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The Compressed Air Environment

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There is little doubt that the diving bell was the first practical means whereby men engaged on engineering construction were enabled to perform their tasks under water in a compressed air environment. The first recorded use of a pressurized diving bell is by Smeaton while repairing the foundations of a bridge over the River Tyne at Hexham in 1778. In 1819 Augustus Siebe invented the supply of pressurized air to a diving dress.

The technique of using compressed air in tunnels and caissons to balance the pressure of water in the subsoil and thus to exclude it from the workings was first conceived and patented by Sir Thomas Cochrane in 1830. The basic principle of Cochrane's patent constitutes, in effect, the modern air lock to be described later. The method was used intermittently from 1839 onwards for shaft-sinking and caisson work but it was not until 1879, when compressed air tunnels were being driven simultaneously in Antwerp under the Scheldt and in New York under the Hudson River, that it began to be used extensively for tunnelling. The first medical lock was used by the late Sir Ernest Moir in the same Hudson River Tunnel in 1889.

Since then the basic principles have remained unaltered and improvements in use have been confined to details in application. Some modern research, for instance, has been devoted to the practicability of keeping workers in a raised environmental pressure for periods extending to days, weeks and even months, with a view to holding men available for work at all times and gaining an overall saving in decompression time. Whilst prolonged immersion of this nature has been proved possible it is unlikely that civilian workmen will ever readily accept conditions whereby during their 24-hour day they are deprived of social and family contacts in a normal atmospheric environment.

This chapter is therefore compiled against a background of normal shiftwork with a regular daily return to atmospheric conditions.

GENERAL APPLICATION

The general practice at present is to fill the whole of the workings with air at a pressure sufficiently greater than atmospheric to exclude the ground water, and for the workmen to carry out their duties in this raised environmental pressure. Experimental work, however, has recently been initiated in which it is attempted to confine the compressed air to the tunnel face. Excavation is performed entirely by mechanical means and the completed tunnel and the tunnelling operatives therefore remain in normal atmospheric conditions. These experiments have not yet advanced sufficiently to permit further discussion.

Whereas in underwater work it is possible to provide divers with compressed gases produced under factory-controlled conditions, in tunnels and caissons the large volumes involved render it necessary to produce compressed air on the site of the works (Fig. 1.1). Since this air is to be breathed by the workmen during the whole of their working period, special care must be taken to ensure that it is clean, dry and cool.

FIG. 1.1. Compressor house for construction of Clyde Tunnels, Glasgow, 1958. Low-pressure air capacity is 29,000 cu ft of free air per minute

PLANT FOR THE PRODUCTION OF COMPRESSED AIR

The pressurized atmosphere is produced by mechanical compressors which may be of a variety of types. In Fig. 1.1 is illustrated a typical compressor installation for a large project and in Fig. 1.2 is shown the detailed layout for the same installation including the accessories required to main-

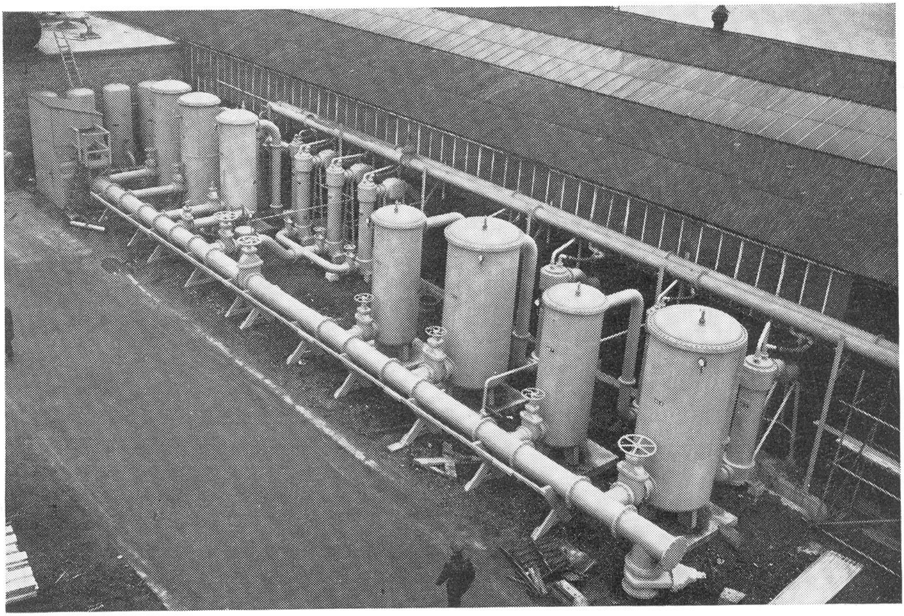


FIG. 1.3. Plant installation for cooling and purifying compressed air before delivery to working chambers

tain high standards of quality. Air is drawn into the compressors through filters placed outside the building, and through underfloor ducting. The compressed air is delivered by overhead piping through after-coolers and oil-separators at a temperature of about 70°F to the mains leading to the workings (Fig. 1.3). The compressed air required for pneumatic tools within the workings and generated at a higher pressure is cleaned, cooled and purified in the same way.

In the vast majority of cases installations such as this are relatively temporary and refinements will naturally be scaled down in accordance with their utility. For instance, where the fresh air is pure there will obviously be no need for elaborate filtration.

One essential provision which must however remain, except possibly when tunnelling in rock, is the constant maintenance of pressure within the working chambers. In order to guard against breakdown of compressor plant or failure in electricity supply, adequate stand-by arrangements must be provided to be brought into operation in an emergency either manually or automatically. It is generally accepted that the minimum capacity of such stand-by should be 50% of the designed requirement. If the prime mover of the installation is other than electrical it will be necessary to supply only enough stand-by plant to safeguard against normal breakdowns. In the case of electrically driven plant on the other hand, an alternative prime mover must be provided to the full extent specified. This can be accomplished in three ways:

(1) By auxiliary engines to replace electric motors in case of failure;
(2) By emergency generating sets to supply current to installed electrical mains equipment;
(3) By a reliable alternative mains electricity supply.

The advantage of a fully electrical stand-by as in (2) and (3) allows other vital plant such as cranes, hoists and pumps to remain in operation during the period of the mains failure.

For the prevention of panic it is highly desirable that some means are provided to allow essential lighting to be restored immediately. This is easily done by the installation of a small stand-by automatic generating set.

Compressors should be capable of operation at pressures up to 4 to $4\frac{1}{2}$ ATA and the pressure should be capable of being controlled over the whole range to the fine limit of $\pm\frac{1}{4}$ lb psi (0·5 ft, sea water; 0·016 Atmospheres). The design should be such that the delivered air is virtually oil-free.

The volumetric capacity of the compressor plant to be installed is a matter of judgement arising largely from experience and careful study of the available geological records of the strata to be encountered. The minimum requirement for ventilation given in the British compressed air regulations (Work in Compressed Air, Special Regulations, 1958) is a volume, at the pressure in the chamber, of 10 cu ft of fresh air per minute per person. It will be found in practice that unless the ground is practically impervious this volume is considerably exceeded by air losses through the working face and elsewhere and by the normal operation of the air locks leading to the working chambers.

For tunnels there is an empirical formula often used as an approximate guide to the compressed air requirements of one face:

$$C = nD^2$$

where C is the capacity in cubic feet of free air 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 average open ground and 24 for open sand and gravel.

The pressure required is normally determined by the depth of the workings below standing water level. Two ATA is the pressure theoretically required at a depth of 34 ft in fresh water and at a depth of 33 ft in salt water. In practice the pressure is varied between fine limits so as to balance the appearance of water in the working face.

In the case of tunnels where the diameter of the tunnel is large compared with its depth below the ground-water level, it may not be possible to exert pressure to balance the full hydrostatic head at the lowest part of the tunnel, the tunnel invert, because of the danger of creating a 'blow' of compressed air to the surface due to the considerable excess of pressure in the highest part, the soffit of the tunnel. In this event the balance of pressure must be adjusted to some safe level in the face and water entering the tunnel below this level dealt with by other means.

CONVEYANCE OF COMPRESSED AIR TO WORKING CHAMBERS

The compressed air is normally conveyed to the working chambers by pipe-line. Wherever possible these pipe-lines should be duplicated to guard against accidental damage to one, and they should be fitted with a non-return flap-valve at the point of discharge within the working chamber in order to conserve as much as possible of the working pressure in case of breakage.

Where the pipe-line is extensive it should preferably be designed for a maximum air velocity of 30 ft/sec to avoid an excessive drop in pressure between the compressors and the working chamber.

Despite some loss in mechanical efficiency it is advantageous to generate at a slightly higher pressure than required in the working chamber and to introduce a pressure-reducing valve into the pipe-line to regulate the working pressure precisely. The advantages of this procedure are that it avoids variations in pressure as the compressors cut in and out and silences the compressor pulsations in the working chamber. Further, it ensures that the maximum pressure to which the workmen have been exposed is known with certainty.

It is essential that all pressure gauges used in the works should be accurate at all times both for technical and medical reasons. A regular drill should therefore be initiated to check and if necessary to recalibrate all gauges at frequent intervals. For proper control it is important to have pressure gauges in the compressor house or control room connected directly to each working chamber. Continuous records should be kept of pressure in the working chambers, the air locks and the medical locks. This can conveniently be done by the use of pressure recorders with circular dials and a capacity of 24 hours' duration. The dials may be graduated with zero pressure either at the centre or the margin of the dial. For air locks and medical locks, where the zero end of the scale is important in registering decompressions, 'outside zero' gauges should be used. 'Inside zero' gauges may be used for working chambers where the pressures are virtually static over long periods.

AIR LOCKS, COMPRESSION AND DECOMPRESSION

Working chambers have to be sealed off from ordinary atmosphere and this is achieved by means of a concrete or steel bulkhead of sufficient strength to withstand the considerable loading applied by the higher pressure contained in the working chamber. Men and materials have to be passed in and out through this bulkhead and for this purpose one or more air locks are incorporated. In Figs. 1.4 and 1.5 are illustrated vertical locks

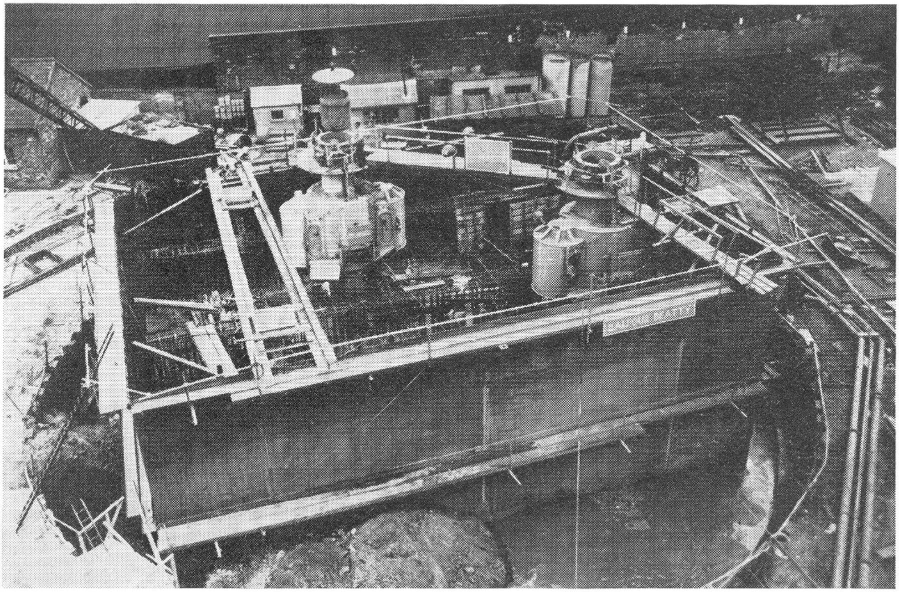


FIG. 1.4. Vertical locks for the sinking of the caisson for the North Access Shaft of the Blackwall Tunnel Duplication, London, 1962

such as are used for caissons and shafts, and in Fig. 1.6 is shown an arrangement of three horizontal locks—two for materials and one for men—to gain access to a tunnel under construction.

The vertical shaft lock consists of 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 with the hoisting rope. Two man-locks each capable of receiving four men are provided as 'blisters' on the outside of the casing of the materials lock. Vertical man-locks are of necessity small so they are not generally used for extended decompressions. The men are decompressed as rapidly as is practicable and transferred to a detached horizontal lock where they are recompressed to the full working pressure and then decompressed by stages.

As will be seen in Fig. 1.6 a horizontal lock is generally built of cylindrical steel sections embedded in the bulkhead so that it protrudes on the free air side. This ensures that, when under stress, the metal is in tension and, if damaged, repairs can more easily be effected. The end doors are both hinged to open into pressure. For man-locks the design of the hinges is important since it is vital for decompression purposes for the door at the free air end to remain sealed until the moment the pressures are equalized. A detail of the hinge is shown in Fig. 1.7. The door seals against a machined seating on the end plate of the lock by means of a special rubber seal fitted to the door. Care must be taken to maintain these seals in perfect condition.

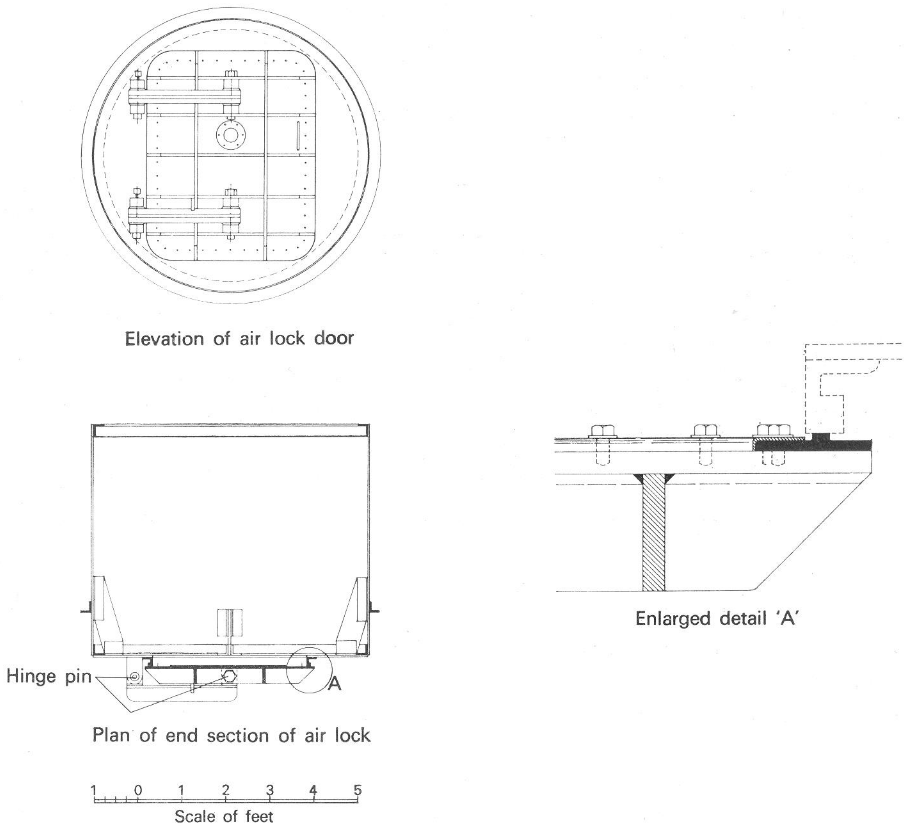


FIG. 1.7. Detail of hinge and rubber seal for man-lock door

When it is required to put the lock under pressure, air is supplied from the working chamber. This operation must however be under the control of the lock keeper on the free air side and piping must be installed for this purpose, as shown in Fig. 1.8, to allow for the handling of materials and for the compression and decompression of personnel. All locks are generally

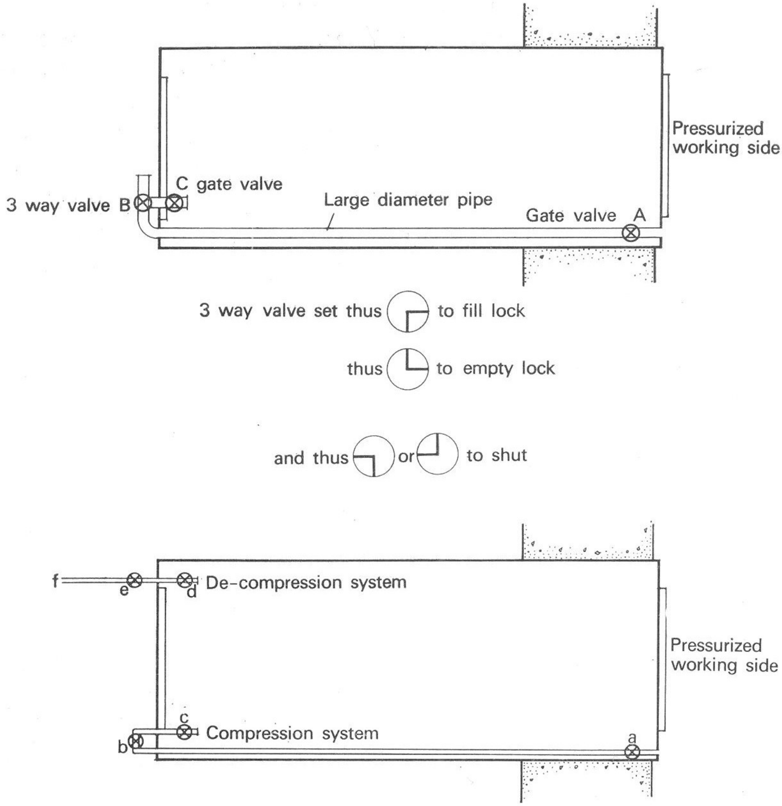


FIG. 1.8. Pipe connections through air locks for the pressure change of men and materials

equipped with both systems so that the materials locks also can be used for men in emergency. The diameters of the pipes are usually 4 in. for materials and 1 in. for men.

The operation of the valves is as follows:

A, a and C are normally kept open and are provided purely as safeguards.

B is a three-way valve for operating the lock for materials; the function of this valve is described in Fig. 1.8.

b and c are normally kept shut and used only when men inside the lock are compressing themselves without the help of the lock keeper in order to enter the pressurized working chamber. Valve b is first opened by the lock keeper and eventually closed by him when the men have passed through the lock.

d is a safeguard and is generally left open.

e is operated by the lock keeper and can be used by him to control decompression. Ideally, this valve is opened to initiate the first rapid stage of decompression. At point f automatic gear is installed to control the second slow stage in accordance with whatever requirements are given in the regulations. British regulations require that an additional small bore exhaust pipe shall be installed 'which shall be operated only in emergency and which shall normally be sealed or protected'. Obviously this pipe would have a valve within the lock only to be operated if something happened to the lock keeper resulting in interruption of the normal process of decompression. Equally there should be a provision requiring another small bore pipe with a valve on only the free air side to prevent anyone inside the lock, either from inadvertence or design, shutting themselves inside the lock by closing valves C, c and d. The position of the open end of this pipe within the lock should be made as inaccessible as possible (e.g. underneath the floor decking).

During decompressions from the higher pressures, men will have to spend long periods, up to 2 hours or more, in the lock and careful consideration must be given to their comfort. A level floor and adequate seating should be provided. Not less than 18 in. width of seating should be given to each man and a minimum of 25 cu ft of air space per man should be allocated. Timber is the most widely used material for the floor decking and seats but because of the added fire risk in compressed air, all timber within the lock must be fire-proofed and non-inflammable materials substituted wherever possible.

Good lighting is essential and this is most conveniently provided by bulkhead fittings with low voltage lamps, the wiring being run in conduit. Means of communication between the inside of the lock and the lock attendant are essential. In addition, the lock doors should be fitted with glass portholes so that the lock keeper can see what is happening in the lock and the men in the lock can observe the lock keeper's clock and pressure gauge. This is a requirement of the British regulations. The pressure recorders mentioned earlier will provide a permanent record of all decompressions.

Decompression under the present British regulations is initiated by a rapid drop in pressure to half absolute pressure. This results in a quick temperature drop in the lock and the formation of dense fog due to condensation of water vapour held in the air. In order to combat both of these effects thermostatically controlled high-powered fan-heaters should be placed in the lock, preferably in an inaccessible position. The thermostatic control should be set to an upper limit equal to the temperature in the working chamber, with a lower limit only a few degrees below. The electrical capacity should be about 1 kilowatt for each 200 cu ft of lock space.

For all decompressions involving a large number of men and for all decompressions of extended duration, fresh air for ventilation must be supplied to the lock during decompression. This can be provided conveniently by tapping the main pipe-line supplying the working chamber and running a perforated pipe under the control of a stop-valve under one or both bench seats in the air lock. Consideration must also be given under these circumstances to the provision of toilet facilities within the man lock.

Man-lock keepers have to be trained for their position and they must above all be reliable. As well as being required to control all decompressions, they must keep a complete record of the entry and exit of each man. When any man presents himself at the man-lock for decompression, the lock keeper must be able to ascertain quickly from his own records (or those of a colleague) how long the man has been exposed to pressure, in order to determine the time of decompression. The man-lock keeper should be in telephonic communication with all other man-lock keepers whose locks may give access, directly or indirectly, to the same working chamber. This is again so that the man-lock keeper can quickly determine the time of entry of the man into compressed air. It is possible that there may be two working chambers at different pressures and connected by an intermediate lock. Although it is probable that the pressure difference between the two chambers will not be such as to require a controlled decompression, nevertheless the main man-lock keepers must be kept informed of the passage of individuals through the intermediate lock, so that, if necessary, the individual will be decompressed from the higher of the two pressures even if he presents himself for final decompression at the main man-lock connected to the lower pressure working chamber. This requirement necessitates having a lock keeper in attendance on the intermediate lock. Certain personnel, such as engineers, foremen and maintenance men, may, in the course of their duties, have to enter the working chamber more than once in any one day. Care must be taken by the man-lock keeper to ensure that all decompressions therefore take account of the history of previous exposure to pressure during the period specified according to whatever regulations may be in force. This is relatively simple where there is only one man-lock, but where there is more than one, the man-lock keepers must check with each other about previous exposures of all such personnel.

The process, mentioned earlier, of rapid decompression in a vertical lock, transfer to a horizontal lock, followed by recompression and a controlled decompression, is known as 'decanting'. It is permissible when the vertical lock is too small, as it usually is, to permit controlled decompression. It is also permissible when, because of the dimensions of the access available, it is only possible to provide one horizontal lock, which then has to be used for the passage of both men and materials. A lengthy decompression in such a lock would mean a hindrance to the progress of the work, as it would not be possible to pass materials through the lock while it was occupied by men.

Under present British regulations the process of rapid decompression in the main lock, transfer to the decanting lock and recompression to previous working pressure must not occupy more than 5 min. Decanting has never been regarded as a completely satisfactory method of decompression, and it should be avoided wherever it is possible to make a lock available solely for personnel, particularly at pressures of $2\frac{1}{2}$ ATA and above.

Personnel applying for employment in compressed air must be given, in writing, advice as to precautions to be taken in connection with such work. Where the pressure to which the man is to be exposed is never going to exceed 2 ATA, this advice need consist only of instruction in compression procedure, of a warning not to attempt compression if suffering from a severe cold or earache, and of a warning that all requirements of the examining doctor and of the man-lock keeper must be obeyed. Where the pressure is to exceed 2 ATA, the man must also be given, again in writing, a warning that he may develop compressed air sickness and that he must be recompressed in order to cure this. Instructions must be given as to how he is to arrange to return to the site for recompression should he be off the site when the sickness develops. He should also be warned that he is exposing himself to the risk of later bone damage and that, despite all the precautions which will be taken to safeguard his health, an absolute guarantee that he will not suffer cannot be given.

With a working pressure above 2 ATA, every man should be required to carry a label indicating that he is employed in compressed air and that, if he is found in a state of collapse, he should be returned to the site for recompression. The police, ambulance service and hospitals in the vicinity should be notified of the fact that work under compressed air at a pressure exceeding 2 ATA is being undertaken and that men may be found in a state of collapse suffering from compressed air sickness necessitating their return to the site for recompression without delay.

MEDICAL LOCKS

Recompression is carried out in a medical lock, which must be provided whenever the pressure in the working chamber exceeds 2 ATA and which must be kept solely for the treatment of men suffering from compressed air sickness. In Fig. 1.9 is illustrated an installation of two medical locks, with an associated first aid room, such as are described in the British regulations.

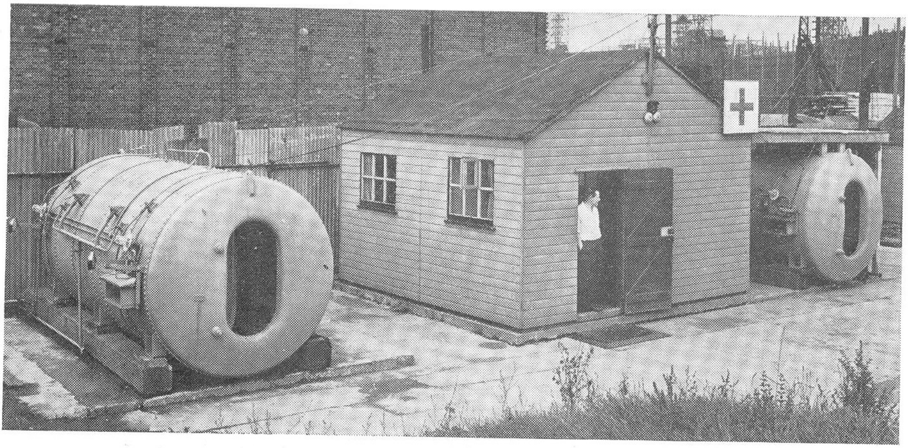


FIG. 1.9. Medical locks at the Clyde Tunnels, Glasgow, 1958

In Fig. 1.10 is shown the interior of a medical lock and in Fig. 1.11 is shown the detailed layout which conforms to these requirements. All air valves must be capable of being operated from outside *and inside* the medical lock so that, in case the attendant has to enter the lock to attend to the patient, he may still control the rate of pressure variation. For the same reason, gauges placed outside the lock and showing the pressures in both main compartments must be visible also from inside either compartment. Ventilation or fresh air supply is best supplied by small valves (petcocks) again capable of operation either from outside or inside the lock. Heating and lighting arrangements should be similar to those in a manlock.

In all probability, a medical lock will be situated on the surface. In hot weather, therefore, it might become too hot for comfort and either shade should be provided or the outer surface can be water cooled.

Care must be taken to provide an adequate air supply to a medical lock. The pressure of the air for the working chamber may not be sufficiently high for medical lock purposes, since it is sometimes necessary to recompress a patient to a pressure slightly higher than that at which he has been working. Further, during conditions of reducing pressure in the working chamber, such as during tide work, the generated pressure when a man returns for treatment may be considerably less than the highest pressure to which he had been exposed during his shift. It is therefore essential to be able to augment the generated pressure at the medical lock. Furthermore, it must be possible to supply air continuously to the medical lock even in cases of compressor breakdown or pipe-line fracture. In order to cover these eventualities, a receiver filled with high-pressure air (at 7 to 9 ATA) should be positioned near the medical lock. Its capacity should be such

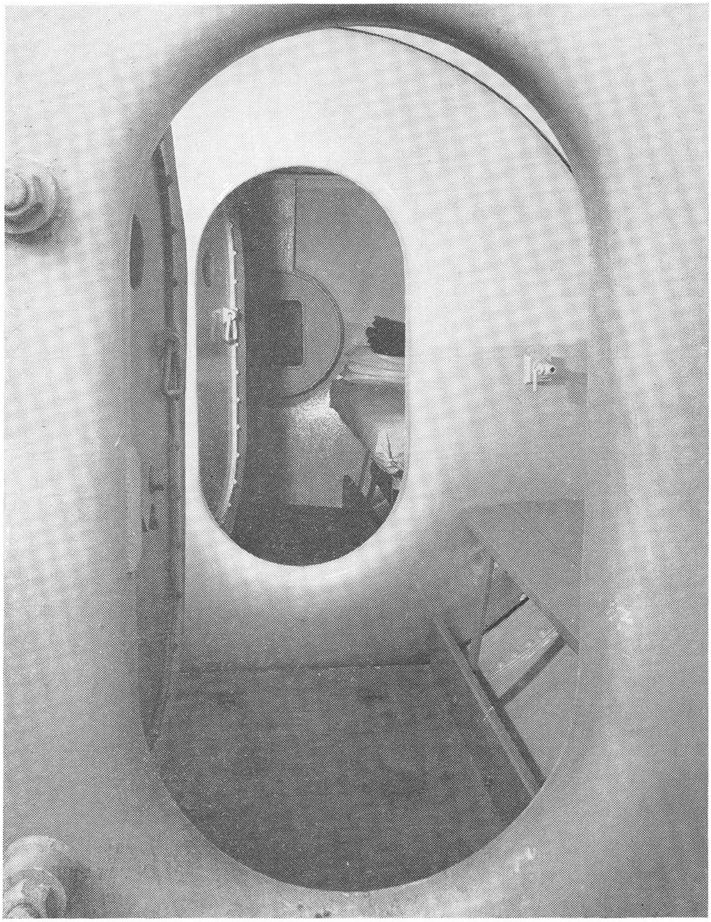


FIG. 1.10. Interior of a medical lock

that the inner chamber of the medical lock can be filled at least twice with air at the working pressure or slightly above. The receiver should be fitted with a non-return valve on the supply side and a pressure-reducing valve, set to deliver air at a pressure slightly above the working pressure, on the delivery side. The low-pressure line (i.e. at working chamber pressure) should also be fitted with a non-return valve in this vicinity and both it and the line from the high-pressure receiver should be led through an additional filter before entering the medical lock. Automatic decompression controls are not usually fitted to a medical lock, mainly because the attendant will have to slow down the rate of decompression considerably when treating a troublesome case.

The food lock shown in Fig. 1.11 is for the purpose of passing food and

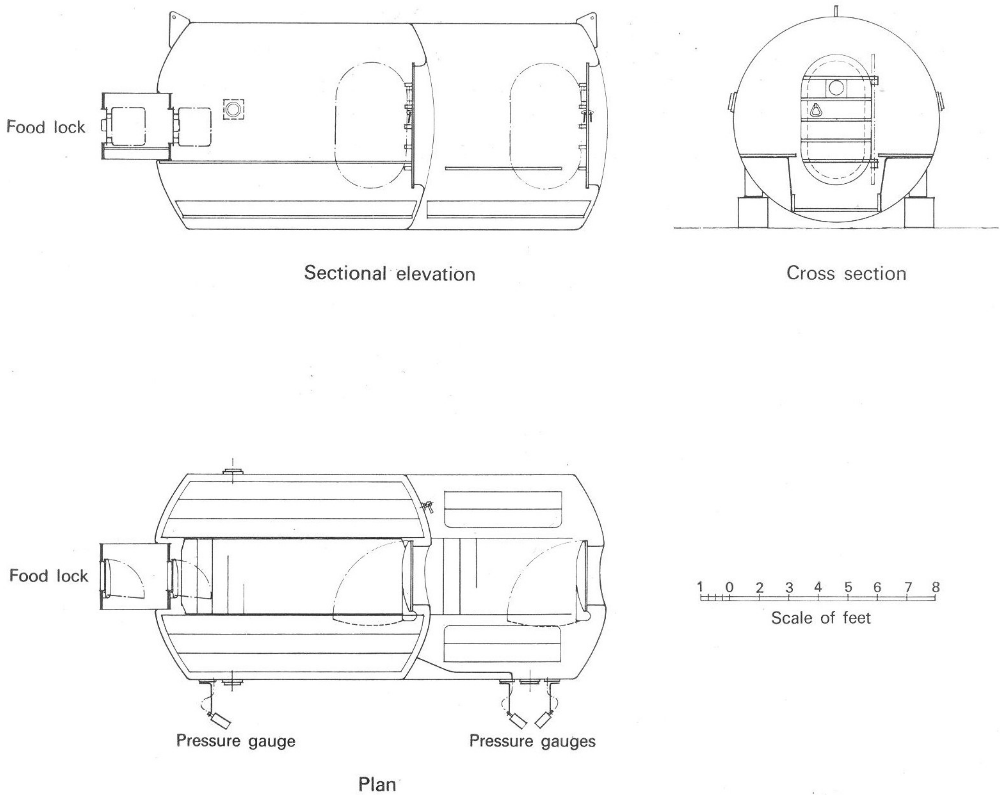


Fig. 1.11. Diagrammatic arrangement of a typical medical lock

hot drinks to the patient. The dimensions should be as small as possible to avoid variations in the rate of pressure drop resulting from its use during decompression. The attendant must learn whenever possible to confine the use of the food lock to periods outside the controlled section of the decompression.

The medical lock must be situated adjacent to the first aid room, with all the normal equipment for dealing with accidents. The first aid post must have a telephone connected to the medical lock. It must also have a telephone on the normal public system, so that an emergency case of compressed air sickness developed away from the site can be reported to the attendant and transport arranged if necessary. The first aid post must also be connected to the site internal telephone system whereby the attendant can communicate with all man-lock keepers so that he can quickly ascertain the details of the last exposure of a patient to compressed air. A pressure recorder should be connected to each of the two compartments of the medical lock, so that a complete record of each and every treatment is available. The first aid attendants should also write into a log book a detailed record of all circumstances relating to each treatment, with details of the previous period at work in compressed air, details of his symptoms and the time at which they began, the time of entry into the medical lock, details of how he responded to treatment, when it was completed and how the patient felt afterwards. Such records are invaluable not only for medical purposes but also in some cases for legal evidence. With pressure in the working chamber above 2 ATA it is essential that the first aid post (including the medical lock) be manned throughout the 24 hours of every day in order to cover not only the construction work but also weekend maintenance.

WAITING PERIOD AFTER DECOMPRESSION

The normal manifestation of Type I compressed air sickness, as is described elsewhere, consists of pain in the joints of the arms and legs. All other manifestations are classed as Type II and immediate recompression is vital. Fortunately, symptoms usually develop during decompression or within a short time afterwards.

In order to be reasonably certain that such cases will occur on the site, where immediate treatment is available, British regulations require all men, where the working pressure is above 2·2 ATA, to remain on the site for at least 1 hour after decompression has been completed, and this period is increased to a minimum of $1\frac{1}{2}$ hours for pressures above about $3\frac{1}{2}$ ATA.

Because of this enforced waiting period, British regulations require that a suitable shelter be provided for the men, and accommodation for changing and washing. The scale of such facilities will be influenced by the numbers of men employed and the expected duration of the compressed air working. On a major compressed air undertaking, such facilities should be of relatively high standard and should include one hot shower and one wash basin for every four or five men of the maximum number who are likely to be involved in one decompression. It is desirable to provide drying racks for working clothes to ensure that the men always go to work in dry clothing. The shelter accommodation should be considerably better than the normal requirement of a temporary working site.

COMPRESSED AIR RECORDS

In addition to the register kept by the man-lock keepers, the individual medical record cards and the medical lock treatment-book, the current percentage relationship of total recompressions to decompressions should also be available. This is generally calculated for two groups, shift workers and others. Shift workers should include all men who are regularly exposed to compressed air for more than 4 hours per day, whether or not they are actually working on a shift basis. 'Others' should be those men who are not normally exposed to compressed air for more than 4 hours per day except on isolated occasions. Such a report may take the form shown in Table 1.1.

TABLE 1.1
An example of the table produced for Type I cases only. It is a direct measure of the efficiency of the decompression process
For week ending 28th May 1967

	For week	*To date*
Shift Workers		
Decompressions	479	22,163
Recompressions	2	169
Percentage	0·42	0·76
Others		
Decompressions	295	9,654
Recompressions	1	49
Percentage	0·34	0·51

In conclusion it must be strongly emphasized that the conduct of civil engineering works under compressed air requires an expertise which can be acquired only by practical experience. It is essential therefore that those in authority supervising the day-to-day operations should have this experience, should be fully aware of the dangers involved and should appreciate to the very highest degree the precautions which must be exercised to allow the work to proceed in safety for the structure and, more important, for the men.

Even with a lifetime of experience there is still much to be learnt to ensure the same safety for man in compresssed air as he enjoys in his natural environment.

Acknowledgements

Acknowledgements are due for permission to publish the photographs of Figs. 1, 3, 9 and 10 to the Corporation of the City of Glasgow and to their consulting engineers, Sir William Halcrow and Partners, and of Fig. 4 to the Greater London Council, to their consulting engineers, Messrs. Mott, Hay and Anderson, and to the main contractors, Messrs. Balfour, Beattie and Co. Ltd.

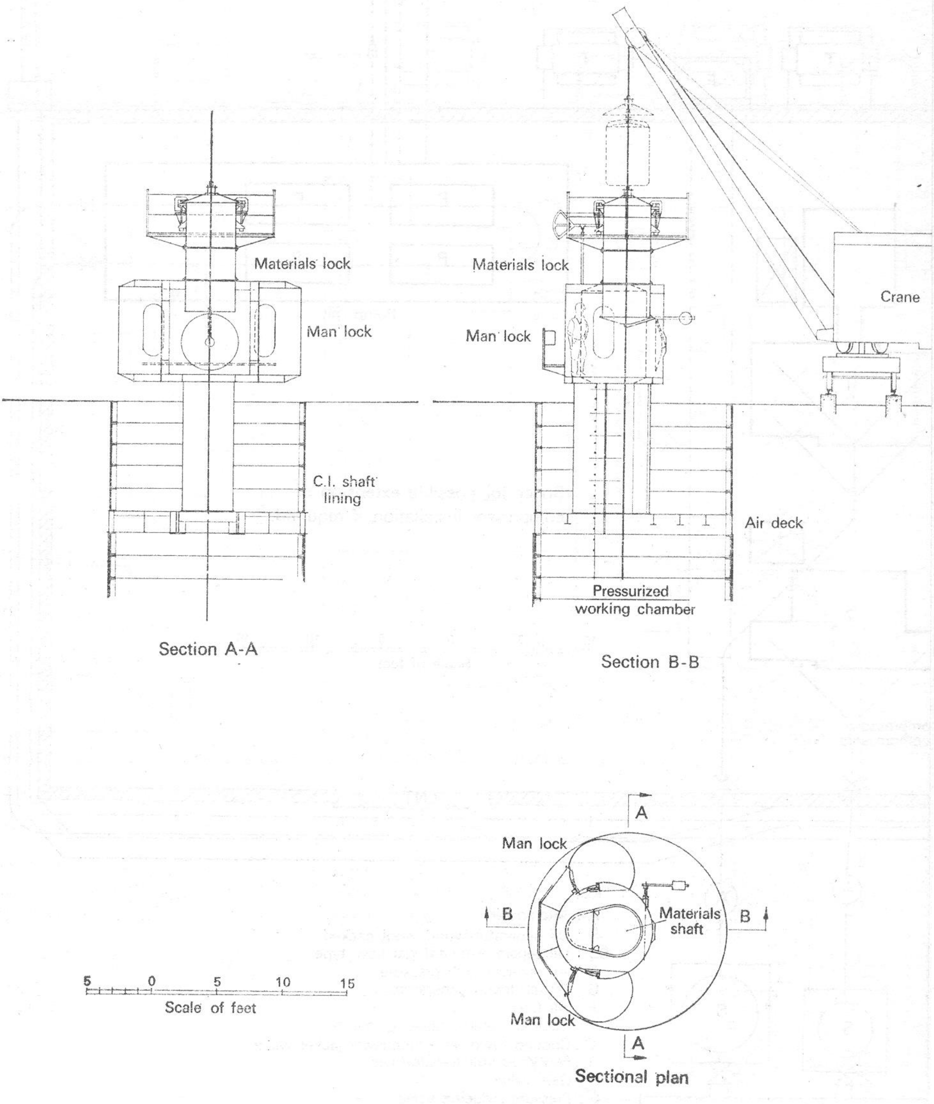


FIG. 1.5. Diagrammatic layout of a typical arrangement of a vertical air lock

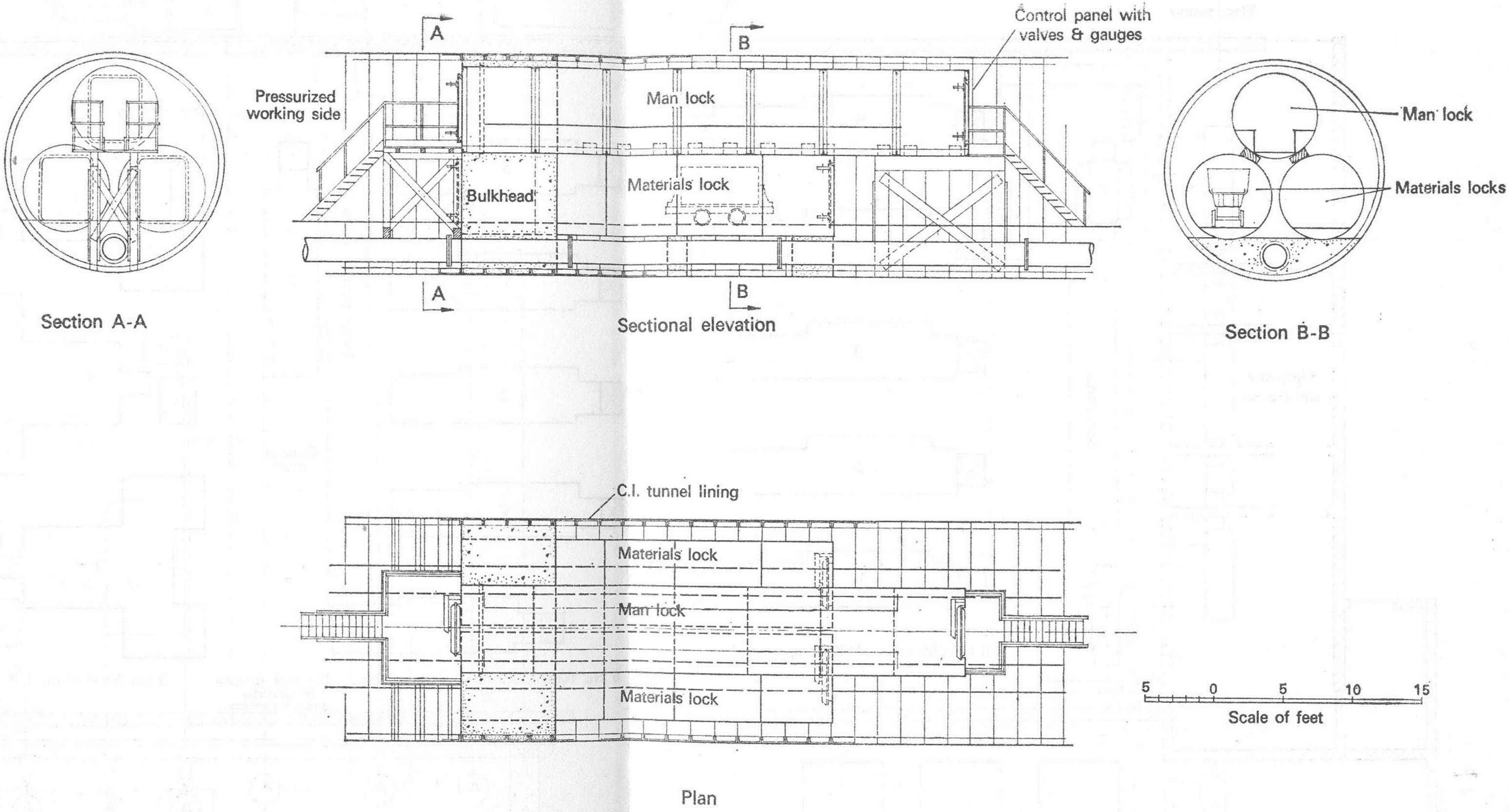


FIG. 1.6. Diagrammatic layout of a typical installation of horizontal air locks

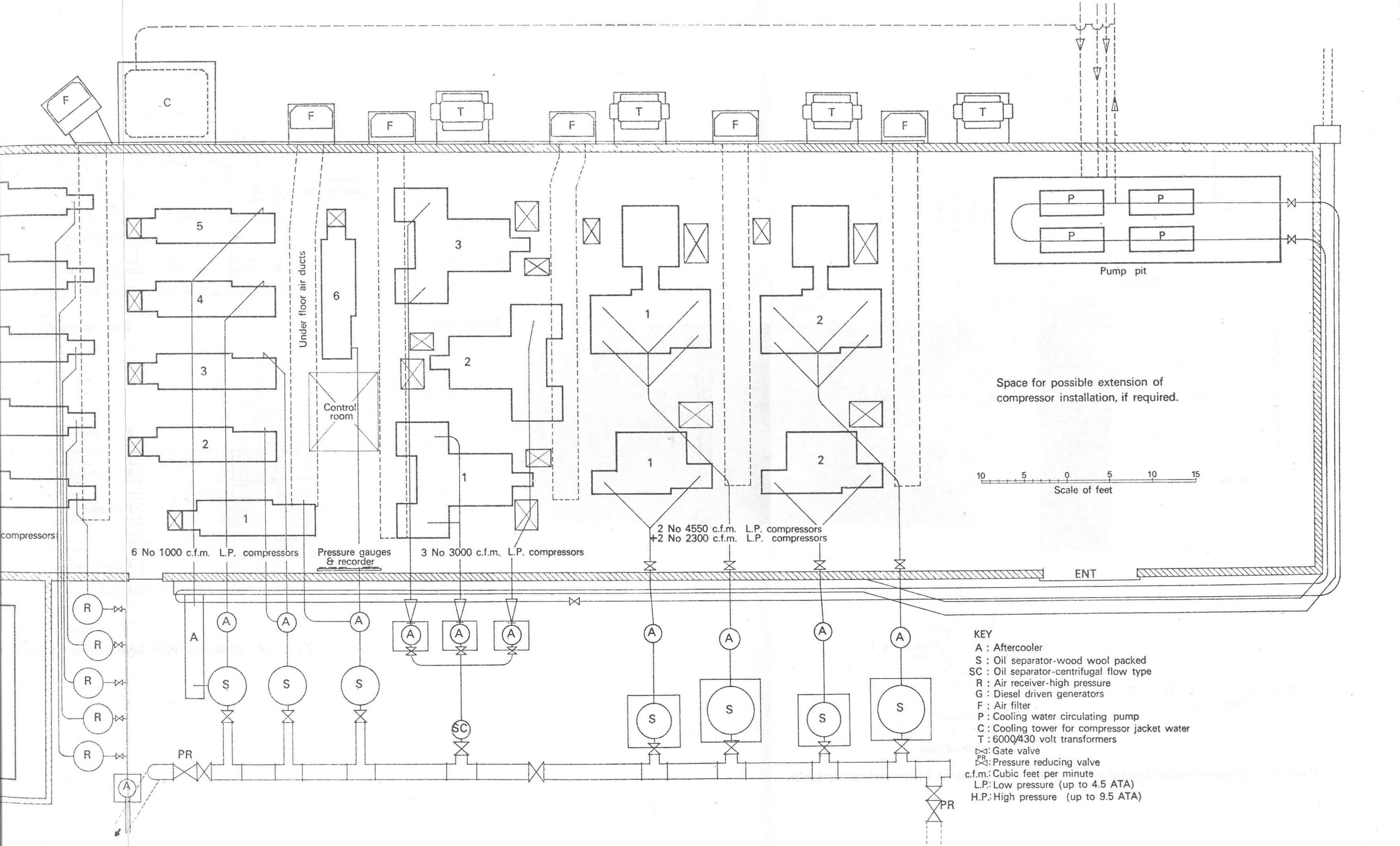
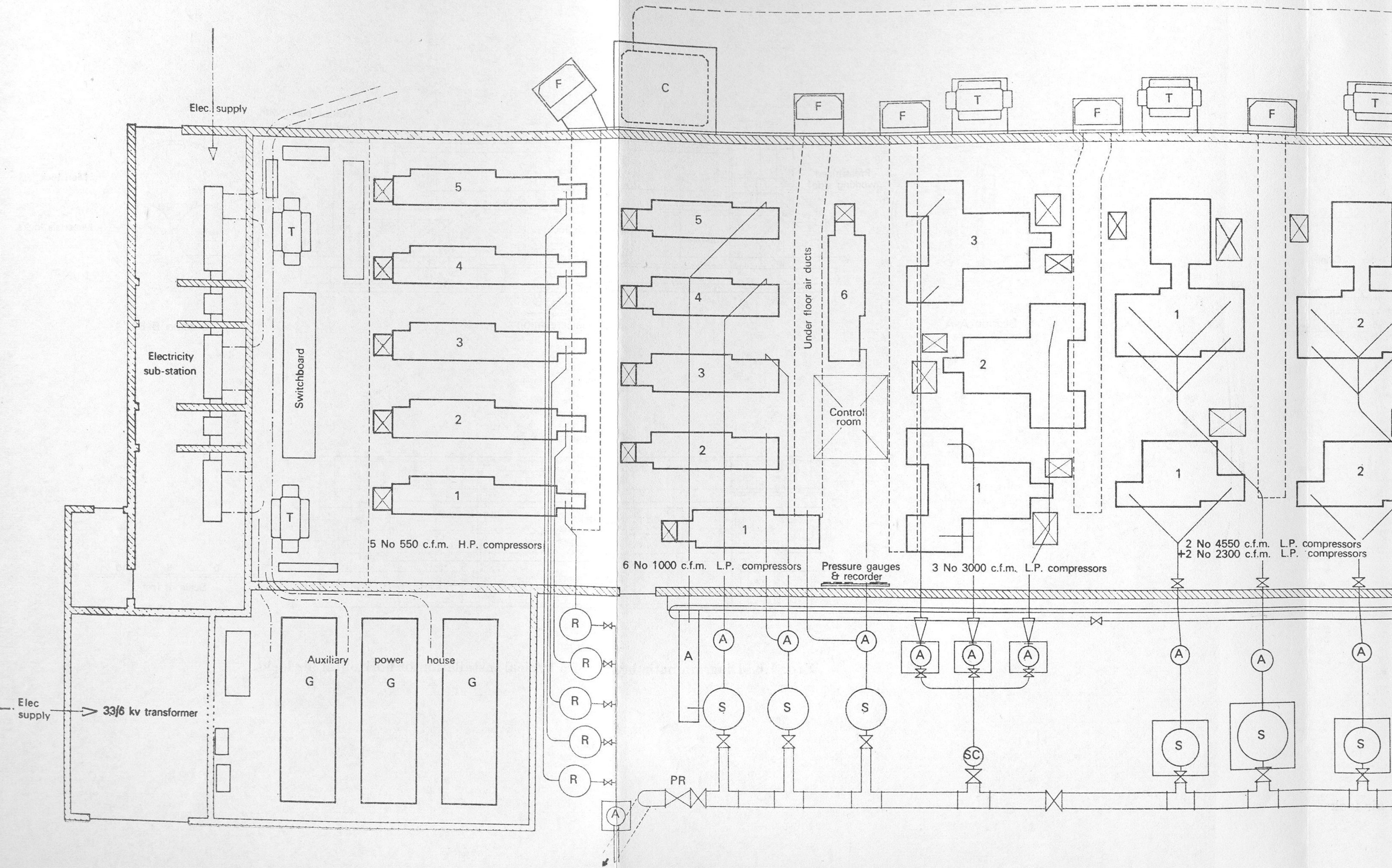


FIG. 1.2. Diagrammatic layout of compressors and ancillary equipment for the installation shown in Fig. 1.1



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