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The Compressed Air Environment

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HISTORICAL INTRODUCTION

Hugh Snell was the physician who looked after the health of the men who worked on the original Blackwall Tunnel, the first large contract in Britain to use compressed air, and his book *Compressed-air Illness*, published in 1896, was one of the first to appear in the English language on this subject. He claims that the idea of using air pressure to displace water from a working place was first mentioned in 1691 by Denys Papin. In 1830 the English engineer Cochrane (later Lord Dundonald) certainly took out a patent for using compressed air to keep back the water met with in driving shafts or tunnels, but it was not until 1839 that the celebrated French engineer, Triger, solved the practical problems and was able to employ this method successfully for sinking a shaft through a layer of quicksand to reach a bed of coal at Chalons in France (Triger 1841). The first physiological observations on man at a pressure of 4 ATA were made by Trouessant in 1845; he mentioned the effects on the ears and the difficulty in whistling at pressure, but expressed surprise that there were no gross changes in the vital functions.

It was left for the physicians Pol and Wattelle (1854) to describe the pathological effects experienced by compressed air workers and to point out that: 'The danger does not lie in entering a shaft containing compressed-air; nor in remaining there a longer or shorter time; decompression alone is dangerous.' They reported muscular pains in the limbs, respiratory and cerebral symptoms due to decompression and the fact that some men died.

Caissons were first used in Britain by Hughes (1851) during the construction of the foundations of a bridge at Rochester in Kent and shortly afterwards by Brunel for the Saltash bridge which carried the railway from Devon across to Cornwall. In the United States compressed air was used in the construction of a bridge over the Pee Dee river for the railroad from Wilmington to Colombia, sometime just before 1869, and in the same year the bridge over the Mississippi at St Louis was started. There caissons were used up to a pressure of 4.45 ATA (Woodward 1881).

The first use of compressed air in tunnels was probably in 1879 in connection with the tunnel under the Hudson River to connect Jersey City with New York (Jacobs 1910), and certainly by 1886–1890 compressed air was being used in Great Britain to construct tunnels for the City and South London Railway.

PRACTICAL CONSIDERATIONS

The usual practice is to fill the whole of the working chamber with air at a pressure sufficiently greater than atmospheric to exclude the groundwater and for the workmen to carry out their duties in this raised environmental pressure. Because of the traditional practices of the civil engineering industry, it is usual to work a three-shift system within the 24 h day so that the men have an opportunity to indulge in regular social activities. The introduction of working patterns similar to those used in saturation diving, in which the workmen would be kept at pressure for periods such as a week at a time, at first sight appear very attractive, in that the ratio of work period to decompression time would be much improved (Behnke 1969, 1974). It could also be economically sound in spite of the fact that the men would no doubt demand high financial recompense for working such a system. However, there are several problems to be considered. A major difficulty to its introduction would be related to the large numbers of men who, when compared with a diving team in saturation, would have to be fed and accommodated under pressure. In addition, saturation pressures would have to be limited to 22.5 psig (1.5 kg/cm^2) in order to avoid the toxic effects of air when breathed for long periods at greater pressure (both oxygen toxicity and nitrogen narcosis are potential hazards). But 'no decompression excursions' to 50 psig (3.4 kg/cm^2) for several hours could probably be made from the storage pressure every 12 h or so. This would involve the construction of an intermediate lock separating the tunnel into low- and high-pressure zones. At the end of 7–10 days in pressure the men could be decompressed to atmospheric pressure. No proven routines for such a system exist at present, but as saturation diving on air is currently being investigated, it would require only modest readjustment of the programme to make it applicable to the compressed air situation.

Up to 1971 in the USA almost all compressed air work was carried out using the State of New York Code (1920) and its amendments. This called for a split-shift system in which there were two working periods separated by an interval at atmospheric pressure. Experience indicated that this is not economically sound and that it is better to have a single working shift, with one fairly long decompression, than to have two shifts of half the length, with two slightly shorter decompressions. Ideally the civil engineers would like to divide the day into three 8 h shifts, each worked by a gang who could hand over to the next shift before leaving the face. Unfortunately, at higher pressures this is not possible, because the length of decompression becomes such that, when added to the working period, insufficient time is left in free air between shifts for the men to become completely free of excess dissolved gas in the tissues before starting the next shift. For instance, the CIRIA Code of Practice (1982) specifies an obligatory time in free air between shifts of 12 h and limits the decompression time plus working time for work at 14 psig (0.9 kg/cm^2) and above to no more than a total of 10 h in any 12 h.

Air supply

Because very large volumes of compressed air have to be used in order to fill the work place, be it tunnel or caisson, it is necessary to compress on site. Nevertheless, the air must be of a quality which can be breathed for long periods without harm by the men at work in the pressurized environment. It is, therefore, essential that the compressors draw their air from a place remote from engine exhaust fumes and other contaminants, and that aftercoolers, scrubbers and (if oil-lubricated compressors are used) filters must be fitted to ensure that the compressed air reaching the pressure chambers is odourless and suitable for breathing. Ideally, in temperate climates the temperature in the working chamber should not exceed 21 °C (70 °F).

The supply of air to the working chamber should be sufficient to provide at the working pressure at least 300 litres/min (10 ft^3/min) per person in the chamber (Fig. 2.1). As it would be hazardous for the pressure to drop accidentally owing to the breakdown of compressor plant or failure in electricity supply, adequate standby arrangements must be provided and brought into operation in an emergency, either manually or automatically. It is generally accepted that the minimum capacity of such standby equipment should be 50% of the designed requirement. In the case of electrically driven plant, an alternative prime mover must be provided to the full extent specified, either by auxiliary engines to replace electric motors in case of failure, by emergency generating sets to supply electricity to the installed electrical mains equipment, or by a reliable alternative mains electricity supply. The advantages of a fully electrical standby is that it allows other vital equipment such as cranes, pumps and lights to remain in operation during the mains failure. It is in any case desirable to arrange for essential lighting to be restored immediately following failure, and this can be done by the installation of a small standby automatic generating set.

In Great Britain the law requires that, except in an unforeseen emergency, no person shall be compressed to a pressure exceeding 50 psig (3.4 kg/cm^2), so that compressors are usually capable of maintaining working chamber pressures up to 4.5 ATA. It is important that the working chamber, man-lock and medical lock pressures are capable of being controlled over the whole range of 0–50 psig to a fine limit of $\pm \frac{1}{2}$ psi (0.034 kg/cm^2).

An air supply to the man-locks, independent of that to the working chamber, must be provided so that in case of fire in the working chamber the man-lock can be pressurized with air which is

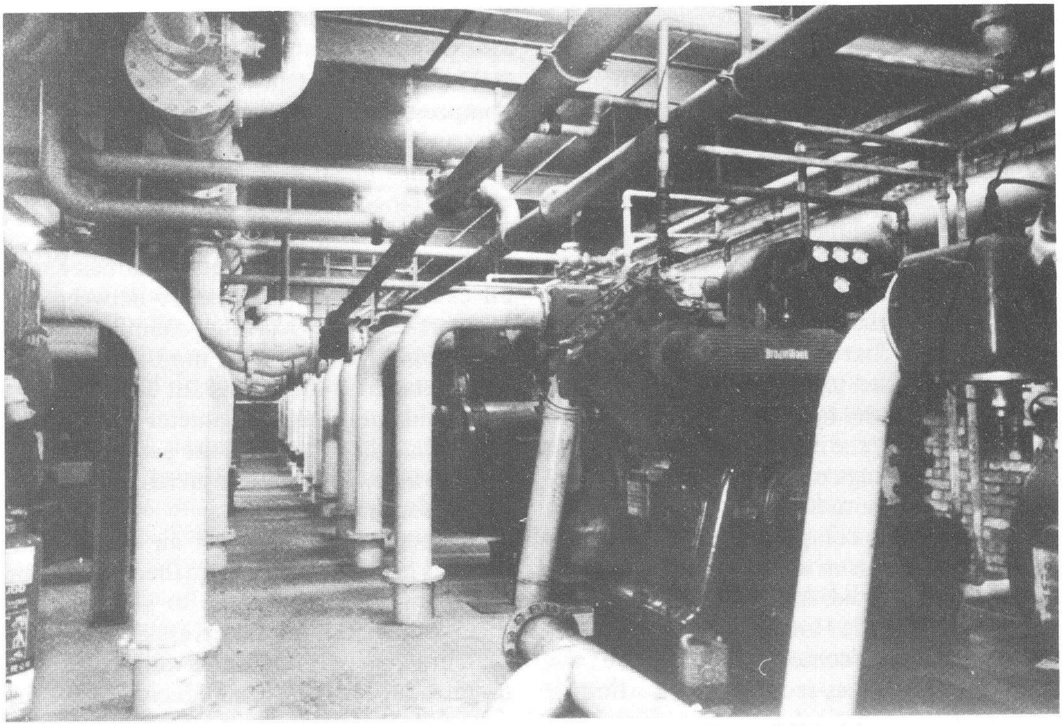

FIG. 2.1. Typical compressor house. Mass Transit Railway, Hong Kong, G.K.L. joint venture

uncontaminated with smoke. Fires are not unknown during tunnel construction, because it is traditional to keep bales of straw available near the face for the purpose of giving body and cohesion to earth plugs which may have to be used if the face starts to disintegrate. The straw bales can easily be ignited by sparks from welding and cutting operations being carried out in the vicinity, and burn well in compressed air. Hydraulic oil leaks and baulks of timber used in shoring up the face also add to the fire hazard. It is for these reasons that it has been suggested that a fire water main extending to the working face with outlets spaced every 200 ft should be installed. It must be remembered that Public Fire Service personnel should not be permitted to enter the working chamber unless they have been passed as medically fit and trained for work in compressed air. Rather it is recommended that experienced compressed air workers should be trained by the Public Fire Service in appropriate firefighting and rescue techniques. This should include the use of self-contained air breathing apparatus.

Medical locks must also at all times have the means to be independently pressurized to at least 0.7 bar above the expected maximum working pressure. They must also have available an emergency air supply with separate power source, controls, compressor and pipe work.

The volumetric capacity required from the compressors has to be estimated by the engineers. The estimate is influenced by the expected geological nature of the ground to be encountered and the number of men expected to be in the working chamber at any one time, as this determines the minimum ventilation rate of the working chamber as required by the appropriate regulations. Usually the air losses through the working face and the unlined tunnel walls and by the operation of the locks leading to the working chamber result in a ventilation rate far in excess of the minimum requirement for the safety of the men. Haxton and Whyte (1975) give an empirical formula which can be used as an approximate guide to the compressed air losses from each tunnel face:

$$C = nD^2$$

where C is the loss in cubic feet of 'free air' (air at atmospheric pressure) per minute, D is the diameter of the face of the tunnel in feet and n is a factor related to the ground conditions. The value of n has been found by experience to vary between 12 for an average open ground and 24 for open sand and gravel.

Basically, the working pressure required is determined by the depth of the workings below the standing water level. In practice, the pressure is varied so as to keep the working face dry. In the case of a large tunnel, the lower part of this face will require a significantly greater pressure of air than the upper part. Care must be taken that the pressure used to control the appearances of water from the bottom of the face is not so great as to cause a 'blow-out'—that is, the creation of a false passage from the tunnel to the bed of the overlying river from the top of the face. If this does occur, it is followed not only by the ingress of water from the river, but also by a deluge of sludge into the tunnel, which may create a situation that is difficult to control. The necessary compromise of air pressure to avoid this may result in a wet lower half of the face having to be tolerated. An ingenious but logical design feature used in the Hong Kong Mass Transit Railway scheme to overcome this problem was the use of an elliptical cross-section for the tunnel, which minimized the vertical while maximizing the horizontal diameter (Fig. 2.2).

Pipes and gauges

The compressed air has to be conveyed from the compressor house by pipeline to the various pressurized chambers, and it is usual to duplicate these lines and to fit them with non-return flap-valves at their discharge points in order to minimize losses from the chamber in the event of breakages.

Pipelines should be of such a diameter as to avoid an excessive drop in pressure between the compressors and the working chamber, even at air velocities up to 30 ft/s (9.1 m/s). Pipe work to man-locks, material locks, decant locks and medical locks must be of such a diameter that appropriately rapid changes of pressure are possible for compression of men, stage decompressions and, where in use, decanting procedures.

Although the volumes of air required are such that it is not practical to store them in high-pressure bottles, it is advantageous to generate and store them in large-volume receivers at a slightly higher pressure than required in the working chamber and to introduce a pressure-reducing valve into the system to regulate the working pressure exactly. Such a system avoids the inevitable variations in

FIG. 2.2. Tunnel with elliptical cross-section. Mass Transit Railway, Hong Kong, G.K.L. joint venture

pressure from the compressors as they cut in and out, and it damps the compressor pulsations before they reach the working chamber. It also facilitates the maintenance of a steady known pressure to which the workmen are being exposed.

In the compressor house or control room there should be a pressure gauge connected directly to each working chamber. Continuously recording pressure gauges should be kept in the immediate vicinity of the working chambers, air locks and medical locks. For the working chamber, a pressure recorder with a circular dial having a capacity of 24 h/rev is sufficient. In connection with every man-lock and medical lock, where an attendant will be carrying out timed decompressions, it is essential that the pressure gauges have a chart speed not slower than 1 rev in 4 h for circular charts or 120 mm/h for strip charts, so that measurements of time can be recorded with precision. It is particularly important that all pressure gauges used in the work should be accurate to $\pm \frac{1}{2}$ psi (0.034 kg/cm^2), and they should be checked regularly and recalibrated if necessary.

Man-locks

The working chamber is sealed from atmospheric air by means of a suitable concrete or steel bulkhead, and arrangements are made so that men and materials can pass in and out of the chamber without loss of pressure by installing air locks. There must be separate locks for men (man-locks) and materials (muck-locks), not only to avoid injuries from moving skips and equipment, but also because the men will usually require a timed decompression and this would hold up the transfer of equipment and spoil in and out of the working chamber. For tunnels the man-locks are usually horizontal, but for shafts and caissons they are often vertical.

Horizontal locks are generally cylindrical in shape and embedded in the bulkhead so that they protrude on the free air side. Both of the end doors of the lock are hinged to open into pressure, which facilitates obtaining a seal at the periphery of the door when it is closed. When the system of decompression requires a gradual fall in pressure right down to 0 psig, as in the UK 1958 Tables, it may prove difficult to obtain this in the circumstances of a compressed air contract site, where damage to door seals and sills can so easily occur. One advantage of the Blackpool Tables is that they are multistage procedures and the final stage before decompression to zero is at 4 psig (0.28 kg/cm^2), so that with these Tables there is no problem with leakage from poorly sealing doors at very low gauge pressures.

One problem which is particularly vexing is that of the control of the inner door of a single-compartment man-lock. In Britain for safety reasons there is a requirement for the inner door of the man-lock when it is not in use always to be left open when men are in the working chamber, on the grounds that if there is a need to rapidly evacuate it, as in flooding of the tunnel, they could immediately retreat into the man-lock and close the inner door. They would then be safe and could decompress at leisure. However, if the inner door is left open, then an outside lock-keeper is unable to get men into the working chamber until the inner door is closed. This might prove disastrous if some accident occurred within the working chamber as a result of which all the men became disabled or unconscious. There are at least three solutions to this problem and the civil engineers have to decide which system they will adopt.

(1) Employ an inside lock-keeper who will be responsible for operating the inner door when required. This man will spend his shift at pressure and will have to be cared for as a full-time compressed air worker and paid as such.

(2) Devise and fit some remote control system for operating the inner door of the man-lock from the outside lock-keeper's position.

(3) Use a multicompartment man-lock so that it is possible for an outside lock-keeper to get men both in and out at any time, irrespective of whether the inner door to the working chamber is open or shut (Fig. 2.3).

A typical and, in fact, classical arrangement of a caisson with blister man-locks was used recently on the Tyne at Newcastle during the construction of the foundations for the new Redheugh Bridge (Fig. 2.4). Similar arrangements have been used for over a century (Fig. 2.5). The shaft from the caisson usually has a cylindrical materials lock with a swinging door at the bottom end and a quick-release cover at the top end which is lifted off by crane. Two 'blister' man-locks, each capable of taking four men, are provided on the outside of the casing of the materials lock. Blister locks are necessarily small and, although seats may be provided, they are unsuitable for prolonged decompressions, because, for example, they have no toilet facilities. In Great Britain if decompression times of more than 30 min are required on exit from a caisson, a system of decanting is operated.

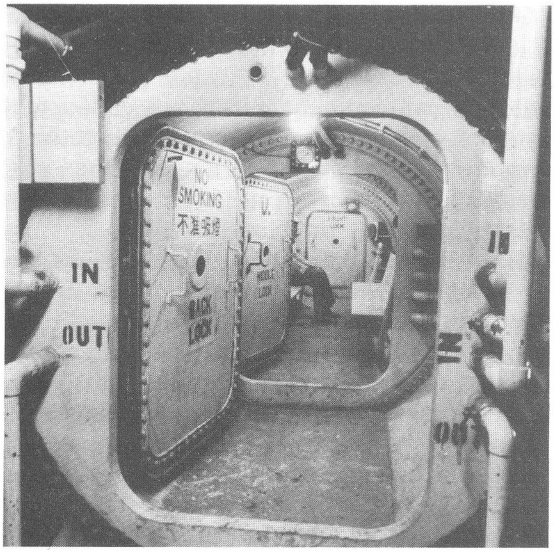

FIG. 2.3. Multi-compartment man-lock enabling men to enter working chamber from outside in an emergency, irrespective of whether the inner door is open or closed. Mass Transit Railway, Hong Kong, G.K.L. joint venture

Decanting

In decanting, men are rapidly decompressed in the man-lock and then transferred to another so-called 'decant lock' in which they are recompressed to 1 psig (0.068 kg/cm^2) above the full working pressure. After a 5 min wait the men are decompressed in the usual manner according to the tables in use at that contract. Tradition requires that the whole manoeuvre of rapid decompression from working pressure to atmospheric pressure, transfer to and recompression in the decant lock to slightly above working pressure, should not take longer than 5 min. This is an arbitrarily selected time limit, which by experience has been shown to be practical in that it is rare for decompression sickness to come on during the transfer procedure, and the final decompression sickness rate is not significantly greater than that for the orthodox technique. Obviously problems will eventually arise with decanting if the 5 min limit is greatly exceeded. In addition to being used in connection with blister locks, decanting is also used when space is at a premium and it is impossible to arrange for a muck lock as well as a horizontal man-lock. In these circumstances the men are usually hurried through

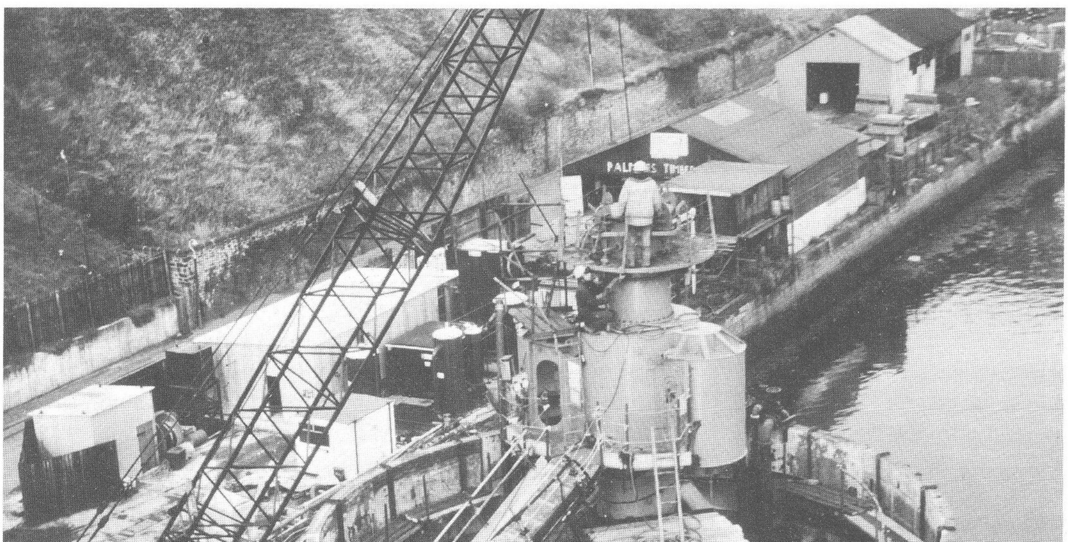

FIG. 2.4. Blister man-locks on caisson at Newcastle upon Tyne, 1981

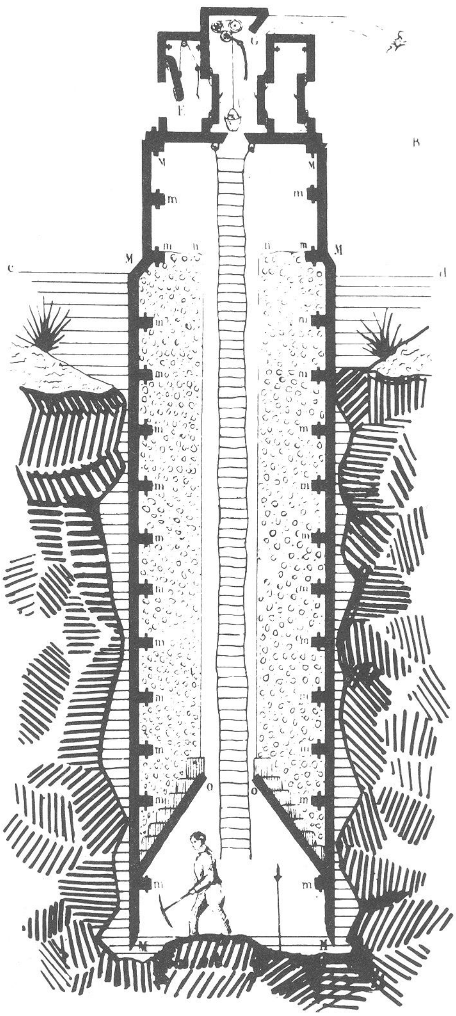

FIG. 2.5. Blister man-locks used on caisson at d'Argenteuil, 1861

the single lock at the level of the tunnel and have to transfer to a decant lock at the surface. In such cases men should not have to climb ladders, as this will tend to precipitate decompression sickness, but some form of hoist lift must be provided. Decanting should only be used with men who are already experienced at going in and out of compressed air. If an individual complains of discomfort in his ears, sinuses or teeth, the changes in pressure must be halted and the man transferred to another lock where he can be dealt with individually. The US Federal Code does not normally provide for decanting (Kindwall 1975).

Comfort in man-locks

It is essential to ensure comfort in man-locks and decant locks, since workmen may have to spend two or three hours being decompressed at the end of a long spell of hard work. A level floor, adequate ceiling height and seating are essential. It is recommended that a sitting space of 600 mm (2 ft) wide with back support should be provided for each person to be decompressed.

It is important that men should be in a comfortable position during decompression, with room to move their limbs and not hunched up. During rapid decompression the air temperature will fall, and care must be taken not to allow the wet bulb temperature to drop below 10 °C (50 °F), as this can result in vasoconstriction and interfere with gas clearance from the tissues.

It is sensible to provide men undergoing timed decompressions with dry, warm, extra clothing or blankets to prevent chilling and with hot drinks to promote vasodilatation, and to arrange for the lock to be warmed. Heating, however, must be such that there is no fire hazard. It can be achieved by protecting the lock from the elements by siting it in a warmed shed. The chamber itself can be warmed by applying electrical heating tapes to its surface. On the other hand, climatic conditions may be such that the lock must be protected from becoming too hot. This can be done in the simplest way by means of sun-shades and by spraying cold water onto blankets thrown over the chamber to make use of the cooling effects of evaporation.

Seats, the floor and any other furniture in the lock must be of fire-retardant material. Means of verbal and non-verbal communication between the men and the attendant must be provided. Silencers should be provided on the air inlets, since the rapid entry of air into the lock can result in very high noise levels which may be damaging to the ears.

Precautions must be taken to ensure that lighting does not present a fire hazard. Fire-fighting equipment in the chamber is probably best provided by buckets of sand and buckets of water.

Medical locks

Medical locks for the treatment of decompression sickness have to be available in the proportion of one per 100 compressed air workers on site whenever the working pressure is 2 ATA or above, and for 24 h after the last man-lock decompression from such pressures. They must be kept solely for the treatment of men suffering from decompression sickness. The only exception is that a medical lock may be used by the doctor to test new men being examined for their fitness to work in compressed air. Lock tests need only be brief and should never immobilize the only lock for more than a few minutes. A medical lock must never be used as a decant lock. It should be situated as near as possible to the man-lock and be in an enclosed building for protection from the weather and sun. The building should be capable of being kept at about 20 °C. The lock should have clear head room at its highest point of not less than 1.85 m (6 ft), so that most men may stand up in it, and consist of two compartments, so that an attendant can enter while the lock is under pressure. The inner compartment should be long enough to allow a man to lie down (not less than 1.85 m).

Under no circumstances may smoking be allowed in the medical lock. It should be provided with fire-retardant mattress, blankets, dry garments and a food lock, so that drinks or meals as well as small items of medical equipment can be rapidly passed in and out when men are under treatment.

Heating and lighting and a telephone system should be provided in such a way that there is no fire risk. Means of non-verbal communication must also be provided, both between the inside and outside of the compartments and between the compartments. Windows should be so placed that all persons in either compartment can be observed at all times by the medical lock attendant.

The best extinguishing agent for fire-fighting in the chamber is water (Schmidt *et al.* 1973). Experience suggests that purpose-built deluge systems relying on automatic fire detectors are often disappointing when tested under operating pressures and conditions. Fire-fighting equipment can most simply be provided by a bucket of sand and a bucket of water. However, best of all would be the installation of a manually directable fire hose permitting the occupants of the chamber to control localized small or incipient fires with minimal damage to chamber apparatus. Care must be taken to ensure that sufficient water pressure is always available to operate the hose, even when the chamber is at maximum working pressure.

Controls of locks

Although every man-lock must be in the charge of a competent lock attendant, who must be able to control from the outside both the rate of compression and the rate of decompression, the valve arrangement should be such that persons in the lock can control for themselves the pressurization of the lock if necessary. Normally the rate of compression recommended for men never exceeds 10 lb/in^2 (0.7 kg/cm^2) and the rate of decompression 5 $lb\ in^{-2}\ min^{-1}$ (0.35 $kg\ cm^{-2}\ min^{-1}$) but in 'decanting' a more rapid decompression and recompression may be essential if the 5 min rule is to be obeyed. Only in an emergency should those inside be able to reduce the air pressure in the chamber. If a special valve, clearly marked for use in an emergency and enclosed in a breakable glass-fronted box (as is done with a fire door key) is provided, the men can use it to reduce pressure in the lock should the outside lock-keeper accidentally be incapacitated or absent.

Some decompression tables require considerable skill to follow accurately and, in order to make it easy for the man-lock attendant, the engineers sometimes supply a mechanical device involving a clock-driven cam which automatically controls through a Fisher valve the pressure in the chamber (Haxton & Whyte 1965). In the United States the Occupational Health and Safety Act of 1971 requires the use of automatic devices to control decompression when pressures in tunnels or caissons exceed 12 psig (0.84 kg/cm^2). Such devices are not really needed when decompression procedures using multiple stages are in operation, because only rapid changes of pressure are required between stages and these are simple for the lock-keeper to carry out. It should be remembered that when automatic devices are used, the lock-keepers quickly forget their skill at changing the man-lock pressures smoothly and accurately, and in an emergency requiring a manually controlled decompression or when an unusual decompression procedure is required they may not be able to cope.

During long decompressions it may be necessary to flush the lock in order to counter the rise of CO_2 and CO which will inevitably occur. A skilled lock-keeper should be able to flush through a lock for several minutes without disturbing the ambient pressure from its correct value, according to the decompression schedule being used, by more than $\frac{1}{2}$ psi (0.034 kg/cm^2). In cases where automatic equipment is used to control the decompression, it should be possible to flush the chamber merely by admitting more air while allowing the equipment to make the necessary adjustment to exhaust flows to maintain the preset pressure level.

The Threshold Limit Value–Time Weighted Average for CO and CO_2 (as adopted by the

American Conference of Governmental Industrial Hygienists 1978 and reproduced in Guidance Note EH 15/78 from the Health and Safety Executive in the United Kingdom) should not be exceeded for any working chamber, man-lock, decant lock or medical lock when measured with a suitable detector. These are the average concentrations for a normal 8 h work day or 40 h work week to which nearly all workers may be repeatedly exposed day after day without adverse effect. The CO value is currently 50 parts per million at any working pressure up to a maximum of 50 psig (3.5 kg/cm^2) and the relevant values for CO_2, which vary according to the working pressure, are as indicated in Table 2.1.

TABLE 2.1

Quality of air within the working chamber. The carbon dioxide content should not exceed the value stated when the air is tested at atmospheric pressure using a suitable detector

Working pressure		*Carbon dioxide content (p.p.m)*
(bar)	*(psig)*	
1	0	5000
1.5	7	3300
2	14.5	2500
2.5	22	2000
3	29	1670
3.5	36	1430
4	43.5	1250
4.5	50	1140

Man-lock attendants are responsible for ensuring that every compressed air worker who enters their lock receives an appropriate decompression for the particular duration and pressure of exposure to which he has been exposed. They must, therefore, be reasonably intelligent, disciplined and reliable men. As it is mandatory that proper records be kept of the entry time, exit time and relevant working chamber pressure for every man, they must be able to write legibly and have a visual acuity such that they can clearly read the available copy of the decompression table in use and all the pressure gauges. They must be able to understand sufficiently the theory of decompression from exposure to pressure to be able to determine an appropriate decompression schedule not only for a man who has had one exposure in the last 12 h, but also for one who has had two or even three exposures (the maximum permitted multiple exposures in 12 h by the draft CIRIA Code of Practice 1981).

Lock attendants must also be capable of keeping a particular check when more than one face is being worked simultaneously, as some men may be required to visit first one and then another face. In such cases it is normal for the employer to set up a system in which the worker concerned carries a document on which is noted by the lock-keeper the details of each exposure to pressure in any one period of 12 h. At the end of each exposure a decompression appropriate to the most recent updated information must be given and noted on the document.

Each medical lock should be in the charge of a person trained in its use, who has completed a recognized course of training in the medical aspects of work in compressed air. He should preferably be the national equivalent of the UK State Enrolled or State Registered Nurse, but the minimum qualification recognized is a current certificate of proficiency in first aid. He should be medically fit and willing to go into compressed air. He will be under the supervision of the medical supervisor on the site (i.e. a fully registered medical practitioner supervising the medical aspect of work in compressed air on behalf of the contractor). He should be conversant with the therapeutic recompression procedures normally in use on that site. Only after consultation with the medical adviser should he adopt any variation of the agreed routine therapeutic procedures.

The medical lock attendant will ensure that the lock is adequately ventilated at regular intervals with fresh air (without disturbing the lock pressure) to prevent the build-up of CO and CO_2 levels during a therapeutic recompression. He should maintain a log book showing all the circumstances relating to each treatment, such as the patient's previous experience in compressed air; the time and pressure of the exposure which has immediately preceded the present incident; details of the signs and symptoms, including a record of the details of the therapeutic compression procedure used and whether or not it was successful. The log book should also record the patient's response to treatment, the time he leaves the medical lock and his state at that time. Only by keeping detailed records can cases be studied in retrospect and fair assessment be possible if medico-legal disagreements follow.

MEDICAL FACTORS

Selection

From the earliest days it has been stated that there are certain predisposing factors, such as age, body weight and fatness, which will make some men more susceptible to decompression sickness than others (Hill 1912). Since then a good deal of evidence has been published about these contentions.

Today it is suggested that compressed air workers should not be over 40 years of age (CIRIA Code of Practice 1975), as it has been shown that the decompression sickness rate increases sharply beyond this age (Decompression Sickness Panel 1982), possibly because the cardiovascular system is no longer at its most efficient.

Weight itself does not seem to be a reliable indicator of the sensitivity of caisson workers to decompression sickness (Paton & Walder 1954), but of course this does not provide a reliable indication of fatness (Fletcher 1962), and there is no doubt that fat men, as determined by their skin-fold measurement, are more susceptible to decompression sickness than are thin ones (Decompression Sickness Panel 1971). Unfortunately, no exact or generally agreed criteria yet exist by which men can be eliminated on grounds of fatness, but men who are obviously obese on clinical examination should be excluded from compressed air work.

As in diving, it is most important to exclude those men with chronic catarrh of the upper respiratory air passages, sinus infections, chronic ear infections and any condition which prevents the man easily clearing his ears. It was in connection with unexpected symptoms following a short exposure (45 min) to moderate air pressure (25 psig, 1.75 kg/cm^2) followed by a correct decompression that the importance of air trapping in the lungs was demonstrated by Walder (1963). This may well result from oedema or mucus plugs in small bronchi or bronchioles, and could well occur during the recovery phase of a heavy cold. A clear chest should be an esssential requirement when men are examined for their fitness to go into compressed air.

It is also advantageous to exclude persons suffering from diseases, such as hypertension, epilepsy and diabetes, which could result in sudden unconsciousness and lead to confusion in the diagnosis of decompression sickness. Conditions which might give rise to a surgical emergency, such as a peptic ulcer which could perforate, or a hernia which might strangulate, may also disqualify a man from working in compressed air at pressures which will require prolonged decompression and may therefore delay admission to hospital in an emergency. A good review of the physical examination standards for caisson and compressed air tunnel workers is given by Kindwall (1975). In Great Britain it is now suggested that potential compressed air workers should undergo an examination similar to that used for professional deep-sea divers (CIRIA Code of Practice 1982).

Since careful control of the compressed air environment is essential and involves the accurate manipulation of mechanical devices, men prone to drunkenness during working hours must be excluded. There may be other chronic implications of taking an excess of alcohol, as it has been suggested that this in itself could be a cause of bone necrosis.

Fatigue and general malaise are vague terms, but as early as 1907 Gallivan pointed out that the lowered vitality of any part means lowered metabolism and circulation and thus slower elimination of gases from the tissues. Thus, no man should be exposed to increased air pressure who feels below par physically, as this would be expected to be associated with an increased risk of compressed air illness. This is one reason for insisting on a proper interval in free air after a man has just completed a decompression therapy before going on to his next shift.

Bone necrosis

In recent years a new and important hazard in addition to that of acute decompression sickness has been revealed. This is bone necrosis, which can occur in spite of the use of what on other criteria appears to be a satisfactory decompression procedure. In Great Britain it has been generally assumed that the aim is to achieve a bends rate of less than 2% in compressed air work (Institution of Civil Engineers Report 1936). Paton and Walder (1954) were, however, criticized for this view by Duffner (1955). Recent experience with the Blackpool Tables (1973) makes it clear that although these tables reduce the decompression sickness rate for all exposures above 14 psig (0.98 kg/cm^2) to less than 2% (Fig. 2.6), their use does not eliminate bone necrosis. On the other hand, it has been claimed that use of the Washington State Decompression Tables does avoid disability due to

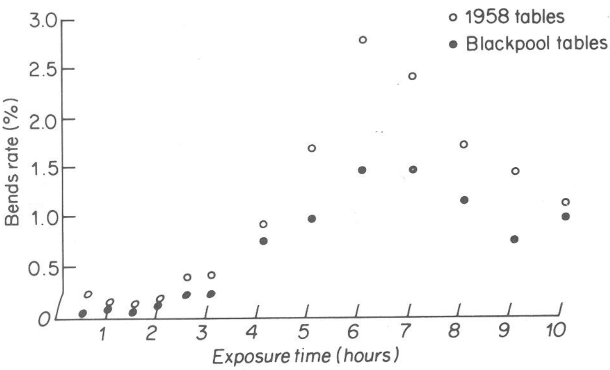

FIG. 2.6. Relationship between decompression sickness rate and exposure time for all pressures at 14 psig (0·98 kg/cm²) and above (1958 UK Tables and Blackpool Tables compared)

bone necrosis (Sealey 1975). However, careful analysis of the way in which they were used suggests that they may have been successful in protecting against bone necrosis because long shifts at the higher pressures were avoided (Walder & McCallum 1973).

It must be pointed out that the links between the decompression procedure used and the prevalence of acute decompression sickness and of bone necrosis are not clear. However, incorrectly applied or inaccurately used decompression tables can be expected to lead to an increase in the incidence of decompression sickness and, hence, to an increased risk of developing bone necrosis, for a greater proportion of men who have had decompression sickness are known eventually to suffer from bone necrosis than those who have not (Trowbridge 1977). Also, it is clear that bone necrosis occurs following long exposures at the higher pressures (Walder & McCallum 1973). For this reason the latest edition of the CIRIA Code of Practice (1982) required that the total of exposure period plus the necessary decompression time does not exceed 10 h in any one 12 h period. Thus, for instance, at 50 psig (3.5 kg/cm²), the maximum pressure allowed by law for compressed air work in Great Britain, the maximum allowable working period to stay within the 10 h limit will be $4\frac{1}{4}$ h, as the decompression time from that exposure is $5\frac{3}{4}$ h. It is important for both the compressed air worker and his employer to monitor regularly by radiography or scintigraphy the bones usually involved by this condition in order to establish as nearly as possible the particular contract or even incident to which the start of a bone necrosis lesion can be attributed.

Advice to compressed air workers

Regulations vary from country to country, and where there are local statutes or regulations these must be followed, but in any case written instructions should always be given to those about to be employed in compressed air concerning the precautions to be taken in connection with such work.

Where the working pressure is not to exceed *2 ATA (14 psig, or 0.98 kg/cm²), the instructions will only be minimal and give information about the compression procedures and a warning not to go into compressed air if suffering from upper respiratory infections.* Whatever the working pressure, every man should be told about the rare possibility of suffering from pulmonary air embolism and to report immediately to the medical centre if any symptoms are noticed during or after decompression. He must at all times obey instructions from the medical adviser and lock-keeper.

When pressures are to reach 2 ATA or above, warning must be given about the danger of developing decompression sickness, the absolute importance of undergoing proper decompression, and how to obtain prompt recompression treatment if suffering from decompression sickness. Every such compressed air worker should carry a label indicating that he is so employed, and that if he should be found ill or in a state of collapse, he should be returned immediately to the work site, where compression therapy will be available. (Going to the accident ward of a hospital will only delay the start of treatment, as most hospitals do not have pressure chambers.) He should be warned about the possibility of developing bone damage in the future. Unfortunately, at present it appears that in spite of adherence to recognized decompression tables (for example, the Blackpool Tables), there is still a risk of suffering from bone damage.

It must not be forgotten by compressed air workers that both ascending mountains and air travel are associated with a reduction in atmospheric pressure and should be avoided during the 24 h following a timed decompression. This does not apply to emergency transport in a helicopter, provided that it flies at an altitude less than 2000 ft. Should a man on a commercial air flight develop symptoms which could be decompression sickness, he should inform the cabin staff and request to breathe oxygen immediately. If SCUBA diving is to be undertaken, it should be regarded as a further compression and the relevant rules and limitations as for a repeated exposure to pressure should be applied.

Decompression

General awareness of the basic physical and physiological problems associated with decompression after an exposure to elevated pressure does not seem to have been evident among those looking after compressed air workers until after the turn of the century, when the Haldane Report (1907), which was primarily concerned with divers, was published. It had, however, previously been recognized that men who were suffering from the effects of decompression could be relieved of their symptoms by putting them back to pressure, and Moir installed a 'medical lock' at the Hudson Tunnel and for this purpose proved its efficacy (Hill 1912).

Many theories had been put forward as to the cause of compressed air illness. They fell roughly into three groups.

(1) Those based on the fact that the temperature drops during decompression. It was assumed that this resulted in exhaustion of the body system to cause neuralgic and rheumatic symptoms.

(2) Those based on the belief that changes in air pressure would affect organs differentially according to their location within the body to give rise to congestion in some. It was even suggested by Bucquoy (1861) that this congestion would result in gas liberation.

(3) Those based on the production of gaseous emboli when decompression is too rapid for the excess dissolved gas to be released in the normal manner via the lungs.

Bubble formation had first been demonstrated by Boyle in 1670, had been experimentally confirmed by Paul Bert (1878) and had been elaborated from time to time over the years until by the turn of the century the bubble theory was well established. It is interesting to note that Oliver, one of my predecessors in Newcastle, claimed in 1909 to have carried out experiments demonstrating bubbles in living frogs after decompression. He was immediately accused by Hill of having pirated his experiments of a similar nature carried out in 1900. This led to a spirited exchange of letters in the *Lancet* of 1909.

A physiological approach to the management of decompression aimed to avoid the unpleasant effects was first described by Haldane in his report which had been 'commanded' by the British Admiralty in connection with diving. It included the construction of a systematic set of two-stage decompression tables based on his critical pressure ratio hypothesis. The British Institution of Civil Engineers eventually co-opted Haldane on to their committee for devising regulations for work in compressed air, and they included in their report of 1936 two-stage decompression tables similar to but not identical with those for divers. The tables did not require any timed decompression following work at pressures of less than 22 psig (1.54 kg/cm^2), because practical experience had shown that this was unnecessary if exceptionally sensitive men were eliminated. They also pointed out that after a certain period of exposure the tissues in all parts of the body become practically saturated with gas. Consequently, exposures longer than 4 h would not give rise, with the same time of decompression, to any significant additional risk. They therefore gave a procedure to be followed for working periods of 6 h or more without specifying an upper limit.

Haldane's 1936 tables proved very effective for a time, but deficiencies appeared as they were used for higher pressures and longer shifts, so that eventually they were arbitrarily adjusted to give the tables which were specified in The Work in Compressed Air—Special Regulations 1958. These tables were devised by Paton and Damant (Paton 1967) and have become known as the 1958 Tables. It is interesting to note that, as well as lengthening the times for decompression, they required timed decompressions to start once the pressure reached 18 psig (1.26 kg/cm^2).

Eventually Hempleman suggested a new approach based on the fact that the uptake of gas by the tissues was probably limited by diffusion rather than perfusion, as suggested by Haldane, and produced the decompression tables which were first used in Blackpool in 1966. These tables differ from the 1958 Tables in three ways: even longer total decompression times; pressure reduction in a series of steps, following naval practice; and timed decompression for exposure to all pressures of 14 psig (0.98 kg/cm^2) and above (Hempleman 1973).

In summary, then, it would appear that over the years there has been a lowering of the threshold at which controlled decompression is required to avoid decompression sickness from 22 psig (1.54 kg/cm^2) in 1936 to 14 psig (0.98 kg/cm^2) in 1966. It is interesting to speculate whether this represents some change in the primary stimulus to decompression sickness such as an increase in the bubble-forming precipitating cause, or whether it is merely an indication of the general softening of man's psychological attitude to pain and the reluctance to suffer from even minor discomforts. Alternatively, it may be due to a more enlightened approach to the wisdom of reporting the symptoms of decompression sickness and requesting treatment. Bends rates are based on the number of occasions on which men are recompressed for the treatment of decompression sickness and not on any retrospective speculation as to whether a man did or did not have the symptoms of decompression sickness.

The use of oxygen to shorten the time required for safe decompression was first mentioned by Bert (1878) and again by Ham and Hill in 1905. It has been discussed by Behnke (1969) and used in Japan. Unfortunately, in Great Britain the view has always been that discipline among compressed air workers is sufficiently poor to increase the risk of explosion and fire. This view is substantiated by the fact that in a catastrophic fire which occurred in Japan when oxygen decompression was used for caisson work, six men in the man-lock were burned to death (Nashimoto 1967).

The situation in the United States has been complex, because different states had different regulations, but it is worth mentioning that in recent years the State of Washington (1963) Decompression Tables, which were first used in Seattle (Sealey 1965), have found general favour and in 1971 became the Federal Standard (Kindwall 1975). Unfortunately, the development of decompression tables for compressed air workers has progressed in a sporadic manner, mainly because of the difficulty in assessing their effectiveness. Suitable contracts are few and far between, and data collection has been unsatisfactory except in those cases when an organized project has been funded independently of the service needs of the contract.

In order to ensure that cases of decompression sickness receive prompt treatment, the CIRIA Code of Practice (1982) requires that all men when the working pressure is between 14 and 40 psig (0.98 and 2.8 kg/cm^2) remain on site for 1 h after the end of decompression and when the working pressure is between 40 and 50 psig (2.8 and 3.5 kg/cm^2) for at least 1½ h. The majority of cases of decompression sickness occur within the first hour or two following decompression (Paton & Walder 1954). To make this waiting period as acceptable as possible, suitable accommodation should be provided, with facilities for changing and washing as well as for storing clothing. It is suggested that one hot shower and one wash-basin be provided for every 4–5 men of the maximum number likely to be involved in any one decompression. Such facilities are usually accompanied by a canteen where the men can be supplied with hot drinks or food as appropriate, and where they can sit in warmth and comfort until it is time to leave the site.

Acclimatization

It has been clearly demonstrated that men who have not experienced work in compressed air before or who have not been exposed to it for 10 days or so are the most likely men to get decompression sickness (Paton & Walder 1954). Interestingly, it has been shown that a change in working pressure appears to require a further period of acclimatization to the new pressure. This has led to the suggestion that there may be families of bubbles, the expansion of which may result in decompression sickness, and that only some of them are potentially dangerous at each pressure range.

Treatment of decompression sickness

As has been mentioned earlier, it was soon recognized that the treatment for decompression sickness and air embolism is recompression. It must always be emphasized to medical lock attendants on compressed air sites that even when the diagnosis is in doubt it is wiser to submit the patient to a 'test of pressure' than to conclude that the condition is unrelated to the previous hyperbaric exposure. Typically, dramatic relief will result from recompression and prove the need for full treatment.

Recompression therapy involves deciding on not only the pressure to which the patient is to be subjected, but also the form of the subsequent decompression and whether or not oxygen will be breathed during some of this time.

Therapeutic recompression procedures for use by both naval and civilian divers are well established. Unfortunately, in Britain many of these are not suitable for use in medical locks on compressed air sites, because the maximum working pressure of the locks is usually too low (50 psig; 3.5 kg/cm^2)

and discipline is such that it is considered dangerous to use hyperbaric oxygen. It must be remembered that compressed air workers, at least in Great Britain, are drawn from the ranks of heavy manual labourers and do not generally have the same degree of training, technical knowledge, skill and insight as professional divers.

In the United States the working pressure of medical locks required by the State of Washington Safety Standards for Compressed Air Work (1963) is 75 psig (5.25 kg/cm^2), and there appears to be no bar to the use of oxygen. In these circumstances, therefore, for Type I decompression sickness ('pain only'), US Navy Diving Table 5 is used; or when symptoms are not relieved within 10 min at 3 ATA 60 ft (18 m), Table 6 could be used. For Type II decompression sickness and air embolism, US Navy Diving Table 6A may be applied.

In Great Britain, where oxygen therapies are not generally advised for use in medical locks on compressed air sites, the CIRIA Code of Practice (1982) recommends the methods which were largely developed by Griffiths (1960) and which Lanphier (1966) has called 'low pressure recompression using air'. There is now considerable experience with these empirical procedures, which have been extensively used on the construction of the Blackwall, Tyne and both Dartford tunnels with good effect. (See also Chapter 19.)

RECORDS

Routine

Good record keeping is invaluable in the assessment of the safety effectiveness of the working procedures in use and also in pinpointing in retrospect where errors may have occurred or, indeed, where the recommended procedures were not adequate for the situation. A lock attendant's register should always be kept in which the man-lock attendant records the following information:

(1) The name, initials and works number of each person who enters the working chamber.

(2) The time of entry into the man-lock, the time of re-entry into the man-lock for decompression and the difference between these two, which is the working period.

(3) If the person has had one or two other exposures to compressed air in the previous 12 h, then this time or times must be added, to give a total exposure period.

(4) The maximum working pressure (that is, the highest pressure to which a person has been exposed in the course of his period in the working chamber or his total exposure period, if applicable). This will be used in conjunction with the exposure period to select the appropriate decompression procedure from the tables.

(5) The time at which the selected decompression procedure was completed and the total decompression time.

(6) Any other particulars as may be prescribed as to conditions in the man-lock or working chamber; if a system of decanting was in use at the time, then the records must be modified accordingly.

Medical

Medical records should include:

(1) The result of each individual's initial and subsequent medical examinations for fitness to work in compressed air, and the results of any bone radiographs obtained.

(2) Decompression sickness case sheets for each individual treated, recording the circumstances of each decompression sickness incident together with the details of the recompression technique used in therapy.

(3) A medical lock treatment book recording all the details of each therapeutic recompression carried out in that lock.

Running estimates of the bends rate for each range of pressure and exposure time should be kept, so that inadequacies in the procedures being used will become obvious and investigations as to their cause identified and remedied. Also, a distinction should be made between those men who work regularly for a full shift and those who work irregularly or for shorter, longer or multiple periods in each day. This is because continuous regular daily working in compressed air leads to a reduction in the frequency with which decompression sickness occurs, which has been described as 'acclimatization'. It is also desirable to make some arrangement by which men who have worked at high pressure on a compressed air site are followed during the subsequent years in order to establish whether or not they develop bone necrosis. Only in this way will it be possible properly to evaluate the safety of decompression tables in protecting men from the long-term ill-effects of working at pressure, such as aseptic bone necrosis.

The overall conduct of civil engineering works under compressed air lies with the engineers. It is essential that, as with diving, they seek the advice of some medical colleague knowledgeable and experienced with this type of work so that they can obtain informed medical opinion concerning the measures necessary to ensure the safety and health of the men subjected to the compressed air environment.

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