I COMPRESSED AIR WORK

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Compressed air is used in civil engineering when tunnelling or sinking bridge piers considerably below the local water table. This permits mining and excavation to proceed unhampered by the ingress of water. Almost all compressed air work is carried out in soft ground, whereas when tunnelling in rock, water ingress usually is managed by pumps. Only rarely is compressed air used in rock tunnelling, when there are multiple fractures or the rock is of poor quality and flooding is severe. The Channel Tunnel from Sangat to Folkestone was driven in its entirety without compressed air, despite some fractures in the chalk rock and water problems, particularly on the French side.

Compressed air forces the water from the soil being mined, which permits normal mining operations in ground that would otherwise be of semi-liquid consistency. This is a requirement when tunnelling under major buildings when no subsidence or settlement of the surface ground can be permitted.

In 1788, the first caisson was built by John Smeaton (builder of the third Eddystone lighthouse) when he designed a diving bell for use in repairing the foundations of Henham Bridge in England. This bell, or caisson, was not intended to be wholly submerged but was the first to use a force pump to provide a continuous supply of fresh air to the occupants. When this bell showed its usefulness, Smeaton built an improved modification, a square iron bell used in the construction of the foundation for the Ramsgate harbour breakwater in 1791. In that case, the pump was placed in a boat on the surface and the bell was supplied by a hose (Davis 1962). Smeaton's successful force pump not only ushered in the era of the compressed air caisson, but also presaged the era of the surface supplied diver.

Caissons for the building of bridge piers were used extensively in France and elsewhere in the 1850s and 1860s, as well as for the mining of coal. The first major caisson project in the USA was the Eads Bridge across the Mississippi River at St Louis. The bridge pier reached a depth of 33.7 m (112 ft) below the usual level of the river. Decompression illness was not yet understood and of the 352 workmen employed on the project, 30 were seriously injured and 13 died (McCullough 1972).

Very large caissons were employed in the construction of the Brooklyn Bridge, one of them being sunk to a maximum depth of 29.8 m (79 ft). Although 110 cases of serious decompression illness were noted by the attending physician, recompression was not used for treatment. It was on the Brooklyn Bridge project that the word 'bends' was coined for decompression illness (DCI). A stilted way of walking effected by fashionable ladies of the era was termed 'the Grecian Bend'. When the 'sandhogs' or caisson workers showed signs of decompression illness, their painful gait suggested the Grecian Bend. The term was shortened to 'doing the bend' and finally 'bends' or 'bent' became legitimized by use (McCallum 1967b). 'Sandhog' is an American term; in England, caisson and tunnel workers are termed 'navvies'.

Compressed air other than for caissons, was first used by the French mining engineer Triger to force water from a coal mine at Chalons, France in 1841. It was Triger who was first to report a case of decompression illness in man (Triger 1845). The first patient for the use of compressed air in subaqueous tunnels, sometimes called plenum process, was taken out in England by Cochrane in 1830. However, it was not until 1879 that compressed air was first used on a small tunnel at Antwerp, Belgium (Richardson & Mayo 1975). Compressed air was used in the USA for the first time in 1879 by Haskin, in an attempt to drive railroad tunnels under the Hudson River. He started two brick-lined tubes, each 21 ft high and 20 ft wide (6.4 and 6.1 m), outside dimensions, but this work was suspended in 1883 (Richardson & Mayo 1975).

THE PHYSICAL PLANT

Caissons

Caissons are generally used for sinking bridge piers or structural building foundations and provide a means of removing silt and clay underwater so that bedrock may be reached on which is placed the bridge foundation. In the construction of pier No. 3 of the Auckland Harbor Bridge in 1958, pressures reached 49 pounds per square inch gauge (433 kPa, absolute) or a seawater depth of approximately 103 ft (31 m) (Rose 1962). The edges of the caisson are bevelled so as to cut into the soft bottom as weight is applied from above. Today, caissons are usually made of steel and concrete, constructed in dry docks and then towed to the construction site supported by their own buoyancy. When the caisson has been located at its approximate final position, construction on top is continued, adding weight to the bridge pier until the caisson touches bottom with the rising and falling tide. It is positioned accurately using surveyor's transits and then buoyancy chambers within the caisson are flooded. The working chamber at the bottom of the caisson is filled with compressed air to force out the water and the weight of the caisson forces it into the mud as the workers commence digging and send the excavated material to the surface. Two shafts extend from the surface into the caisson, one for removal of muck and the other for use by the workmen. A muck lock is placed atop the muck shaft to allow for removal of muck, and a small decompression chamber or blister lock is placed at the top of the man shaft.

Decanting

The blister locks on top of the caisson are usually quite small. Because of the physical constraints at the work site, large decompression chambers cannot easily be attached to the man shafts from the caisson. When decompression times exceed 30 min, workmen rapidly decompress in the blister locks, and then with a large excess nitrogen load, quickly run to a large chamber located nearby where they first recompress and then slowly bleed off the pressure to complete their decompression. This procedure is known as decanting. The surface interval in free air should not exceed 5 min. The 5-min free air interval corresponds to the 5-min surface interval permitted by the US Navy during the surface decompression of divers. However, this process is dangerous, as getting a large gang of workers from one lock to another within the 5-min period is sometimes difficult. During work on the Auckland Harbor Bridge, despite tight regulation, surface intervals of up to 8 min occurred (Rose 1962). Additionally, if only one of the workers has difficulty equalizing an ear, the remainder of the shift is endangered due to slow recompression. Furthermore, there seems to be a higher incidence of decompression illness among compressed air workers using decanting, but this may vary from contract to contract, depending on whether or not the 5-min rule is tightly enforced. Decanting is equally controversial in the diving field—it is not permitted in the USA.

Automated Caisson Systems

The Japanese have now devised a fully automated system in which a hydraulically powered scoop can reach all corners of the caisson. The scoop delivers the muck to a hopper, which removes it from the caisson. the scoop is directed by an operator using a closed-circuit TV camera. Thus, no men need be exposed to the compressed air environment in the caisson itself. Only when the scoop needs maintenance or when boulders impede excavation, are men required to enter the caisson. Not only does this innovation vastly speed up the work, it is also safe to much greater depths than could be achieved if shift work were necessary in the working chamber. Typically, caisson work cannot be carried out at pressure greater than 50 pounds/square inch, gauge (psig; 445 kPa, absolute; 3.4 kg/cm^2, gauge). Only compressed air is used to pressurize tunnels and caissons, as the use of exotic helium mixtures to prevent nitrogen narcosis would be prohibitively expensive. Work at pressures greater the 445 kPa can be carried out, if the excavating machine is fully automated and the workmen are not exposed to the working pressure except for maintenance.

The automated caisson has already been used in Japan to pressures of 600 kPa (73.4 psig) and work is planned to 800 kPa (103 psig). Workers entering the caisson for maintenance breathe a tri-mix gas of N_2-He-O_2. Decompression, after 1-hour shifts, is accomplished using decompression tables developed by Nashimoto and Sterk (Nashimoto, pers. comm. 1991).

Compressed Air Tunnelling

For economic reasons, contractors try to avoid using compressed air when digging tunnels whenever possible. In soft sand or mud, wells are often drilled ahead of, and in the immediate vicinity of, the heading to lower the water table locally. In this way, water in the tunnel becomes manageable with pumps or with very low pressures of air. However, when the sand or muck becomes porous or the tunnel runs under a river or lake, there is often no practical way of keeping the water out except for considerable air pressure in the tunnel. Recently developed pressure-balanced shields have often allowed tunnelling without the use of compressed air, with soil and water pressure being maintained ahead of the shield. Tunnel driving at extreme depths has been carried out using this method.

In the USA, Federal law requires that in tunnels of 4.25 m (14 ft) or greater finished bore, there must be two entirely separate locks parallel to each other leaving the operative heading. The decompression lock is for the exclusive use of the workmen and the muck lock is for the removal of excavated material (Fig. 1.1). In smaller tunnels, there is generally a single lock called a 'combination lock', in which workmen decompress and, between shifts, muck is removed (Fig. 1.2). If digging is proceeding rapidly at high pressures in small tunnels, there is often difficulty in 'mucking out' as the combination lock is occupied for long periods by the men coming off shift. On large contracts where there is a decompression lock reserved for workmen, it is frequently provided with two compartments in sequence, to allow for visiting inspectors, engineers, electricians, etc., to lock in and out past a shift undergoing decompression.

All compressed air tunnels are excavated using a shield which is driven forward by hydraulic jacks around its circumference. The direction of the tunnel ('line and grade') is determined by differential jacking of the shield perimeter. Openings in the shield allow removal of the muck carts, usually with the aid of automated machinery and conveyor belts. Some shields are equipped with cutting heads rotating the full circumference of the tunnel as the shield moves forward. The tunnel is lined with either steel or concrete liner plates for its entire circumference or with rings made of circular L-beams that support wooden lagging. On smaller jobs, the rings are placed at 4- to 6-ft intervals and the spaces between them are lined with heavy hardwood timbers (Fig 1.3).

FIG. 1.1. View of pressure bulkhead, Baltimore Subway. The lower square door is for use of the muck train, which can be decompressed in the lock seen beyond. Above it is a rectangular door to the separate man lock. Pipes to the left carry water for the fire main and ventilation to the face of the tunnel. The large flexible ventilation tubing is in use prior to starting pressurization of the tunnel. (Courtesy of Kiewit/Shea Contractors)

A rule of thumb is that there must be at least 2 ft of earth above the tunnel for every pound of pressure used. An unbalanced pressure always exists on the face of the tunnel, because of the difference of hydrostatic head at the top and bottom of the heading. In large tunnels, the difference is quite

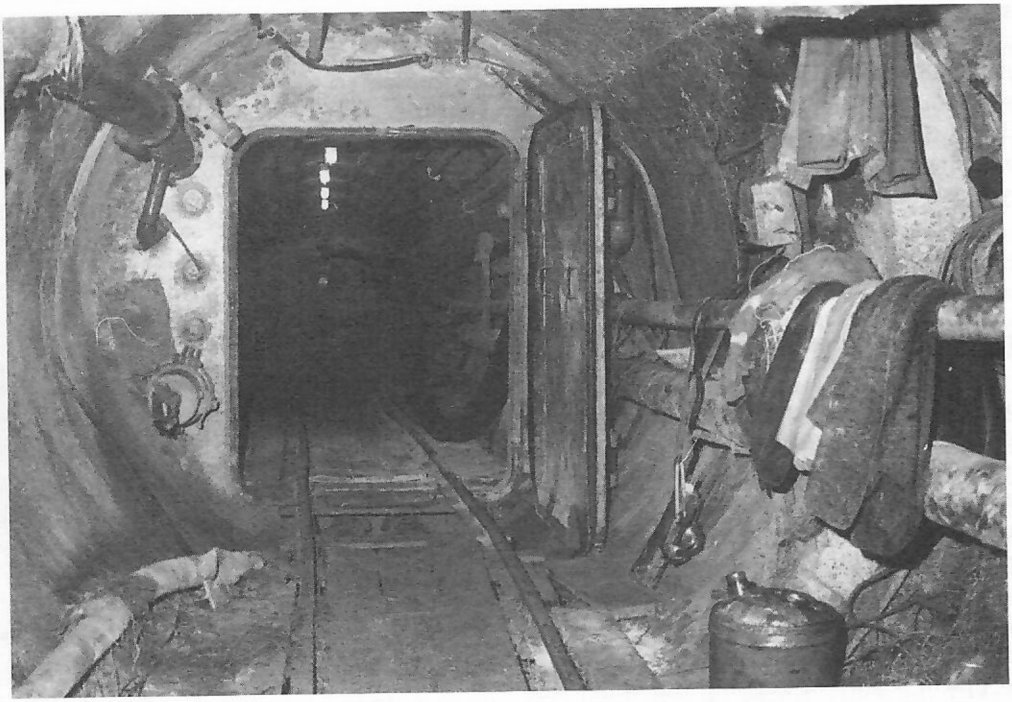

FIG. 1.2. View from the pressurized heading into the combination lock which is used for both the muck trains and for decompression of the workmen. Combination locks are permitted in smaller tunnels such as this 8 ft (2.4 m) finished bore tunnel. A removable track section allows closure of the door. (Courtesy of Wisconsin Department of Health)

considerable and sometimes causes trouble. For example, in a tunnel of 20 ft (6.1 m) diameter, with a hydrostatic head of 50 ft (15.2 m) on the crown, the pressure head at the axis of the tunnel will be 60 ft (18.3 m) corresponding to a pressure of 26 psig (277 kPa). This means that there will be an excess pressure at the crown of the tunnel of about 5 psi (30 kPa), and if the ground is at all porous, there will be continual loss of air at this point. At the same time, the pressure at the invert or bottom of the tunnel is 5 psi (30 kPa) too low and water will flow into the tunnel under a head of about 10 ft (30 kPa). If there is only minimal cover, the pressure at the crown head could be held to only about 20 psig (236 kPa), which would mean that water would flow into the bottom of the tunnel under a head of about 20 ft (6.1 m) of water. On some jobs, depending on the ground, the tunnel pressure may be varied when men are mining the upper or lower half of the tunnel.

Although one-half pound of pressure for each foot of water head (10 kPa/m) is the theoretical requirement, soil resistance to water flow generally reduces the air pressure required by 10–30% depending on the depth of the tunnel and the characteristics of the ground (Richardson & Mayo 1975). When water collects in the bottom of the tunnel, it may easily be removed by placing 'mop lines' on the tunnel floor. The mop lines are connected to a pipe which leads to the surface allowing the pressure in the tunnel to drive the water out. Mop lines can also be used for additional ventilation at the face when CO_2 levels rise or when noxious fumes accumulate from blasting. Methane is rarely found in compressed air tunnels, as the pressure generally keeps it out. Only when compressed air is removed from a tunnel does methane become a serious threat if it is present in the ground.

SAFETY REQUIREMENTS IN CAISSON AND TUNNEL WORK

Fire

Fires rarely occur in caissons because of their all-steel construction, with no flammable material usually being present. However, hydraulic fluid and electrical insulation can present a real fire hazard. On one tunnel project where the author provided medical supervision, a serious fire occurred that severely injured two workers who had inhaled smoke, the electrical insulation being the only available fuel. In tunnels, pools of hydraulic fluid often accumulate after maintenance has been carried out on hydraulic jacks and this must be removed. The most serious fire danger occurs in tunnels lined with wooden lagging, where straw is used to caulk the seams at the invert. Some US states prohibit the use of wooden lagging because of the fire danger. A wet fire main should extend all the way to the heading with sufficient pressure to overcome the air pressure within the tunnel. Maintaining a water pressure sufficient for fire fighting is not usually complicated by the pressure within the tunnel, as the additional pressure head gained by dropping the pipe to the level of the tunnel compensates for the increase in air pressure. Outlets should be provided every 200 ft (60 m) with 100 ft (30 m) of rot-proof hose attached to the fire main at each fire point. A fire main and hoses must also be provided in the decompression lock. Chemical and CO_2 fire extinguishers are prohibited because of the danger of contamination in confined spaces. Sand is not effective on fires under pressure. Water is very efficient and is the only acceptable fire-fighting medium.

On some compressed air jobs, the contractor has provided the workers with Mine Safety Appliance 'self-rescue units', which are hermetically sealed and worn on the belt. In the event of fire and smoke, the units can be broken open and the men breathe through a Hopcalite catalyst which removes carbon monoxide and other contaminants. The capacity of these units is limited, the catchphrase being 'one man, one hour, one way, one percent (CO)'. For instance, 2% CO would reduce functioning time to 30 min, and so on. The compressed air environment makes it difficult to open the units, as the two halves are forced together. A sharp blow on a muck train rail will break the seal and separate the two halves.

FIG. 1.3. Workmen at the face of an 8 ft (2.4 m) finished bore sewer tunnel being driven under 43 psig (394 kPa) pressure. The tunnel lining is made up of 4 ft sections of maple heart timbers supported by steel ribs. The straw is used for caulking the invert. Hydraulic fluid, straw and wooden planking present serious fire hazards. (Courtesy of Wisconsin Department of Health)

Draeger makes a self-rescue unit that has a plastic tear plug which opens the unit, relieving the pressure imbalance.

Air Supply for Caissons and Compressed Air Tunnels

The supply of air must be sufficient to carry off pollutants in the air and to accommodate the air lost during the periodic decompression of the muck lock. Because caissons are tightly closed structures, open only at the bottom, air supply requirements are modest compared to tunnels, and can be accurately predicted, as long as sufficient allowance is made for air loss due to opening and closing the muck lock, and decompressing the workmen. A ventilation rate of 30 cu.ft ($0.85\,m^3$) per man per minute should be sufficient to carry off contaminants and keep the working chamber comfortable.

The contaminants that must be closely monitored are CO_2, CO, oxides of nitrogen, oil vapours and methane. Today, large rotary compressors are typically used to supply the necessary volumes. It goes without saying that the intakes for the air must be located away from sources of CO and oxides of nitrogen such as auto and truck exhausts. *This also applies to the intakes of the air compressors for high-pressure tools which exhaust into the tunnel.* The author medically supervised one contract where this was neglected, nearly causing the death of a workman from pulmonary oedema (secondary to oxides of nitrogen) and subsequent decompression illness.

In tunnels, the supply of air that is required is considerably greater than in caissons, and may vary widely, depending on the porosity of the ground, the type of tunnel lining and how much of the concrete lining has been completed at any given time. Large air receivers or volume tanks are generally interposed between the compressors and the tunnel. These are at a higher pressure than the tunnel and serve not only as a small air reserve, but allow for cooling of the air after compression and smooth out any pulsations if piston compressors are used. A pressure-reducing valve, pre-set by the tunnel foreman, bleeds air from the tanks to the tunnel at the desired pressure.

An additional factor is the amount of CO_2 present in the tunnel. Certain kinds of muck ferment to produce CO_2 and occasionally iron-containing soils catalyse a reaction which produces CO_2. The more CO_2 that is produced, the greater the ventilation requirement. Carbon dioxide generated in the soil by compressed air tunnelling in populated areas has produced problems on occasion, by seeping into nearby basements, layering near the floor and putting out pilot lights in furnaces and water heaters.

Richardson & Mayo (1975) provide a useful rule of thumb which is calculated in imperial units by multiplying the square footage of the working face by 20 and adding 200 cu.ft per man. This gives the number of cu. ft of free air required per min. This represents only an average, however, and actual requirements may considerably exceed this, especially in porous ground.

As an absolute safety requirement, there must be two separate sources of compressed air available. Emergency diesel-generated lighting must be provided as well as emergency power for man hoists. There should be two independent supply pipes to the tunnel of sufficient size to minimize pressure drop and there must be wholly independent power supplies. In the event of electric power failure, the secondary compressor plant is immediately activated. The back-up system is typically diesel-powered. Back-up air is an absolute requirement, because loss of air pressure may lead to flooding and loss of the tunnel, and a whole shift may experience decompression illness. In the UK, the Construction Industry Research and Information Association (CIRIA) Code of Practice requires the standby air source to be at least 50% of the primary source, whereas in the USA the Occupational Safety and Health Administration (OSHA) states it must be of equal capacity.

Gauges showing the pressure in the heading and the decompression locks should be installed in the compressor house and at the lock tender's station outside the decompression locks. Care must be taken to ensure the gauge lines are dry and not 'water bound', which would give a spuriously low reading on the surface in the compressor house and cause the permanent recording graphs to read low. They must also be tested periodically for leaks as well as the presence of water. Recording charts are a necessity for documenting pressure exposures to the workmen. Circular charts with recording pens having 24-h rotation are satisfactory. Charts must be kept for the heading pressures as well as the man lock.

Unless one is using two locks in series for decompression, the door to the heading must be kept closed so that in the event the entire working crew is incapacitated, the decompression lock can be decompressed and entered by a rescue team. A handy method of ensuring this is to rig a door spring or bungee cord to hold the inner door bumped shut. Using this arrangement, the door from the lock to the heading is not dogged shut, which allows quick access to the lock from the tunnel in an emergency, yet it is closed and will seal if the lock is decompressed.

An air supply pipe from the compressor plant should be continued all the way to the heading or working face. Most of the air should be delivered there to maximize air quality for the workers. Additionally, there should be smaller vent holes in the supply pipe at 200 ft (60 m) intervals for the length of the tunnel to eliminate pockets of 'dead air'. Throughput of the compressed air is usually assured by the porosity of the ground, but in very tight tunnels, mop lines, opened at the face, may be necessary to ensure adequate ventilation. All air supply openings in the chamber should be equipped with flapper valves so that the tunnel will not be depressurized should the operative air supply pipe be accidentally broken at the surface.

During decompression, it is vital that the decompression lock is ventilated to prevent the build-up of CO_2. It is critical that effective silencers or mufflers are provided to the supply of air so that near continuous venting of fresh air into the lock is not prohibitively noisy.

MONITORING THE ATMOSPHERE

It is recommended that the following minimal standards for air composition and purity be maintained in the caisson or tunnel:

- *Oxygen*: 20–22%.
- *Carbon monoxide*: less than 50 ppm by volume.
- *Carbon dioxide*: less than 0.25% by volume.
- *Oil or particulate matter*: 5 mg/m^3 for environments between 1 and 2 bar gauge pressure (200–300 kPa).
- *Methane*: less than 10% of the lower explosive limit.

Carbon dioxide dramatically increases the incidence of decompression illness and although 0.25% is given as a maximum, it is highly desirable to maintain CO_2 below this level if at all feasible.

Air sampling is usually carried out once every 8 h by the shift foreman or the project safety engineer. If standard colour tube indicators supplied by MSA, Bachrach, Draeger or Kitigawa are used in the tunnel, they are accurate as read in the compressed air environment. These colour tubes indicate the level of contamination for a given volume of gas. This corresponds to the amount delivered to the lungs with each respiration. Therefore, no compensatory calculation is required. If, however, a gas sample is taken in an evacuated test cylinder in the compressed air environment, and subsequently analysed in the laboratory, the reading will be spuriously low. That is because decompression dilutes the number of contaminant molecules in proportion to the pressure. Therefore, the laboratory result must be multiplied by the number of absolute atmospheres present in the working atmosphere. The same caveat applies to continuous monitoring equipment on the surface, drawing samples from the tunnel. For example, if a methane monitor at the surface is continually sampling air from a tunnel being driven at a pressure of 14.7 psig (202 kPa), the monitor should be set to read 200 ppm when calibrated with 100 ppm calibration gas on the surface. At present, there are no commercially available continuous reading electronic methane monitors which function when the monitor itself is taken into the compressed air environment.

SUPERVISION OF WORKMEN

The project engineer and shift foremen should be knowledgeable in the use of compressed air and familiar with the basic physiological problems attendant to its use. They should be thoroughly familiar with the decompression tables in use, the symptoms and signs of decompression illness and barotrauma, and where to refer workers should decompression illness occur. They should be able to instruct workers in ear clearing and how to avoid injury when working in the compressed air environment. They should be responsible for maintaining proper logs, records of decompression, be familiar with the hazards of fire in the compressed air environment and the provisions of all safety codes being enforced on the project. A single individual should have overall responsibility for the compressed air aspects of the project, including ultimate enforcement of the rules and preservation of records. Typically, this would be the project engineer or safety engineer. Some jurisdictions have required licensing of this individual as an 'air master'. In the event that compressed air regulations are not followed, the air master is subject to loss of his licence, thus causing the work to be suspended until another air master could be installed. This has been shown to put 'teeth' into the enforcement of regulations. This individual is also responsible for assuring that gauges are accurate, gauge lines have been inspected for leaks or flooding, and that the required physical examinations for the workmen are current.

Instructions to Workmen

A notice to the workmen should be posted prominently in the decompression lock and also in the change house containing special information regarding their work in compressed air. The following is an example of such a notice:

Suggestions for the Guidance of Compressed Air Workers

1. Eat moderately before going on shift.
2. Be temperate, avoid excessive alcoholic beverages the night before or within 8 h of going on shift.
3. Sleep at least 7 h daily.
4. Take extra outer clothing into the tunnel when going on shift and wear it during decompression to avoid chilling during that period.
5. Do not rest or sit in a cramped position during decompression.
6. Change your position frequently during decompression to ensure that circulation is maintained. Moderate exercise is permissible.
7. Decompress according to the posted schedule, for this means safety and freedom from compressed air illness or 'air pains'. It also safeguards against damage to the bones.
8. Do not undertake strenuous exercise immediately after decompression.
9. Do not take a *hot* bath or shower within 6 h of decompressing. A moderately warm bath or shower is permissible.
10. Do not go to sleep in a cramped position after decompressing.
11. Do not allow yourself to become chilled within 6 h of decompression.
12. Report at once to the physician in charge if you suspect you are suffering from 'air pains' or decompression illness. Do not give men suffering from compressed air illness any intoxicating liquor.
13. *If after decompressing you develop 'niggles' or 'air pains' that persist longer than 30 min, call the medical doctor at once!*
14. If you become ill away from the job site, get in touch at once with the physician in charge, Dr ________, telephone ________.
15. Wear your identification bracelet so it will be known what to do with you in an emergency.
16. Stay within a 50 km radius of the recompression facility for at least 1 h after locking out.
17. Do not re-enter the manlock if suffering from air pains or decompression sickness.
18. Do not engage in SCUBA diving at depths greater than 10 m within 12 h of coming off shift.
19. Do not engage in any SCUBA diving within 12 h of going on shift.
20. Do not fly in any aircraft for at least 24 h of coming off shift.
21. See that you are re-examined as required under law.

DECOMPRESSION FOR CAISSON AND TUNNEL WORK

Historically, there were no fixed rules for decompression of workers at the end of a work shift. The exhaust valve was simply opened and the pressure released from the decompression lock. Companies with large exhaust valves experienced more decompression illness than those with smaller exhaust systems. When it became clear that slowing decompression could reduce the incidence of decompression illness, valves were generally not opened fully and a slower continuous ascent was provided. Even though formal decompression tables have been adopted in the USA, continuous decompression is still carried out based on historical precedent. This complicates matters, as it is very difficult to control such decompressions at varying rates by hand and a computer or cam-controlled exhaust mechanism is required. If stage decompression is used, there is no such requirement. The slow bleed-off method is also inefficient and wasteful. for example, if the last stage from 4 psig (127 kPa) to the surface were to take 1 h, at least half of the time is spent at a pressure less than 2 psig (114 kPa), which provides no meaningful bubble suppression. This is not an efficient use of decompression time. In the UK, France, Germany and Brazil, the more efficient stage decompression has been adopted.

Shift Length and Saturation Exposures

Working shift lengths are typically divisible into 24 h as tunnelling usually proceeds round the clock. Shifts of 8, 6 and 4 h are used, the latter at the higher pressures. The French drastically shorten the permissible shift length as pressures rise, so as to increase safety. In the UK, work shift lengths tend to be longer as it is permissible for decompression time to be added to a full 8 h work shift. The 1982 CIRIA regulations stipulate only that there be a 12 h surface interval between exposures and that the total of the combined work and decompression exposures be limited to 10 h per day. It is the author's view that the time between shifts should be at least 16 h, and that 12 h is too short a period for adequate nitrogen clearance. It is clear that if the present theory regarding the half time for the slowest tissues is correct, employees are not completely free of work-absorbed nitrogen when re-entering compressed air after the first shift of the week. This would be true even for a 16 h hiatus.

In the USA, all work—including decompression—must be completed within an 8 h shift, guaranteeing a 16 h surface interval. Behnke (1980) has suggested construction of saturation habitats in tunnels with storage pressures up to 22 psig (250 kPa). This would be the pressure limit because of the cumulative effect of oxygen toxicity from compressed air. At that pressure, the $F\text{I}_{O_2}$ would be equivalent to 53% O_2 at the surface. Much deeper, 8 h excursions to working pressure can be made without a decompression obligation. A major problem with saturation exposures is the space required for the workmen's living quarters and securing the cooperation of the unions for these exposures. Saturation would be feasible only on the largest projects. To date, it has not been utilized.

The Beginning of Enforced Decompression Codes

In the USA, the first formal decompression code was that of the State of New York, adopted in 1922. It embodied the split shift, which meant that the men worked for a period of time in a tunnel during the morning, then decompressed to the surface to eat lunch. After approximately an hour's surface interval, the men re-entered the caisson or tunnel and decompressed at the end of the day from the second shift using the same decompression time as for the first shift. This table was adopted almost universally in the USA and was the only schedule in widespread use until 1963. The 1922 New York decompression code was seriously flawed from a physiological standpoint, in that the decompression times were vastly shorter than naval schedules and the surface interval was pitifully inadequate as a means of eliminating sufficient nitrogen to avoid decompression sickness. Additionally, the decompression from the second exposure of the day did not take into consideration the residual nitrogen from the morning exposure. Furthermore, it exposed the workers to the trauma of two decompressions per day instead of one. This schedule appears to have been worked out by the unions and the contractors and it is obvious that no diving physiologist was consulted. Unfortunately, the split shift is still officially enforced in Japan.

In the UK, decompression tables using continuous decompression were devised in 1936. Even with J. B. S. Haldane sitting on the committee, it is evident that the contractors were able to change the no-decompression limits based on 'practical' considerations. This is to say that they dictated that no decompression stops were required at pressures up to 22 psig (250 kPa) if 'sensitive individuals were eliminated'. They also came to the conclusion that saturation occurred at 4 h and that for any exposure longer than 6 h no additional decompression was required (Walder 1982). We know today that these are fallacies. In 1958, improved tables were devised by Paton and Damant (Paton 1967). When the 1958 tables were put into use on the Clyde tunnels, however, they were found to produce a 19% incidence of aseptic necrosis of the bone (McCallum 1967a). This was an indication that further modifications had to be made.

New Developments

In 1966, Hempleman devised new tables that were first used at Blackpool and came to be known by that name. The Blackpool tables were much longer, adopted stage decompression and required decompression for all exposures greater than 14 psig (202 kPa) (Hempleman 1973). The Blackpool tables represented a quantum leap in improvement in the decompression schedules, but still produced a reported incidence of decompression illness. Unfortunately, they also continued to produce an incidence of aseptic necrosis. Five of 59 workers on the Dungeness SB Power station contract developed bone disease on the Blackpool tables (Trowbridge 1977). K. P. Yau (pers. comm. 1987) reported that 83% of the men working on the Hong Kong subway project reported decompression illness in association with the Blackpool schedules. However, 'official' bends rate, derived from those who actually received treatment, was low (Lam & Yau 1988). Bone necrosis was also reported on the Hong Kong project. The incidence was possibly worsened by engineers and other 'short stay' personnel visiting the tunnel several times a day and 'adding up' their decompression times to be taken all at once, at the end of the day (D. N. Walder, pers. comm. 1987).

In the USA, the only major decompression schedules in widespread use were the 1922 New York tables, which continued to be used until Duffner devised the Washington State tables in 1963. The Washington State tables abolished the split shift, greatly extended the decompression time, but only took three compartments—the 30, 60 and 120 min tissues—into consideration for Haldanian calculation. Continuous decompression at varying rates was retained instead of stage decompression, as Duffner found that the contractors and unions refused to stray from tradition (G. J. Duffner 1983, pers. comm. 1983).

The Washington State tables also have another major flaw. For each 2 psi pressure range (14 kPa increment), a decompression time is provided for shift lengths 'over 8 h'. This would be disastrous if ever used. For example, at 20 psig (236 kPa), if an emergency occurred causing a foreman to work two 8 h shifts totalling 16 h, his decompression requirement using the Washington State code would be *only 113 min*. In saturation diving, such an exposure calls for over 14 h decompression.

The Washington State tables were used in Seattle on a water tunnel project and later on the San Francisco Bay Area Rapid Transit subway project. In Seattle, they were used up to pressures of 34 psig (330 kPa), whereas in San Francisco they were rarely used above 17 psig (216 kPa), except for a 2 week interval under the Embarcadero, where pressures rose to 36.5 psig (348 kPa). Ten years later, Sealey surveyed 83 men who had taken part in the construction of the Seattle tunnel and found that none of these individuals had aseptic necrosis of the humoral or femoral head. Four men were found to have shaft lesions in the proximal tibia, one of these being bilateral (Sealey 1975). Annual X-rays of the men working on the Bay Area Rapid Transit project failed to reveal any evidence of aseptic necrosis, but it must be remembered that there was only one 2 week period when they were exposed to pressures at which this could occur. Dysbaric osteonecrosis is unknown at pressures less than 17 psig (216 kPa) (D. N. Walder, pers. comm. 1971).

Dysbaric Osteonecrosis in American Tunnellers

In Milwaukee, the author began X-ray surveys in 1969 of all the compressed air workers who came in for treatment of decompression illness. At that time, the State of Wisconsin was using a split shift schedule, a modification of the 1922 New York Code. It was found that 35% of the men were suffering from aseptic necrosis of the bone. This finding prompted the formation of a new State Code Committee in the summer of 1970 and on 1 August 1970 the Washington State tables were adopted by emergency order. At that time, there had been no report of aseptic necrosis in conjunction with their use. In 1971, the Washington State tables were adopted as the Federal Code under the newly created Occupational Safety and Health Administration (OSHA) (US Bureau of Labor Standards 1971). No further cases of aseptic necrosis were reported in Milwaukee until 2 years after the completion of a sewer tunnel section in which pressures of up to 43 psig (392 kPa) had been necessary. At that time, a tunnel foreman and an inspector both presented with dysbaric osteonecrosis as a consequence of decompressing on the

OSHA-enforced tables. A subsequent survey of the workers involved in that project evidenced a 33% incidence of dysbaric osteonecrosis using the federally enforced schedules (Kindwall *et al.* 1982). The OSHA table has never previously been used at pressures greater than 36.5 psig (348 kPa).

The True Incidence of Decompression Illness

The reported incidence of decompression illness as manifested by the number of men appearing for treatment is always artificially low. Typically, workers tend to 'tough out' minor symptoms of bends and only report for treatment when the symptoms are unbearable. Too frequent treatment for decompression illness might risk their jobs in the tunnel and cause them a loss of pressure pay. Therefore, the true incidence of decompression symptoms can only be evidenced through the use of an anonymous reporting system. On the tunnel jobs in Milwaukee, the author has used a system whereby the individual workers simply write an X or an O on a slip of paper along with the date and the shift, which is then deposited in a box when going on shift. If a worker has had symptoms since coming off the previous shift, he writes an X; if he has had no symptoms, he writes an O. Using this method, it was discovered that up to 26% of a shift might have decompression illness without anyone reporting for treatment and, on one job, at pressures between 19 and 31 psig (229 and 310 kPa), one or more individuals in the workforce was affected on 42.5% of working days. Nevertheless, the official decompression illness rate for that project was only 1.44%. This was based on the number of patients treated.

The appearance of decompression illness in tunnel workers seems to be capricious and sporadic. The same anonymous reporting system revealed that, conversely, decompression illness was not experienced by any tunneller on over 50% of working days. This was despite the use of tables known to be grossly 'inadequate'. It is mandatory that all compressed air projects adopt an anonymous decompression illness reporting system if any meaningful statistics are to be generated.

In the past, it has been customary to adopt a rather cavalier attitude towards minor musculoskeletal pain, with the feeling that selected workers should be tough enough to put up with this kind of discomfort. However, recent findings suggest that there may be measurable cerebral damage associated with 'pain only' decompression illness (Gorman *et al.* 1987).

Development of the Milwaukee Tables

When it was discovered that the present OSHA decompression tables produced dysbaric osteonecrosis, an application was made for a grant from the National Institute of Occupational Safety and Health (NIOSH) to develop new decompression tables. Funds were received and work on the new tables commenced in 1979. As all of the previous decompression models based on mathematical theories had proved to be inadequate at the deeper depths and especially with longer exposures, an empirical approach based on practical experience was required. For this reason, the author collaborated with Peter Edel who had a computer databank holding the records of 15 years of successful and unsuccessful commercial dives in the Gulf of Mexico and elsewhere. In principle, the computer was used to draw a line between the dives in which decompression illness was not seen, and those which produced it. Haldanian or neo-Haldanian calculations using a proprietary model filled in the gaps. Edel turned out two versions, Autodec 2 and Autodec 3. Autodec 2 was a somewhat shorter table and the total decompression times were similar to those for the OSHA tables, but stage decompression rendered them more efficient. It was hoped that they would be successful when tested, as the Autodec 3 air tables were prohibitively long but based on additional data. Human testing revealed that Autodec 2 decompression produced decompression illness in more than one subject and caused a dysbaric lesion in the proximal tibia of another subject as seen on bone scan. Further testing on Autodec 2 was abandoned.

The Autodec 3 air tables were too long to be commercially useful. For this reason, oxygen breathing was introduced at the shallow stops. The savings in time made the Autodec 3 oxygen variant commercially feasible. By way of comparison, the present OSHA decompression table calls for 4 h of decompression following 4 h of work at 44 psig (400 kPa). The Autodec 3 air decompression table called for 10 h 46 min following a similar exposure. The oxygen variant of Autodec 3, however, calls for only 3 h 21 min decompression.

The new oxygen tables were tested at 2 psi

(14 kPa) increments, from 14 to 46 psig (195 to 413 kPa). There was no reported incident of decompression illness in any of the test subjects. A bone scan and follow-up X-ray 6 months after the last exposure failed to reveal any dysbaric osteonecrosis. Decompressions were made from the longest shift possible at each pressure which could be carried out within an 8-h shift when combined with the decompression time. These are the only shifts which will be used in actual practice. Only two or three test exposures were made at each pressure, making it impossible to predict the incidence of decompression illness. However, catastrophic error was ruled out in the computation of these tables. It should be noted that these caisson tables were the first to have any kind of laboratory testing before being recommended for use in industry. The final tables and a summary of their development were delivered to NIOSH on 1 December 1983 (Kindwall *et al.* 1983). Nevertheless, the 1971 OSHA schedules still remain in force in the USA, as there are *no funds available to pay for the administrative requirements for change at this time.*

The Use of Oxygen Decompression Internationally

Oxygen decompression was first used experimentally for the decompression of tunnel workers in 1959 in Japan (Nashimoto 1967), but this work ceased when a fire killed six men undergoing decompression. Oxygen decompression was put into use on a regular basis in Germany in 1972, when their first oxygen tables for caisson workers were promulgated. They were pleased with the results and reported that 'the rates of decompression sickness decreased remarkably in spite of longer shifts' (A. Altner, pers. comm. 1986).

Recent German experience with new oxygen tables developed by Faesecke (1991) has been excellent. These tables have been used on the Kiel Canal tunnel at pressures up to 480 kPa (56 psig), with an overall decompression illness of 0.5% (19 cases in approximately 4000 man-decompressions). There were no neurological findings and all responded to treatment on US Navy (USN) Table 5 with complete resolution. At 430 kPa (50 psig), a new 3 h work shift produced a rash of eight cases despite 2 h oxygen decompression at 9 m (33 ft). When the work shift was shortened to 150 min, using the same decompression, no further cases were seen (K. Faesecke, pers. comm. 1991).

The French adopted oxygen decompression tables for tunnel workers in 1974, but these remain to be tested on a large project (J. C. Le Pechon, pers. comm. 1987). Brazil used oxygen decompression successfully in 1976 in the construction of the São Paulo subway with a nearly 80% reduction in decompression illness (Ribeiro 1985). Because of the Japanese accident, there has been much resistance on the part of the British and American regulating bodies to adopt oxygen decompression. This is despite the fact that some 14 000 experimental oxygen decompressions were carried out without mishap in 1938 and 1939 in the City of New York during the construction of the Queen's Midtown Tunnel (Jones *et al.* 1940). The oxygen delivery system was of poor design on that project, providing workers with greatly increased breathing resistance. No overboard dump system was used. Despite the fact that there was a considerable build-up of oxygen in the decompression lock, there were no fires and there were no serious cases of decompression illness among these workers who breathed oxygen.

Physiological Advantages of Oxygen Breathing

Oxygen breathing has other advantages which must be considered. End (1939) described a marked reduction in blood sludging in animals suffering decompression illness when the arterial pressure of oxygen (Pa_{O_2}) was raised. Mathieu *et al.* (1984) reported that red blood cell filterability is doubled after 15 hyperbaric oxygen treatments. Pimlott *et al.* (1987) showed the importance of the state of the formed elements of the blood when they reported that there was an 81% decrease in the deformability and filterability of white cells after exposure to air at 151 kPa for 4 h. Very recently, Zamboni (1990) has shown that adherence of white cells to capillary walls is vastly reduced under conditions of hyperbaric oxygenation. Because of these favourable haematological changes, the beneficial effects of oxygen decompression are undoubtedly greater than the simple enlargement of the 'oxygen window'.

It must be realized that oxygen may have possible toxic effects when breathed for long periods on a daily basis, and indeed some commercial divers have experienced this. However, the toxicity of oxygen is understood, and its early signs—should they appear in tunnel workers—are easily reversible. This is not true for bone disease and possible brain damage.

Attitude of Regulatory Authorities

Nevertheless, regulatory bodies in the UK have been adamant in refusing to accept any change in the present tunnelling decompression schedules until it can be assured that 'no new risk is added'. In the USA, the Office of Variance Determination of the OSHA has now admitted that 'oxygen decompression may be feasible' and that they will permit contractors to apply to use this method under 'an interim order'. In 1988, Dr Yodaiken, director of the US office of Occupational Medicine of OSHA, stated in a memorandum to his staff that the present OSHA tables are 'flawed by modern standards' and that 'the OSHA tables have failed any reasonable test of adequate performance over the past 16 years'. He went on to say that 'there is no dispute within the scientific community that the Autodec 3 oxygen tables would be a great improvement'. He further noted that 'oxygen decompression can be very safe as proven by the German, French and Brazilian experience. In summary, oxygen decompression is long overdue in caisson work'.

ACCLIMATIZATION

It has been consistently noted that workers acclimatize or habituate to the compressed air environment and become less prone to decompression illness after 7–10 days of daily exposures. Should a worker take a 2 week vacation, he loses this acclimatization and may suffer decompression illness following his first work shift after his return. In one Milwaukee contract with 28 psig (290 kPa) in the tunnel from the first working day, there was an 8.57% incidence of *treated* decompression illness during the first week of the contract. By the second week, after acclimatization had occurred, the rate of decompression illness fell to 1.44%, which was the average of *treated* cases for the entire contract. An outbreak of decompression illness often occurs when the pressure is raised by 2–3 psi (14–21 kPa). The workers then have to acclimatize to the new pressure. An explanation of acclimatization is not forthcoming, though possible causes include loss of platelets and/or consumption of complement.

POSSIBLE CENTRAL NERVOUS SYSTEM DAMAGE IN COMPRESSED AIR WORKERS

Rozashegyi (1967) reported that 42% of 31 caisson workers who had never suffered from manifest decompression illness of the central nervous system (CNS) had abnormal EEGs. Of 179 individuals who had suffered from decompression illness and who could be examined after 4 years or more, sequelae of lesions caused by decompression could be found in 130, and in about half of all of these cases the sequelae were serious. Rozashegyi went on to point out that EEG records showed 'pathologic' changes in two-thirds of 57 subjects who had suffered from decompression illness of the CNS many years before. A borderline EEG record was found in an additional 10% and a completely normal record was found in only one-quarter of all cases (see also Chapter 21).

In 1988, magnetic resonance imaging (MRI) was used to look for brain damage in compressed air workers in Milwaukee (Fueredi *et al.* 1991). MRI was performed in 30 subjects who had been engaged in tunnel work, of whom 19 had been exposed to various degrees of compressed air, whereas 11 were age-matched controls who belonged to the same labour union but who had never been exposed to hyperbaric air. The MR scanning was undertaken using a 1.5-Tesla Phillips MRI unit, obtaining axial, sagittal and coronal T-1, proton density and T-2 weighted images. Ventricular size was measured objectively. Foci of increased T-2 intensity, also known as 'unidentified bright objects' (UBOs), deep within white matter tracts, were evaluated as to their number and location. Psychometric testing was carried out on both groups to exclude pre-existing brain disease.

The 19 subjects in the compressed air group has a statistically higher number of white matter lesions (more than 152) than the control group (22 lesions) ($P = 0.05$). Altogether, 37% of the compressed air group had more than 20 white matter lesions each (7 of the 19 subjects), whereas only

18% of the control group has 10 or 11 lesions each. The experimental group were five times more likely than the control group of having high-grade lesions and a high statistical correlation was found between the number and severity of lesions in the compressed air group as compared with the control group when linear trend analysis was performed ($P = 0.02$). Ventricular size was normal in all the subjects. The distribution of white matter lesions was 100% in the centrum semiovale and 50% in the optic radiations. Additionally, three subjects in the compressed air group had two internal capsule lesions and one basal ganglia lesion. There were no statistical differences in the psychological testing between the two groups.

MEDICAL TREATMENT LOCKS

In the UK, medical locks for the treatment of decompression sickness must be available in the ratio of 1 to 100 compressed air workers on site, whenever the working pressure is 2 ata (303 kPa) or above, and for 24 h after the last man-lock decompression from such pressures (Walder 1982). In the USA, a recompression chamber must be available whenever pressures exceed 12 psig (182 kPa). As men are seldom stricken with decompression illness at the actual job site, but typically after they go home, a central location for the recompression chamber in the city near the job site is considered acceptable. All compressed air workers should carry a bracelet or a necklace identifying them as a compressed air worker and stating that, should they be found unconscious or incapacitated, they be taken to the recompression facility instead of a hospital. The author's preference is that the recompression lock be located in a hospital. The requirements for the medical lock are similar in most countries, specifying minimum head room and seating and that it must consist of two compartments. Minimally, each chamber should be equipped with proper heating, lighting and a communications system with the exterior. In the USA, the chamber must be capable of reaching a maximum pressure of 75 psig (610 kPa), so that a maximum treatment depth of 6 ata (600 kPa) can thus be utilized. Unfortunately, contractors and chamber manufacturers involved in chamber design often read the law literally and have constructed chambers on which the safety valve lifts at 75 psig (610 kPa). The chamber should be constructed so that its maximum operating pressure is at least 10% or preferably 1 ata (100 kPa) greater than the highest intended treatment pressure. This is to avoid inadvertent unseating of the safety valve which may later not re-seat. For example, from the test of a safety valve on a 75 psig (610 kPa) chamber, the valve did not re-seat until the chamber pressure had dropped to 20 psig (236 kPa). In the USA and most other countries, it is mandatory that the medical lock be equipped with overboard dump masks for oxygen breathing. In the UK, however, this is not a requirement.

Fire safety in the treatment chamber is an absolute requirement. Cigarettes, matches and lighters are excluded. Inflammable material, unless required for the treatment of the patient, should not be allowed in the chamber. The mattress should be covered with a fire retardant flash cover, and the blankets, sheets and pillows should be treated with a fire retardant. A fire extinguishing system in the form of a water hose is a minimal requirement. Chemical extinguishers are unacceptable because they contaminate the atmosphere.

TREATMENT OF DECOMPRESSION ILLNESS

The essential treatment for any decompression illness is recompression. Moir, a British engineer, was the first to apply air recompression—or what had been termed the 'heroic mode', which is really a homeopathic method—to relieve decompression illness when he took over as job superintendent to finish the tunnels under the Hudson River in 1889. The mortality rate from decompression illness had been 25% of the men employed. He installed a recompression chamber at the job site and only 2 of 120 men employed in the tunnel over the next 15 months died, which gave an effective mortality rate of only 1.66% (Moir 1896).

Today, most countries in the world, except those under British jurisdiction, provide low-pressure oxygen recompression for decompression illness in tunnel workers. The tables used are versions of the USN Tables 5 and 6 (US Navy 1967). In the UK, the CIRIA Code of Practice recommends low air pressure recompression as developed by Griffiths (1960). These methods appear to be little different from those employed by Moir in 1889, except that the decompression times have been somewhat lengthened. It is the author's view that air recompression treatment is unacceptable in light of our present knowledge. Air recompression 'treatment' ceases the minute the patient reaches maximum pressure and the time spent thereafter is simply devoted to avoiding a recurrence of symptoms. Meanwhile, more iatrogenic nitrogen continues to be added to the patient and it is not possible to send such a person back to work on the next shift. With oxygen decompression, it is possible to avoid prolonged absence as the patient will have less nitrogen in his body following oxygen treatment than his co-workers who have not been treated for decompression illness.

PHYSICAL STANDARDS FOR WORK IN COMPRESSED AIR

Physical examinations of prospective compressed air workers are a universal requirement. The examining physician should choose individuals who are capable of hard, sustained physical work. In addition, changes in atmospheric pressure experienced by tunnel workers and caisson workers impose additional physical requirements, which are outlined in the paragraphs that follow.

Height and Weight

There are no specific height or weight limitations. If a worker is greater than 20% overweight according to the standard height/weight charts, he may be more susceptible to decompression illness. It should be noted, however, that skinfold thickness of the triceps and subscapula alone are correlated with decompression illness. There appears to be no correlation between the size of an abdominal panniculus and decompression illness.

Ears and Sinuses

Prospective workers should be free of lesions which preclude equalizing the middle ear through the eustachian tube. Perforated eardrums are not disqualifying in the tunnel worker as he is not exposed to immersion in water. Some degree of deafness is perfectly permissible and many of these men will be found to have considerable noise-induced hearing loss from the roar of high pressure air and pneumatic tools. This loss is usually most noticeable at higher frequencies. Applicants should be able to understand human speech. The sinuses should also be well ventilated and an individual suffering from suppurative sinusitis or severe allergies should be excluded. Baseline audiograms should be recorded in the event that the worker later files a claim for occupational deafness.

Teeth

An improperly filled tooth can occasionally cause intense pain to a worker undergoing compression if gas is trapped underneath a filling. Workers with severely carious teeth which are unfilled usually do not have problems.

Vision

Monocular vision is acceptable and individuals should be able to see well in dim light. Colour vision is not a requirement. Contact lenses may be worn in compressed air but should be of the soft or gas-permeable variety. With hard contact lenses, there tends to be a build-up of nitrogen behind the lens during decompression causing corneal irritation.

Lungs

A pre-employment chest X-ray is mandatory. Those individuals suffering from asthma should be excluded. The main concern with the lungs is that air-trapping lesions be excluded, as these can produce air embolism during decompression. In actual practice, however, air embolism is extremely rare in compressed air workers, as the decompressions they use are extremely slow as compared to those experienced by divers. Pulmonary function testing is not a requirement, as this usually fails to detect meaningful air trapping in this group of workers.

Central Nervous System

Patients with a history of migraine headaches may experience worsening of the migraine during decompression. This is an individual idiosyncrasy and, if the migraines are well controlled, the patient may be given a trial of work. Those subject to seizures should not work in tunnels, since should they suffer a seizure unexpectedly, there is the hazard of being injured by falls or being caught in heavy machinery. A good neurological examination should be carried out on all applicants and the results recorded. Should the person return later suffering from decompression illness, baseline neurological findings may then be compared with the findings following the diagnosis of decompression illness. The examination should include the cranial nerves, deep tendon reflexes, abdominal reflexes, cutaneous sensation, the Babinski reflex and the Romberg test.

Cardiovascular System

Hypertension is seen frequently in compressed air workers and in the usual case is not considered disqualifying unless severe. The usual criteria for cardiovascular fitness to do hard work applies. At the present time, there is no consensus that patients be examined invasively for possible atrial septal defect.

Musculoskeletal System

First it should be ascertained that the patient can demonstrate pain-free movement of his extremities in all planes. Dysbaric osteonecrosis is the biggest concern here. Pre-employment films should include a total of 12 films, taken of both shoulders, both hips and both knees, including the femur and proximal tibia. Other films may be taken if clinically indicated, but necrosis is not seen in the elbows, hands and feet and only three cases are reported in the world literature which involve the knee. If detailed views are indicated for suspicious areas, CT scanning and conceivably Technitium-99 scanning can be used.

Gastrointestinal System

Hernias may disqualify a person from hard physical work, but if a gas-filled loop of bowel should exit the hernial opening, decompression could cause necrosis of the bowel. An ulcer history does not disqualify a compressed air worker if it is controlled.

Metabolic and Haematological Disorders

Mild diabetes, if controlled by diet or small amounts of insulin, is acceptable if the tunnel worker is not subject to insulin reactions. For other metabolic diseases, the usual criteria for heavy physical work apply. Sickle cell disease is disqualifying in that sickle cell trait alone may produce lesions of aseptic bone necrosis which cannot be distinguished from those secondary to dysbaric processes.

More detailed information regarding the physical examination of caisson and tunnel workers is found elsewhere (Kindwall 1988).

PRESSURE TESTING

Candidates for work in compressed air should be given a 30 psig (300 kPa) pressure test. This is adequate for most purposes. If an individual cannot clear his ears or sinuses at the first attempt, he need not be disqualified. However, if on three occasions the applicant fails to clear his ears, he should be disqualified. Applicants should not have any known allergies or colds when attempting a pressure test. Highly motivated applicants have sometimes had pressure equalization tubes placed through the eardrums when they have experienced an absolute ear block, and have retained them for the duration of the contract.

Records

The chart recording graphs for the tunnel and decompression lock must be retained. Usually, this is required by law. It is the company's responsibility to place these in company archives and, should a company subsequently cease operations, they must be transferred to a government authority. This is in the event that workers subsequently develop medical problems which could be related to their tunnel work. The lock keeper must also maintain a log of all entrances into the compressed air environment of each worker. Each worker must be suitably identified by name or number. The log should include the maximum pressure for each shift and the exposure time. The decompression table used must also be recorded. If decanting is used, this must be noted.

Workers' records should include results of a completed history and physical examination and the results of any laboratory tests. Skeletal X-rays are obtained as a baseline for employment and should be retained. On jobs progressing under high pressure, these should be repeated at yearly intervals. Skeletal X-rays may be omitted if work is not to exceed 16 psig (209 kPa).

Any cases of decompression illness must be recorded and reported to the authorities if the local jurisdiction requires this. In any case, the results of any medical treatment for decompression illness should be maintained in the physician's files. If the physician notes that the incidence of decompression illness is rising, he must notify the employer and take suitable corrective action.

SUMMARY

Compressed air work presents many potential hazards. However, with present-day knowledge of the mechanisms of their production, and with insistence that sound physiological principles be obeyed with regard to compressed air exposure, and subsequent decompression, these hazards may be minimized. The cooperation of a physician knowledgeable in compressed air matters is a requirement when any compressed air project is undertaken.

A consistent problem over the years has been the latency from physiological advances, improvements in decompression and treatment methods before their application to tunnelling and caisson work. This lag period has typically been of the order of 20 years or more, historically because of poor communication between physiologists and supervising engineers, unwieldy bureaucratic mechanisms for regulatory change and an unwillingness to change established methods of procedure. Despite its futility, attempts are regularly made to solve modern high-technology problems using nineteenth-century tradition.

Compressed air is a powerful tool used in underground and subaqueous construction. It is to be hoped that regulatory means may be developed internationally to optimize safety and the working environment of those engaged in the industry.

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