaking device having a current loading very little above the operating level of the equipment, so that even a small surge of current lasting longer than a few seconds would be sufficient to break the circuit. At no time should electrical fuses or circuit-breakers be employed inside the chamber, as the potential energy sufficient to cause ignition would still lie in contact with the chamber environment.

In addition, isolation of the chamber from earth via an isolation transformer, has advantages, particularly when employed with a warning system coupled between the input side of the transformer and earth, such that an alarm is sounded should an electrical potential greater than a given pre-set level be recorded. With such a system in use, all equipment capable of conducting electricity must similarly be isolated from earth, and any electrical equipment operated ancillary to the chamber be earthed to the chamber. It is seldom practicable that all such criteria can be met.

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