Decompression Sickness: A Review

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Work in compressed air is a dangerous activity, whether it is carried on under water in a conventional diving suit, in self-contained breathing apparatus or in a diving bell, or in relatively dry conditions in a caisson or an underwater tunnel. Surprisingly large numbers of men have worked at one time or another in compressed air in tunnels or caissons and it is the dangers which arise to the health of these men that are considered here.

When a tunnel is driven through water-logged strata or through porous ground under a river, the open end of the tunnel must be sealed off and air pumped in to balance the hydrostatic pressure, should there be any danger of water flooding in and bringing with it unmanageable quantities of silt or sand. A pier of a bridge may be constructed in deep water by means of a caisson (Fr. *caisse*, a box), which is a compressed air chamber in which a gang of men excavate foundations. In both tunnels and caissons men come and go through an air lock and must be compressed on entering and decompressed at the end of the work period. Although working conditions in these circumstances have much improved over the last 60 years, our understanding of the reactions of the human body to atmospheric pressures greater than the normal and of the pathogenesis of decompression sickness is still insufficient to prevent illness completely.

In engineering practice it is customary for working pressure to be expressed as gauge pressure in pounds per square inch (p.s.i.g.) which is the pressure over and above the normal atmospheric pressure of 14.7 p.s.i. (1.03 kg./cm.²). For certain calculations absolute pressure (gauge pressure plus atmospheric pressure) is used, and for clarity it must always be stated whether gauge or absolute pressure is referred to. In naval practice it is usual to think in terms of feet of sea water, each 33 feet of depth corresponding to about one atmosphere or approximately 15 p.s.i. Sometimes the unit of pressure used is the atmosphere (atm.). On the

European continent pressures are expressed in kilogrammes per square centimetre (kg./cm.²). Although the use of these different units can be confusing, it is not difficult to convert one into another.

Decompression procedures used for deep sea divers are generally held to be safer and to result in much less decompression sickness, particularly bone disease, than those used for tunnel and caisson workers. It is often asked why tables and procedures similar to those used in diving are not applied in civil engineering work, and to answer this a brief description of the particular circumstances affecting such work must be given.

Civil Engineering Projects

The practical and human problems in caisson and tunnel work are quite different from those encountered in deep sea diving. These civil engineering projects occur sporadically and irregularly; they may be situated anywhere in the British Isles and may be reduced or may disappear during time of war or economic difficulty.

A high turnover of labour is characteristic of civil engineering compressed air work, and in a contract which at any one time employs two or three hundred men in compressed air, many more than this number will have been exposed to compressed air for greater or lesser periods by the time the contract is completed (Table I). For example, at the Dartford Tunnel (Golding, Griffiths, Hempleman, Paton, and Walder, 1960), over a period of two years during which between 250 and 320 men were on the active compressed air list at any given time, 1,200 men actually worked in compressed air at one time or another. A very high proportion of men attracted to this type of work by the high rate of pay do not remain at it for more than a few weeks, probably because it is not only dangerous but physically hard. The Work in Compressed Air Special Regulations, 1958 (Ministry of Labour and National Service, 1958) ensure that fit young men

are selected from those new to the work and that older experienced men are also in good health. Nevertheless the general standard of health must be somewhat lower than that of naval divers. Compared with naval divers, compressed air workers are poorly trained in decompression procedures and are undisciplined; they are often itinerant, living away from home in lodgings or camps, and tend to drink heavily. If more than one contract is being carried out in the country at the same time, men may move from one site to another at short notice if they know that the pay is better. This mobility, variations in the level of working pressure, and the occurrence of strikes may lead to loss of acclimatization to work at high air pressure and consequently to a greater risk of decompression sickness. The difficulty of identifying individual workers who move from contract to contract is well illustrated by the files of the Central Registry of Compressed Air Workers at the University of Newcastle upon Tyne which contain records of 42 different men named Gallagher, 14 of whom have Patrick as their first name and 38 of whom have at some time been employed at the same work site (Griffiths, personal communication).

The work is heavy labouring, usually for an eight-hour shift at pressures which may on occasion reach a legal maximum of 50 p.s.i.g., although the majority of work is carried out at much lower pressures. Work in compressed air may go on for many months, especially if constructional difficulties are encountered or the undertaking is large. In the two tunnels under the River Clyde, one of which was opened for use in July 1963 and the other in March 1964, work in compressed air went on for about three and a half years between May 1959 and January 1963 (Haxton and Whyte, 1965). In deep diving, on the other hand, although pressures are very much higher than those used in caisson or tunnel work, the periods of exposure to pressure are comparatively brief. The total period of time for which a diver is engaged on a particular project is often quite short, perhaps a few days or weeks, and a small number of highly trained and experienced men is involved.

Gas Bubbles as the Cause of Decompression Sickness

Men have worked in diving bells, diving suits, and caissons in pressures over 4 atmospheres absolute since the sixteenth century, with many serious accidents (Bert, 1878). Bert made a clear distinction between the effects of compression and decompression and gave credit to Pol and

Wattle (1854) as the first authors who had attempted to explain decompression accidents. Pol and Wattle neatly summed up the main problem in compressed air work in the phrase 'on ne paye qu'en sortant'. Bert showed that decompression sickness was related to the appearance of nitrogen bubbles in the blood and tissues following rapid decompression, and that very slow decompression would prevent symptoms occurring. He advised immediate recompression for treatment of symptoms.

His observations were based largely on detailed and painstaking animal experiments, but his description of decompression accidents in humans is accurate and still relevant. He concluded that post-decompression phenomena depended for their intensity on the height of pressure to which men had been exposed and to the rapidity of decompression; that up to 2 atmospheres absolute there appeared to be no ill effects but that above this level cutaneous lesions and limb pains appeared more and more frequently, and that it was not until over 3 atmospheres absolute pressure had been reached that the very serious accidents occurred. Bert drew attention to the variation found between different individuals in the effects of decompression and also in the same persons in different and ill-understood circumstances. His animal experiments included the use of reduced pressures as well as increased pressures, the toxic effects of oxygen at increased pressures, and explosive decompression. Although it is now universally accepted that gas bubbles are the cause of decompression sickness, the exact mechanism by which pains are produced and the site of the lesion are still unknown, and the rôle of the bubbles in aseptic necrosis of bone has not been demonstrated in man or in animals.

Decompression Procedure

Until the early part of this century men were habitually decompressed very rapidly, taking only a few minutes even after several hours at high pressure, and severe symptoms, gross disablement, and deaths were common (Hill, 1912). Compressed air was first used in tunnelling at the Hudson River, New York in 1879 where a maximum pressure of 35 p.s.i.g. was reached, but no complete medical record of this contract was made. Ryan (1929) quotes a figure of 12 deaths in a year in 50 workmen driving the Hudson River tunnel in 1890, and Boycott (1906) gives a mortality rate of 25% per annum for the same undertaking. After a medical lock was introduced the death rate dropped to about 1%.

TABLE I
COMPARISON OF VARIOUS COMPRESSED AIR CONTRACTS

<i>Contract</i>	<i>Period of Compressed Air (mths)</i>	<i>Daily Work Force (Compressed Air)</i>	<i>Total No. of Workers in Compressed Air</i>	<i>Maximum Pressure (p.s.i.g.)</i>	<i>Shift Length</i>	<i>No. of Decompressions</i>
East River Tunnel, New York 1914-21	84	—	—	48	Two shifts daily of 1½ to 4 hrs according to pressure	1,360,000
Silent Valley, Belfast 1927-28	—	—	—	30	Two shifts of 3 hrs with ½-hr intervals	3,600
Hooghly River Bridge 1930-32	24	—	—	45	Two daily ? length	44,500
Howrah Bridge, India 1938	6	—	509	40	4 hrs	12,400
Feisal and Ghazi Bridges 1946	—	—	—	36	8 hrs	12,500
Tyne Pedestrian Tunnel 1948-50	18	24	376	42	6 or 8 hrs (4 hrs for 3 mths)	40,000
Thames Caisson 1950	3	15	—	35	—	2,100
Lincoln Tunnel, New York 1955-56	18	300	704	34	Two shifts daily of 1½ to 4 hrs according to pressure	138,000
Auckland Harbour Bridge 1955-58	24	151	393	49 (one pier)	8 hrs, 6 hrs, and 4 hrs; 3 hrs for short period	10,026
Dartford Tunnel 1957-59	24	250-320	1,200	28	8 hrs	122,000
Clyde Tunnels 1958-63	60	Max. 200 Av. 150	1,362	34	8 hrs	240,259
Blackwall Tunnel 1960-64	44	200	1,536	39	8 hrs	81,000
Tyne Road Tunnel 1963-66	38	90	650	42	8 hrs	44,800

The earliest book on decompression sickness among compressed air workers to be published in the United Kingdom was by Snell (1896), who was appointed by London County Council as a full-time medical officer in charge of compressed air work on the first Blackwall Tunnel. It was driven through loose gravel for much of its course and up to about 80 men were employed at any one time in compressed air. They worked three shifts of approximately eight hours and there were over 200 cases of decompression sickness recorded, of which Snell

discussed 50; they included two or three cases of paralysis. The exact method of decompression and its duration are not stated, but Snell instances rapid decompression as a minor cause of decompression sickness. At Blackwall each man-lock had two pairs of air-cocks, the larger for decompressing material and the smaller for men. With the smaller cock fully open, air could escape in 4 minutes to atmospheric pressure whereas the larger one allowed air to escape in 30 seconds. Men were not allowed to use the larger one but this regulation was often

TABLE I—Continued
COMPARISON OF VARIOUS COMPRESSED AIR CONTRACTS

Decompression Sickness				Type II as % of Total Decompression Sickness	Decompression Procedure	Decanting
Type I (Bends)	Type II	Type I Rate (%)	Type II Rate (%)			
680			0.05	—	New York 1921 Code. Up to 36 p.s.i.g., 3 lb. in 2 min. Over 36 p.s.i.g., 1 lb./min.	No
27	—	0.76	—	—	Drop to half absolute pressure, then 7 min./lb.	No
117	—	0.26	—	—	'One pound per minute from all pressures'	No
344	9	2.8	0.07	2.5	Drop to half absolute pressure in 10 min. then 7-8 min./lb.	Yes
99	1	0.8	—	—	10 min. from max. pressure	No
333	17	0.87 over 18 p.s.i.g.	0.04	4.2	Mainly British 1958	No
89	—	4.0	—	—	Institution of Civil Engineers, 1936	—
42	2(?)	0.03 overall 0.07 over 15 p.s.i.g.	0.001	4.5	New York State—three-stage	No
218	44	2.6 over 18 p.s.i.g.	0.44	17	Modified British 1958	Yes
650	35	0.56 overall 0.93 over 18 p.s.i.g.	0.04	5.0	British 1958 and extra 5 min. at $\frac{1}{2}$ p.s.i.g.	No
398	71	0.2 overall 0.29 over 18 p.s.i.g.	0.04	15.0	Modified British 1958. Decompression increased by average of 7 min.	No
824	39	1.05 over 18 p.s.i.g.	0.04	4.0	Modified British 1958 (10 min./lb. in slow phase)	For pilot tunnel only
693	18	1.7 over 18 p.s.i.g.	0.04	2.5	British 1958, and extra 5 min. at $\frac{1}{2}$ p.s.i.g.	No

disobeyed. A lock made out of a boiler was used for treatment. Snell emphasized a close relationship between the amount of decompression sickness and the ventilation of the compressed air space and the CO₂ level in the air. He was of the opinion that less illness would have occurred if shorter shifts had been worked at the high pressures.

In 1904 the New High-Level Bridge was constructed at Newcastle upon Tyne with the help of three caissons. Here the shift length varied with the pressure, *e.g.*, the shift was 10½ hours at 25 p.s.i.g.

and 7 hours at 30 to 35 p.s.i.g., but it included breaks in free air of 1½ hours for breakfast and 1 hour for dinner so that the longest period in compressed air at one time was 4 hours. The decompression time was 1 minute for every 3 pounds of pressure so that the maximum decompression time was less than 12 minutes. A medical lock was also provided (Parkin, 1905; Boycott, 1906).

A major advance in the control and mitigation of the hazards of work in compressed air was the work of Haldane (Report to Admiralty, 1907; Haldane

and Priestley, 1935). Haldane concluded from animal experiments and observations on divers that bubbles of nitrogen do not appear in the body unless the amount of supersaturation is more than that of a decompression from a total pressure of $2\frac{1}{2}$ atmospheres. The absolute pressure could always safely be halved, whether the pressure was high or low, up to about 6 atmospheres, as the volume of nitrogen released would be the same whether the pressure was reduced from 4 to 2 atmospheres or from 2 to 1 atmosphere. Nitrogen would be eliminated more rapidly than by reducing pressure at an even rate, and the time spent at high pressure would be reduced. Thereafter decompression was carried out to atmospheric pressure at a rate calculated to avoid critical supersaturation with nitrogen in any part of the body. The safety of rapidly halving the absolute pressure was confirmed in experiments first with goats and later with men. Haldane's hypothesis, on which the statutory decompression table in force in Britain is still based, revolutionized the conduct of compressed air work and provided a scientific basis for decompression. A disciplined procedure was encouraged and the mortality and morbidity of the previous era were reduced. A supplement to the Admiralty Report of 1907 contained a stage decompression table which was widely used for divers in civil work, and to some extent at tunnels and caissons.

Hill (1912) commented, however, that the mathematical calculations on which the Admiralty table of stage decompression was based had never been published and so could not be critically examined. He doubted the superiority of stage decompression over a uniform rate of decompression on the basis of experimental work with pigs, and also because the Admiralty table was based largely on theoretical data about the circulation of the blood which could not be regarded as fixed in the variable conditions of activity of the human body.

In 1935 the Institution of Civil Engineers appointed a committee to draw up Regulations for the guidance of engineers and contractors undertaking work under compressed air. This Committee included J. S. Haldane, Sir Robert Davis, and Captain G. C. C. Damant. In their report (Institution of Civil Engineers, 1936) the Committee stated that practical experience in tunnelling work had shown that for long exposures to pressures up to 35 p.s.i.g. the decompression times could be less than those in the Admiralty tables, but that at pressures over 40 p.s.i.g. the times were too short. The Committee thought that, for exposures greater than 4 hours' duration, the liability to symptoms of decompression sickness did not increase, because by this time the body had become

more or less fully saturated with nitrogen, and that the working period could thus be safely prolonged provided that adequate time was given for decompression. The assumption that saturation of body tissues with nitrogen is complete in a period as short as 4 hours is not now accepted.

These Regulations contain a table of recommended decompression times for varying periods in compressed air up to 50 p.s.i.g. using the principle of stage decompression. However, the recommended times are qualified by allowing a progressive reduction to two-thirds of their value for men with previous experience in compressed air work 'without having shown serious symptoms'. Thus, an experienced man could be decompressed after a 6-hour shift at 28 to 30 p.s.i.g. in 32 minutes, compared with 65 minutes by the table in use today. In contrast, the length of working period was progressively reduced as the working pressure increased, so that at 50 p.s.i.g. only a 4-hour period of work was recommended.

The Report also advised that new starters should work only half a shift on first entering compressed air, and that recording gauges should be used in locks. It appears to have been the practice when working at high pressure to have two shifts separated by a 3- or 4-hour interval, but it was pointed out by the Committee that this doubled the number of decompressions for a full shift and took more time, which had to be paid for. It was considered safer and more economical to have a single long shift in pressure and a prolonged decompression following it. Nevertheless, the Report contains suggested times of working periods for a system with two periods per shift which has now been abandoned in the United Kingdom but is in use elsewhere. In the State of New York in the United States of America, regulations are based on a two-period per shift system, but even there this system has been criticized as inadequate and contributing nothing to the safety of the workers (Duffner, 1962). In order to achieve satisfactory decompression, a three-stage procedure has also been used in New York, but it appears that the main reason for using 'split shifts' was pressure from the men's trade union.

The recommendations of the Institution of Civil Engineers were widely used until a new decompression table was compiled by the Compressed Air Committee of the Institution of Civil Engineers and the Ministry of Labour. Discussions with the Home Office had in fact begun in 1939 but were interrupted by the War. The new table was first used shortly after work in compressed air had begun in a tunnel under the River Tyne in 1948 (Paton and Walder, 1954) and was adopted in the present

TABLE II

THE BRITISH DECOMPRESSION TABLE (RULE 8) FROM THE WORK IN COMPRESSED AIR SPECIAL REGULATIONS, 1958.

Section 1	Section 2	Section 3															
'Basic pressure' more than (a) to not more than (b) lb. per sq. in. (a) (b)	Lowest permissible pressure in first two min. after starting decompression (lb. per sq. in.)	Fastest permissible reduction of pressure from figure in Section 2 to zero. Shortest permissible times (T) in minutes, and fastest permissible rates (R) in minutes per lb. for the working periods in the different columns.															
		'Working period': More than (c) but not more than (d) hours															
		More than 4 hours		(c) (d) 3½-4		(c) (d) 3-3½		(c) (d) 2½-3		(c) (d) 2-2½		(c) (d) 1½-2		(c) (a) 1-1½		(c) (d) ½-1	
		T Min. R Min. per lb.	T Min. R Min. per lb.	T Min. R Min. per lb.	T Min. R Min. per lb.	T Min. R Min. per lb.	T Min. R Min. per lb.	T Min. R Min. per lb.	T Min. R Min. per lb.	T Min. R Min. per lb.	T Min. R Min. per lb.	T Min. R Min. per lb.	T Min. R Min. per lb.	T Min. R Min. per lb.	T Min. R Min. per lb.	T Min. R Min. per lb.	T Min. R Min. per lb.
18-20	2	13	6½	6	5	2½	4	2	4	3	7	1½	2	1	2	1	½
20-22	3	24	8	14	11	3½	10	3½	9	3	11	2½	6	2	4	1	2
22-24	4	35	9	22	18	4½	16	4	14	3½	16	3	9	2	8	1½	3
24-26	5	46	9	32	28	5½	23	4½	19	4	16	3	12	2	14	2	4
26-28	6	56	9½	42	38	6½	31	5	25	4	22	3½	15	2½	11	2	5
28-30	7	65	9½	52	48	7	40	5½	32	4½	27	4	20	3	14	2	7
30-32	8	74	9½	61	57	7	50	6½	40	5	32	4	25	3	16	2	8
32-34	9	83	9	70	65	7	59	6½	49	5½	37	4	29	3	18	2	10
34-36	10	91	9	78	74	7½	68	7	58	6	43	4½	34	3½	21	2	11
36-38	11	98	9	87	82	7½	76	7	67	6	53	5	39	3½	26	2½	13
38-40	12	105	9	95	90	7½	84	7	75	6	62	5	44	3½	31	2½	14
40-42	13	113	9	102	98	7½	92	7	83	6½	70	5½	49	4	35	2½	16
42-44	14	120	8½	109	105	7½	99	7	91	6½	77	5½	55	4	39	3	18
44-46	15	127	8½	116	112	7½	107	7	99	6½	85	5½	63	4	44	3	20
46-48	16	133	8½	123	120	7½	115	7	106	6½	93	6	72	4½	48	3	22
48-50	17	139	8	130	126	7½	122	7	114	6½	101	6	80	4½	52	3	24

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Work in Compressed Air Special Regulations of the Ministry of Labour which came into force in 1958 (Table II).

Compressed air illness was made a notifiable condition under the Factories Act in 1938 and a prescribed disease qualifying for benefit under the National Insurance (Industrial Injuries) Act of 1946. Notified cases of decompression sickness are a better indication of the amount of work in compressed air being carried out in a particular year than they are of success in the control of the condition. It is usually only the more severe forms of decompression sickness which are notified, while chronic bone lesions have only recently been recognized widely and accurately recorded.

The Work in Compressed Air Special Regulations, 1958

Introduction of these Regulations had the effect of requiring every contractor employing men in compressed air above 18 p.s.i.g. to observe certain minimum standards of conduct and to follow a decompression procedure which, at the time, was felt to be the safest practicable method.

The Regulations describe in detail the arrangements required when work is being carried out in compressed air on a civil engineering contract. They specify the design and equipment necessary

for the man-lock in which workers will be compressed, and decompressed at the end of their shift. A competent lock attendant must be in charge and must keep a register in which is entered the time at which a man goes into the lock, the pressures in the working area at the beginning and end of his shift, and the time taken to decompress him. Compression and decompression must be carried out according to rules set out in the Regulations. Medical examination must be carried out by an officially 'Appointed Doctor' who must certify a man's fitness for work in compressed air within the three days before he starts work, unless he has been employed in the work within the previous three months. He must also be examined every four weeks if the air pressure at work is above 18 p.s.i.g., and after an upper respiratory tract infection. The employer must supply each man with a label to be worn next to the body showing that he is a compressed air worker and giving the address of the medical lock.

Each man has a personal Compressed Air Health Register in which a record of the examination is entered; this he should take to each employment in compressed air. The local hospital must be informed that compressed air work is being undertaken and given the name of the Appointed Doctor and the date of completion of compressed air operations.

Medical Selection and Supervision In deciding on a man's fitness for work the doctor excludes, among others, those with ear or sinus trouble and the obese. It is usual for a new worker to be taken into a medical lock by the attendant and instructed in clearing the pharyngo-tympanic tubes when air pressure is increased. A radiograph of the chest is not compulsory in civil engineering, although it is required by the diving regulations.

Decompression The procedure for decompression from pressures of 18 p.s.i.g. up to 50 p.s.i.g. is set out in a table in the Regulations which specifies the minimum decompression times allowed for various lengths of shift (Table II). At the end of a shift in compressed air the men enter the man-lock and the pressure is then lowered fairly rapidly to half the absolute pressure. If, for example, a man has worked for more than 4 hours at a pressure of 25 p.s.i.g. then the pressure can be dropped rapidly to 5 p.s.i.g. This figure is arrived at by adding gauge pressure and atmospheric pressure to obtain the absolute pressure, $25 + 15 = 40$ p.s.i., halving the result and subtracting atmospheric

pressure to give gauge pressure again, $\frac{40}{2} = 20$,

$20 - 15 = 5$ p.s.i.g. After this initial drop the pressure must be reduced to atmospheric pressure at a slow steady rate of 9 minutes per pound, and all this takes nearly an hour to complete.

Since the construction of the Tyne Pedestrian Tunnel in 1948 there have been several major compressed air undertakings covered by the 1958 Regulations, such as the Dartford Tunnel (1957-59) and the Blackwall Tunnel (1960-64) under the River Thames, the Clyde Tunnels (1958-63), the Tyne Road Tunnel (1963-66), and a number of power station cooling water tunnels.

The decompression table has also been used in other countries, often with modifications (Rose, 1962; Meesters, 1967), and modifications have already appeared in Britain (Whyte, 1967).

Evaluation of the 1958 Decompression Table

Sufficient use of the table has now been made to have produced a body of opinion critical of it and some other aspects of the Regulations. The bends and more serious forms of decompression sickness (Table III) can still occur much too frequently, and from time to time there are deaths following work in compressed air (Annual Report of Chief Inspector of Factories for 1963).

Paton and Walder (1954), in their investigation

TABLE III
FORMS OF DECOMPRESSION SICKNESS

Acute	
Type I	Mild limb pain ('the niggles') Severe limb pain ('the bends') Skin mottling and irritation ('the itches')
Type II	Vomiting with or without epigastric pain Vertigo ('the staggers') Tingling and numbness of limbs Paralysis or weakness of limbs Dyspnoea ('the chokes') Severe headache Visual defects, such as flashes of light or scotomata Angina, symptoms suggesting coronary dysfunction, irregular pulse Collapse, hypertension Coma Death
Chronic	Neurological and psychiatric forms, including paralysis Aseptic necrosis of bone —juxta-articular, head, neck, and shaft lesions

of decompression sickness at the first Tyne Tunnel, in which the bends rate was 0.87% of decompressions, did not comment critically on the decompression table itself. Duffner (1955) considered it faulty on the grounds that no two-stage procedure based on the usual calculations was adequate but that a three-stage procedure was much better.

Rose (1962) made a statistical survey of decompression sickness in caisson workers employed on the construction of Auckland Harbour Bridge in New Zealand, in which pressures from 27 to 49 p.s.i.g. were used in six steel caissons. There were no regulations governing work in compressed air in New Zealand so that the tables of the Institution of Civil Engineers (1936) and of the British 1958 Special Regulations were critically examined and compared. The latter table was eventually adopted for use at the Auckland Harbour Bridge but with modifications. Rose points out that the table is more straightforward than that of the Institution of Civil Engineers, but, although it involves a much longer period of decompression at lower working pressures, this margin narrows as pressure rises, until at or near the limit at the highest pressure of about 49 p.s.i.g. the decompression time was shorter by 2 minutes than the Institution of Civil Engineers' table. It was noticed that for shifts of over 4 hours the number of minutes per pound decreased as the pressure increased, e.g., at 30 to 32 p.s.i.g. working pressure it was $9\frac{1}{2}$ minutes but at 48 to 59 p.s.i.g.

it fell to 8 minutes. In contrast, the decompression times for working periods of less than 4 hours increased with the rise in pressure. Rose concluded that this apparent discrepancy arose from a desire to reduce the decompression time for shifts of more than 4 hours' duration to a figure acceptable in an industrial undertaking, and that presumably a margin of safety had been built into figures in the rest of the table which had been removed or reduced in the upper range of working pressures.

The decompression times for the Auckland Harbour Bridge contract were therefore increased in the 40 p.s.i.g. and over range to give a more linear relationship between the total decompression time and the working pressure than with either the table of the Institution of Civil Engineers or the British 1958 Regulations. The effects of these amendments introduced at Auckland were not remarkable since difficulties due to the variables which beset all investigations of this type, such as strikes and stoppages with consequent acclimatization effects, made it difficult to draw any firm conclusion. Paton (1963) points out that, although the 1958 table is the mathematical consequence of Haldane's theory, the experience at Auckland again raises doubts about its validity.

It is interesting that many contractors in Britain of their own initiative now routinely use decompression times longer than those required by the Regulations (Whyte, 1967), and this trend can be seen in other countries. Limitation of time spent at high pressures, as is enforced in some statutory decompression tables, is not usual in Britain.

The most striking change of opinion in Britain has been in respect of the maximum tissue exit pressure. In early discussions on this, an exit pressure of 15 p.s.i.g. was considered but was abandoned in favour of 18 p.s.i.g., which became the legal maximum (Paton, 1967). Although it was known that bends could occur from time to time at pressures between 15 and 18 p.s.i.g., it is only recently that civil engineers have felt that this was a serious matter and have in many cases spontaneously insisted on timed decompression for exposures in this range. The factor of acclimatization, to which Paton and Walder (1954) drew attention and which Rose (1962) underlined, has led in some contracts to the introduction of acclimatization shifts of shorter duration than the usual period for the first one or two shifts of new workers. There is, however, general dissatisfaction with the lack of progress in improving the safety of compressed air work, in the occasional and apparently uncontrollable fatalities, and, most recently, in the recognition of the frequent occurrence of aseptic necrosis of bone in caisson and tunnel workers.

The stimulus of the 1939-45 wartime experience of diving and high altitude flying (Fulton, 1948) (although the decompression of high altitude flying differs in important respects from decompression after work at high atmospheric pressure (Gribble, 1960)) brought the present post-Haldane era in which the validity of his 2:1 ratio has been seriously questioned over the whole range of working pressures in diving and civil engineering. It is no longer accepted that full saturation is complete after 5 hours' exposure, and it has furthermore been suggested that gas bubbles are always formed during decompression although they may be microscopic in size.

Acclimatization

It has been observed that in a group of men newly introduced to work in compressed air attacks of bends are very frequent, and in contracts with a high bends rate much of this may be due to a high labour turnover. New starters tend to leave the work after one or more attacks of bends so that a self-selected group is left. If these men are employed for a period in stable conditions of pressure, the bends rate may fall to a low level. This situation may be upset by various factors but mainly by alteration in pressure and by interruption of the work. A rise in pressure of a few pounds or stoppage of work for a week or two due to holidays or a strike is usually followed by a brisk crop of attacks of bends which keeps the medical locks full. In time, if the new pressure remains stable and work is regular, the number of attacks falls off again and may become negligible. This phenomenon of acclimatization was studied by Paton and Walder (1954) using the average daily bends rate per man in groups of men whose employment in compressed air at the first Tyne Tunnel could be followed for continuous periods of time. The longer the period of time chosen the smaller was the number of men available. It was found that there was a steady decline in bends rate from the first decompression up to the tenth to fifteenth day, the rate halving every 5 days, after which the variations were no more than random. Acclimatization appeared to be acquired rapidly and lost equally rapidly.

The mechanism underlying acclimatization is of the highest importance but its nature is completely obscure. Paton and Walder (1954) suggested that its time course resembles that in training people unaccustomed to physical exercise, in which stiffness of muscles occurs at first but later wears off with continued exercise. They postulated that unaccustomed exercise causes minor foci of muscle damage

and that these damaged areas may result in the sensation of stiffness and provide nuclei suitable for bubble formation. However, the cause of stiffness after exercise is still hypothetical and, although their theory may account for acclimatization, it does not explain the rapid loss of acclimatization when the working pressure rises abruptly.

The Use of Oxygen in Decompression

Inhalation of oxygen as a means to prevent decompression sickness or in therapeutic recompression has been used successfully (Jones, Crosson, Griffith, Sayers, Schrenk, and Levy, 1940) so that it is surprising that in civil engineering work it has rarely been exploited. Lack of experimental evidence as to its value and questions of cost have been given as the explanation for this (Behnke and Shaw, 1937). Oxygen has been used extensively in deep diving by highly trained individuals under carefully controlled conditions, but in civil engineering work contractors have been reluctant to use it because of the fire risk. Above about 25 p.s.i.g. there is a risk of oxygen poisoning so that in practice it has been restricted to the second half of decompression following the first drop of pressure to half the absolute pressure. Jones and others (1940) gave oxygen during the last 20 minutes of each regular decompression when the pressure was never more than 17 p.s.i.g. and usually below 15 p.s.i.g. Over three months, 3,884 decompressions were carried out with oxygen inhalation through individual face masks from a specially developed system. No bends occurred in any of the men on oxygen although the pressure range was 34 to 37½ p.s.i.g. and the total decompression time was only 30 to 48 minutes. In another 15,904 ordinary decompressions without oxygen there were 21 cases of decompression sickness (0.13%). In 11,196 decompressions with oxygen, but under less stringently controlled conditions than the first experiment, there were 23 cases of decompression sickness (0.21%), three of which were rather dubious and were therefore discounted. In 9,462 decompressions without oxygen there were 12 cases of decompression sickness (0.12%), all of which were moderate or mild whereas among the men not given oxygen five cases of decompression sickness were severe. It was concluded that with efficient oxygen administration, and proper supervision and education of workers in its use, the incidence of decompression sickness could be reduced and severe cases eliminated. However, the data show that the bends rate during this work was low even without oxygen inhalation. When men were in the

same decompression chamber as those using oxygen masks their bends rate tended to be low because of the relatively high oxygen content in the expired air of the men having oxygen. In Japan, Kita (1964) has reported a reduced prevalence of bends and a shortening of the decompression times by two-thirds to half in 87 decompressions from caisson work at 30 to 34 p.s.i.g. for periods of 3½ to 6 hours. Seventy men were given oxygen during the slow phase of decompression, when the lock pressure had dropped to under 25 p.s.i.g., to avoid poisoning. But the use of oxygen during the later stages of decompression to facilitate release of nitrogen may not be as effective as theoretical considerations suggest because of the associated circulatory changes (Hempleman, 1967). In an oxygen decompression experiment in Japan a man struck a match to smoke, which was forbidden. In the fire which followed, six men died and two others were seriously burnt. New oxygen breathing apparatus was devised which automatically releases expired air out of the lock (Nashimoto, 1967). It is clear that, if oxygen is to be used, discipline and safeguards will have to be of a high order to avoid serious fire accidents.

Respirators in Compressed Air

Fumes from an outbreak of fire in a pressurized tunnel may compel fire fighters to wear respirators. The detection of harmful gases and the use of breathing apparatus in compressed air has been studied recently by the American Bureau of Mines (Berger, Curry, Watson, and Pearce, 1964). Carbon monoxide is toxic only if the ratio of partial pressures of CO and O₂ is altered, but the effects of CO may become prominent on decompression so that it is necessary to treat poisoning with uncontaminated air at pressure. The effect of hydrogen sulphide on the central nervous system is enhanced as its partial pressure rises, and nitrogen dioxide also becomes more toxic.

Oxygen is unsafe above 26 p.s.i.g., and in a self-contained breathing apparatus it becomes dangerous after 30 minutes at 36 p.s.i.g. Gas masks may be difficult to use in pressure because of the increase in air resistance, and canister heating due to oxidation of carbon monoxide may be intolerable. Two types of breathing apparatus were tested. The first was the self-contained demand type using compressed air in which the rate of air withdrawal rises with increasing atmospheric pressure. Thus the operational life of the apparatus is inversely proportional to the pressure at which it is being used, and the fitting of oversize cylinders in order to prolong the time in an hyperbaric environment has

the disadvantage of increasing both bulk and weight. As the result of these factors the use of this apparatus is limited to work at about 15 p.s.i.g., and then for only a relatively short period. The second type was the self-contained recirculating oxygen breathing apparatus with CO₂ absorber (McCaa type). This normally supplies pure oxygen but its use was modified by the American Bureau of Mines to introduce and maintain enough nitrogen to lower the partial pressure of oxygen to a safe level. It was claimed that, with the modified technique, this apparatus could be used safely at pressures up to 45 p.s.i.g. for one hour.

Effects of Pressure on Response to Gas-Detecting Instruments

H₂S, CO, and NO₂ detectors are usually colorimetric tubes calibrated in terms of the volume concentration at atmospheric pressure. The maximum allowable concentrations (M.A.C.) are also expressed as volume concentrations, but both the detector responses and physiological effects depend directly on the weight of the substance. The weight per volume concentration increases with pressure, although the volume per volume is unchanged, so that for H₂S and NO₂ the instrument can be used without correction. For CO the M.A.C. applicable at pressure is obtained by dividing the reading by the absolute pressure in atmospheres. As H₂S in air interferes with the colour response for CO the H₂S must be absorbed first (Berger and others, 1964).

The Bends Rate

In a situation influenced by so many variables, such as length of shift, height of pressure, high labour turnover, acclimatization, physical and mental characteristics of the workers, differences in temperature and humidity, and disciplinary problems, it is difficult to find a suitable index by which to judge the success of a decompression procedure or to compare one contract with another. The bends rate, which is the number of attacks of bends treated by recompression as a percentage of the number of decompressions, is commonly used. While a bends rate of up to 2% has been considered acceptable in Britain, it has varied from 0.87% at the Tyne Pedestrian Tunnel (Paton and Walder, 1954) to 4% at a caisson in the River Thames (Lewis and Paton, 1957). The fallacies in using this measure make it of very doubtful value unless a number of factors can be allowed for. If the work has been carried out at relatively low pressure and

with a low labour turnover, the bends rate is likely to be low compared with a contract where the pressure is high and unacclimatized men are constantly being recruited. The basic information is suspect, as mild bends pain, called the niggles, is customarily accepted by the men as trivial, and even quite severe pain may be self-treated with aspirin and alcohol. Records of attacks of bends depend entirely on the men reporting them, on their being accepted as such by the medical lock attendant or doctor, and on being treated by recompression. A man with severe decompression sickness will of course almost always be recompressed.

A comparison of some of the published data for a number of compressed air contracts in different parts of the world over the last 50 years (Table I) illustrates many of the difficulties in drawing conclusions from such information. Important details, such as the total number of men employed, may not be given so that there is no indication of labour turnover, and the duration of maximum pressure is often not given. In earlier contracts in which decompression was frequently much more rapid than in later ones, and in which the shift lengths tended to be shorter, the bends rate was as good or better. Decanting appears to be associated with a high bends rate but the maximum pressure was also high.

The exceptionally low bends rate of 0.03% was reported from the New York Lincoln Tunnel (third tube) in 1955 (Koopstein and Schuman, 1957). In 138,034 decompressions there were only 44 cases of decompression sickness. The maximum pressure used was 34 p.s.i.g., but for 11 months of the work the pressure was only 15 p.s.i.g. At this pressure one case of decompression sickness occurred. A split shift system was used and a three-stage decompression. No detailed information is available about bone lesions in the men employed in this contract but large sums in compensation were paid in connexion with some 60 or so cases. Although many of these lesions may have related to work in previous contracts (Behnke, 1967), it is not clear whether any of the men employed had bone radiographs prior to being employed or periodic radiographic examinations during and after the work. No simple relationship between bone necrosis and bends has been shown so far (Rózsahegyi and Fried, 1963; Decompression Sickness Panel Report, 1966).

Aseptic Necrosis of Bone in Compressed Air Workers

Until recently, aseptic necrosis of bone in compressed air workers has been reported mainly in

single patients or in very small series, and usually in men presenting with symptoms affecting a major joint. It is now clear that if these lesions are actively sought by systematic radiological examinations a high prevalence of symptomless lesions is found (Fournier, Jullien, and Léandri, 1965; Decompression Sickness Panel Report, 1966). At the Clyde Tunnels, about 20% of compressed air workers remaining at the end of the contract had a bone lesion or lesions, although only 4% of these lesions were juxta-articular and likely to cause disability.

This investigation followed a less extensive one at the Dartford Tunnel (Golding and others, 1960) where symptomless bone lesions were also found. The proportion of men with bone lesions at the Clyde Tunnels was a conservative estimate, as only 18% of the men at risk throughout the whole contract could be radiographed. Some of the lesions called doubtful would now, in the light of further experience of early radiological changes and of hindsight, be regarded as areas of aseptic necrosis. Former compressed air workers from the Clyde Tunnels, who were not included in the survey, have attended Glasgow hospitals with symptoms from juxta-articular bone lesions (Davidson, 1964) and some have been detected subsequently at other contracts. At the Clyde it was found that the presence of a bone lesion could be related to the length of time at compressed air work and to exposure to pressures higher than 30 p.s.i.g., but these two factors could not be separated. As at Dartford, there was no close link between attacks of bends and subsequent bone necrosis.

Some of the most interesting findings in the Decompression Sickness Panel's report arose from the histological changes in the left humerus and right femur of a compressed air worker who had died during treatment for decompression sickness (Bennison, Catton, and Fryer, 1965). An area of necrosis can revascularize extensively, and in a juxta-articular lesion it is when this process is incomplete that collapse of the articular surface may occur and cause disability. It is possible that many bone lesions heal spontaneously before the deposition of new bone on dead trabeculae makes them radiologically detectable.

The Cause of Bone Necrosis It is almost always assumed that bone necrosis has the same pathogenesis as the bends, namely bubbles of nitrogen, and that these cause infarction by forming intravascularly or extravascularly and interrupting the blood supply. A further assumption appears to be that bone has a poor blood supply and, because

of this and the presence of fat in marrow, it is particularly susceptible to damage from gas bubbles.

It is difficult to find in textbooks or journals descriptions of infarction of bone in the sense of visible obstruction to a vessel or end artery, and in fact the blood supply to bone appears to be good. Although an area such as the head of the femur appears to be exceptionally vulnerable to ischaemic damage, one of the striking features of aseptic necrosis of bone in compressed air workers is that it may also arise in the shafts of long bones. Further, aseptic necrosis shows a marked tendency to symmetry so that both shoulders or both hips, or all four joints, are often affected, and lesions round the knee joints are frequently symmetrical. Bone infarction with necrotic areas comparable to those found in compressed air workers has not been produced in experimental animals even though the pressures used and the decompression times have been grossly dangerous by comparison with the conditions in tunnels or caissons.

There is therefore no proof that gas bubbles cause the bone lesions, and other possible mechanisms must be considered. It is worth considering how bone might differ from other tissues on compression and decompression, because of its rigid structure. When the body is compressed the change in pressure is immediately transmitted equally throughout the soft tissues. Is it possible that in certain areas of long bones, because of its combination of comparatively rigid tissue and softer tissue, transient pressure differences occur which produce necrosis by a direct process?

The whole emphasis now in the study of decompression in civil engineering has shifted to the elucidation of the cause of bone necrosis and its prevention, and it is felt that the solution of this problem may also contribute to or solve that of other forms of decompression sickness.

Lung Cysts and Type II Decompression Sickness

It has been suggested that type II decompression sickness (Table III) is caused by gas embolism due to air entering the circulation from without rather than to the formation of gas bubbles by their release from supersaturated blood or tissues. At present, clinical distinction between type II decompression sickness and air embolism is often difficult or impossible in life but, as treatment is similar for the two conditions, the concept still remains a useful one, certainly in the civil engineering context.

During the construction of the Dartford Tunnel, two men had attacks of severe decompression

sickness (type II) and both men were found to have cysts in the lungs (Golding and others, 1960). A further example occurred in a man working on the Clyde Tunnel (Walder, 1966). Other cases have been reported by Liebow, Stark, Vogel, and Schaefer (1959) and by Collins (1962), who described multiple thin-walled lung cysts which appeared in the previously normal radiograph of a 20-year-old man following exposure to a pressure of 50 p.s.i.g. There were gross neurological symptoms after decompression.

Walder (1963; 1966) suggests that the blocking of a bronchus by a mucosal plug or by oedema while a man was at pressure might result in air-trapping in part of a lung so that on decompression the trapped air would expand to form a cyst, or might rupture a blood vessel and cause air embolism. Walder induced histamine bronchospasm in guinea-pigs exposed to compressed air and showed that during decompression bubbles appeared in the circulation and many of the animals died. Further studies on pig lungs, which are similar in structure to human lungs, show that cyst formation and air embolism are possible. If there is gas supersaturation air embolism could also initiate further bubbling.

Routine lung radiography of compressed air workers has unfortunately yielded little further evidence. At the Tyne Tunnel, for example, only one lung cyst was discovered in 183 radiographs of the chest. Even this cyst was overlooked in the initial film until it was seen in a film of the shoulder joint taken much later. The man had meanwhile undergone regular compression and decompression as a tunnel worker without any serious consequences. It is possible that the mechanism which Walder postulates does in fact occur and is the basis of type II decompression sickness but that actual lung cyst formation is not essential or that the cysts so formed are small and do not show on a radiograph.

Neurological Complications of Decompression

The study and recording of central nervous system lesions, other than gross paralysis, and of psychiatric illness as long-term chronic effects of work in compressed air has been almost entirely neglected. Rózsahégyi (1959) has described and classified neurological forms of decompression sickness in men who worked on the building of the Budapest underground railway. He distinguishes four types of neurological damage: multiple lesions in the whole central nervous system, beginning with acute collapse or a Ménière's syndrome, but

rarely recovering completely; multiple lesions in the cerebrum and upper brain stem which may present acutely with coma but are often followed by a vegetative neurosis; lesions in the medulla oblongata, pons, and cerebellum, also producing a type of Ménière's syndrome; and spinal lesions leading to tetraplegia, impotence, vegetative neurosis, and personality changes. Latent damage to the cerebrum may be demonstrable by electroencephalography (Rózsahégyi, 1967). It is to be hoped that Rózsahégyi's work will stimulate further detailed studies of central nervous and psychiatric symptoms in compressed air workers.

Effects on Cerebral Function

Some engineers who carry out measurements and calculations in compressed air have concluded that accuracy and ability are impaired even at moderate pressure. Experimental card sorting at normal atmospheric pressure and at pressures of 2 to 3½ atmospheres absolute was carried out by a group of compressed air workers at Tilbury under the auspices of the Decompression Sickness Panel (Poulton, Carpenter, and Catton, 1963). The results suggested that performance was affected by compressed air at 2 atmospheres absolute, but only while the task was being learnt. Compressed air had little effect if the subjects had practised beforehand. If this is so, then it has serious implications for an unfamiliar emergency in compressed air, and the possibility of impaired judgment of surgeons working in hyperbaric chambers. However, when the same experiment was repeated at the Royal Naval Physiological Laboratory no evidence of a narcotic effect at 2 atmospheres absolute was found, and it is suggested that the findings of Poulton and his colleagues were due to factors other than nitrogen or inert gas narcosis (Bennett, 1966; Bennett, Poulton, Carpenter, and Catton, 1967). Further experimental work on the problem is obviously necessary to settle this point.

Cardiac Effects

Observations on electrocardiographic (E.C.G.) changes in compressed air workers do not appear to have been made in the United Kingdom, and even on the continent of Europe they are not numerous. In a review of the continental literature, including observations of his own, Zannini (1967) describes E.C.G. abnormalities due to compressed air work. These are pulmonary P waves, notched P waves, depression of the S-T tract, flattening or inversion of T waves in leads 2 and 3, and lengthen-

ing of the PQ tract. These, he thinks, may be due to the effect of bubbles in the pulmonary circulation.

He also mentions E.C.G. changes which occur only at high pressure and regress on decompression. They may be due to factors such as changes in autonomic tone, increased oxygen tension, variation in diaphragm level, and transitory changes due to the work load. He considers that electrocardiography should be a routine part of the pre-employment and periodic examinations of compressed air workers and of all cases of decompression sickness.

Blood Changes

Haemoconcentration has been found as a complication of severe decompression sickness, particularly following exposure to altitude (Behnke, 1967), but it may also occur in tunnel or caisson workers (Bennison and others, 1965; Catton, 1967). Blood changes can be anticipated when post-decompression shock occurs and may be associated with air embolism and perhaps also with fat and marrow embolism (Behnke, 1967). Catton (1967) studied various blood samples from compressed air workers employed at 35 to 43 p.s.i.g. but found no diagnostic change associated with the bends and concluded that clinical examination was more informative. One man with type II decompression sickness (paralysis) had no unusual blood changes during recompression treatment.

The relation of the surface tension of human serum and susceptibility to decompression sickness determined by exposing subjects to a standard test of 37,000 feet for 2 hours was studied by Walder (1948). There was a significant difference between the mean static surface tension of susceptible subjects and non-susceptible subjects who had a high serum surface tension. This suggested that raising the surface tension might afford some protection against decompression sickness, and preliminary experiments on susceptible subjects after ingestion of normal saline was followed by a temporary rise in static surface tension and freedom from decompression sickness. This brief report suggests a line of enquiry which might be pursued further in compressed air workers.

Treatment of Decompression Sickness

The Work in Compressed Air Special Regulations, 1958 do not refer specifically to the treatment of decompression sickness other than to make the provision of a medical lock a requirement. There is no statutory method of treatment, so it is

carried out according to the judgment of the lock attendant and the doctor, and can be suited to the needs of the individual patient and his symptoms. The empirical procedures of Griffiths (1960; 1967), which have circulated widely, have generally been the basis of treatment of decompression sickness in Britain. Griffiths believes that, by using the lowest pressure which will completely relieve the symptoms, further absorption of gas is kept to a minimum. He classifies decompression sickness into two types—type I, or the bends, in which there are limb pains without other symptoms, and type II, in which there may be a great variety of symptoms and signs varying from neurological or cardiovascular syndromes to collapse, shock, or coma (Table III).

For type I decompression sickness Griffiths originally recommended recompression either to 3 lb. (0.2 kg.) above the maximum working pressure or more slowly until the pain had gone. After waiting for 15 to 30 minutes decompression is carried out by a modified regulation schedule in which the pressure is dropped rapidly to half the absolute pressure plus 2 lb. and the slow phase is prolonged by taking 15 minutes for each remaining pound of pressure.

Type II decompression sickness necessitates immediate recompression to working pressure or higher if symptoms are not relieved, even up to the working limit of the medical lock, which is usually 50 p.s.i.g. The man is kept at the effective pressure for half an hour after signs and symptoms have disappeared, after which pressure is reduced by one pound every 15 minutes to 15 p.s.i.g., at which it is maintained for 4 hours. From this point there is a gradual reduction of pressure at the rate of 1 lb. every half hour with 'soaks' of an hour each at 8, 4, and 2 p.s.i.g. Treatment can last for 24 hours or more but is usually completely successful.

Similar methods were used at the Tyne Tunnel (Paton and Walder, 1954), where men with bends were recompressed to working pressure plus 3 lb. and then held for either 10 minutes or 20 minutes, after which they were decompressed as for an exposure to a working pressure of over 4 hours according to the Regulation table. In severe cases men were recompressed to working pressure and held until 10 minutes after they had recovered from symptoms. After this the pressure was lowered at a decreasing rate from 1 p.s.i. in 3 minutes to 1 p.s.i. in 8 minutes, according to the height of pressure, and provision was made for slower rates if symptoms returned. Duffner (1955) compared these methods unfavourably with the United States Navy procedure for divers after which less than 2% of patients treated have a recurrence of their symptoms.

In treating type I decompression sickness, about 20% of patients may require further recompression and this has led Griffiths recently to suggest modifying the treatment by taking the initial pressure drop to half gauge pressure rather than to half absolute pressure. In this way the number of men requiring further recompression after treatment has been much reduced.

American practice (Lanphier, 1966) has favoured the use of the United States Navy Treatment Tables (*Diving Manual*, 1963) which take no account of the pressure at which the patient has worked. These tables are, of course, designed for the complications of deep diving and may involve taking the patient to a pressure of 6 atmospheres absolute (90 p.s.i.) but Lanphier recognizes the need for procedures suited to compressed air workers as opposed to divers. He quotes Griffiths' methods in full and concludes that they can be used 'with good expectations of success'. With the U.S. Navy Treatment Tables Lanphier states that oxygen is now considered obligatory during the final stages, but, although he recommends the use of oxygen in low pressure recompression, it is still considered experimental.

Some of the theoretical considerations involved in the treatment of decompression sickness are discussed by Hempleman (1967), who points out that although it is rare for a tunnel worker who does not often work at over 40 p.s.i.g. to have to be recompressed beyond 45 p.s.i.g. to relieve his symptoms, divers commonly require recompression to pressures higher than 45 p.s.i.g. after dives to depths at a pressure greater than this. Thus there is sometimes a connexion between the original exposure pressure and the therapeutic pressure.

It has been suggested that there is a plasma deficit in animals and humans with decompression sickness and that this may be sufficiently large to cause death (Cockett, Nakamura, and Kado, 1965; Cockett and Nakamura, 1964). Experiments on dogs by these workers indicated that plasma replacement with dextran but without recompression was effective in treating moderate decompression sickness and shock. They also used hypothermia to extend the time interval between the attack and the application of recompression. They conclude, however, that recompression is still the treatment of choice but that infusion of dextran will correct the plasma deficit prior to recompression.

Occasionally in deep sea divers there is a paradoxical response to recompression in which deterioration in the patient's condition occurs instead of relief (Barnard and Elliott, 1966). This has also been seen in a compressed air worker who

had pain in the tibia (Griffiths, personal communication).

Post-Mortem Examination of Fatalities

There is still much to be learnt about the pathogenesis of the occasional fatalities which follow decompression. Pathologists without special knowledge of the problem could contribute significantly by recording the presence or absence of a number of important features. A detailed description of the points to be looked for has been drawn up for the M.R.C. Decompression Sickness Panel (Fryer, D. I., personal communication). Radiography of the thorax should be carried out before the necropsy is begun to detect a lung cyst which might otherwise be damaged or destroyed before it was recognized, and to show whether there is gas in the heart or great vessels. Removal of the humeri and femora may help to elucidate the cause and natural history of aseptic necrosis of bone. Some areas of recent bone damage may not be demonstrable by radiography (Decompression Sickness Panel Report, 1966), and the histopathology of these is important.

The brain and spinal cord should be displayed and examined carefully for intravascular bubbles and removed whole for fixation in formalin and subsequent examination. The heart should be opened under water to show any gas in the chambers. Gas bubbles should also be sought throughout the body and their presence recorded separately. Patent atrial septum should also be noted, and haemoconcentration looked for.

The Decompression Sickness Panel

High altitude flying and deep sea diving are the subject of intensive study by full-time experts at the research establishments of the Royal Air Force Institute of Aviation Medicine at Farnborough and the Royal Naval Physiological Laboratory at Alverstoke.

The study of industrial decompression sickness has been almost entirely neglected in the United Kingdom since Haldane's original work (Paton and Walder, 1954). There is no group of full-time research workers primarily concerned with civil engineering decompression problems and able to carry out a long-term programme of research comparable to institutions which exist in some continental countries. The only official body seriously engaged in research in this field is the Decompression Sickness Panel of the Medical Research Council's Occupational Health Committee. Although nearly all the members of the

Panel are concerned for only part of their professional time with the problems of work in compressed air, the presence on it of academic, naval, air force, and clinical members, and of many general practitioners acting as physicians to civil engineering contracts, enables the Panel to collate information and stimulate research into compressed air problems.

Over a period of nearly 20 years members of the Panel have been responsible for investigations into a number of compressed air projects, including important studies of decompression sickness at the first Tyne Tunnel (Paton and Walder, 1954) and at the Dartford Tunnel (Golding and others, 1960); investigations into mental skill in compressed air (Poulton, Carpenter, and Catton, 1963); and investigations into aseptic necrosis of bone in tunnellers working in compressed air (Bennison and others, 1965; M.R.C. Decompression Sickness Panel, 1966). A Registry of Compressed Air Workers was set up at the University of Newcastle upon Tyne in 1964, and a trial of new decompression tables is currently being undertaken at two compressed air contracts. These tables (Blackpool Trial Tables, 1966) are based on a decreasing critical ratio as the pressure to which the men are exposed rises, instead of Haldane's fixed 2:1 ratio. For an 8-hour shift the decompression times are substantially longer than the Regulation times but are still shorter than in some schedules in use abroad (Table IV). This trial is primarily an attempt to reduce or control bone necrosis, and the long-term radiographic follow-up of compressed air workers is an essential part of the experiment. The civil engineering contractors concerned, the Factory Inspectorate, and the Civil Engineering Research Association are all co-operating with the Panel in this trial, and use of the tables in some other countries may contribute additional data.

International Co-operation

Information on the success of decompression schedules in other countries is often difficult to find or to assess. A small international working party held at the Ciba Foundation in London in October 1965 has helped to clarify this situation. The proceedings of this working party have now been published (*Decompression of Compressed Air Workers in Civil Engineering*, Oriel Press, Newcastle upon Tyne).

Future Development

Although the Work in Compressed Air Special Regulations, 1958 were a major advance in the control of compressed air work they have proved disappointing in practice. Unfortunately, regulations, although necessary, may have the effect of inhibiting any experimentation, and this can deter attempts at improvement where the procedure is not wholly effective. A contractor is understandably unwilling to vary a procedure laid down by law, and particularly to shorten decompression times should this be required by a scientific investigation, in case this should lay the firm open to civil action should anything go wrong. However, the Regulations allow the Chief Inspector of Factories to grant a certificate of exemption from their requirements in certain circumstances, and this procedure is being applied in the use of the Blackpool Trial Tables.

Many people concerned with compressed air work feel that all the provisions of the Regulations should apply to pressures of 15 p.s.i.g. upwards, instead of 18 p.s.i.g. as at present, that acclimatization shifts should be a requirement, that the times spent at high pressures should be specifically

TABLE IV
DECOMPRESSION PROCEDURES CURRENTLY IN USE IN GREAT BRITAIN AND THE UNITED STATES OF AMERICA

	Pressure p.s.i.g.	Shift Length (hours)	Decompression Procedure	Total Time (min.)
Great Britain				
1958 Regulations	not exceeding 24	5	Quickly to 4 p.s.i.g., then to 0 p.s.i.g. in 35 min.	about 37
Royal Navy Diving Tables	24	5	19 min. at 13 p.s.i.g., 40 min. at 8.7 p.s.i.g., 45 min. at 4.3 p.s.i.g.	about 107
Blackpool Trial Tables	24	5	30 min. at 8 p.s.i.g.; 60 min. at 4 p.s.i.g.	about 94
United States of America				
Washington D.C., 1966	24	5	To 8 p.s.i.g. in 3 min.; to 4 p.s.i.g. in 4 min.; to 0 p.s.i.g. in 110 min.	117
Seattle, Washington	25	6	Intermediate details not known	125

limited, and that compulsory radiological examination of major joints before and during employment should be introduced.

Some improvements in the general requirements in the Regulations could also be made to bring the general level of conduct of compressed air operations by contractors up to that now observed by the most experienced firms. In particular, recording barographs should be required on all manlocks.

Medical Supervision Under the 1958 Regulations there must be an Appointed Doctor to carry out the required medical examinations. In an emergency any duly qualified medical practitioner can be called upon, but it is not stated what qualifications or training he should have for this work. The doctor's function is not related to the use of the medical lock, for which the only requirement is that it shall be constantly under the charge of a person trained in its use. Supervision of recompression and other treatment, and responsibility for the medical attendants and first-aid services are not at present included as part of the doctor's duties. In practice, contractors usually arrange with the Factory Inspectorate that the Appointed Doctor for the contract will also act as its medical officer. Such appointments are almost always given to local general practitioners as a part-time post.

This system can work very well but it has unsatisfactory aspects. The great majority of doctors have no experience of compressed air problems and are ill-equipped to deal with them. No formal training is available, even if the practitioner had time to take it. The contrast between this situation and the specially trained medical staff of the Navy is very great. In other countries, full-time doctors are frequently appointed to compressed airwork contracts, and future Regulations in Britain might well specify trained medical officers at least for large contracts employing say 20 men or more in compressed air at any one time. For smaller numbers of men, a short period of formal training for the doctor should be required. The main problem of a full-time medical appointment is the short-term projects and sporadic nature of compressed airwork, and the change in location from contract to contract which would tend to deter most doctors from making a career of this work. A solution might be to arrange secondment of naval medical staff to such contracts at cost to the contractor. A start might be made in ensuring full medical supervision of compressed air work if provision for a full-time doctor, fit to enter compressed air, were included in the specification for the contract when it is put out to tender. Formal

training for lock keepers and medical attendants should also be included as a requirement in the Regulations.

Developments which may markedly affect future compressed air work are the use of analogue computers to control decompression (Stubbs and Kidd, 1967), decompression with oxygen, the use of ultrasonics to detect the formation of bubbles in tissues during decompression (Walder, 1967), and investigations into the rate of inert gas uptake and elimination in tissues and the aetiology of inert gas narcosis which are being investigated at the Royal Naval Physiological Laboratory.

The tendency to use longer decompression times should lead to the provision of more comfortable and better equipped locks to which men can be rapidly transferred from the man-lock by decanting, that is, by a fast decompression and recompression within a few minutes.

In contrast to this trend, Hills (1966) has proposed a new hypothesis, based on the empirical schedules of pearl divers off the Australian coast, which allows a saving of about one third of the decompression time for a dive of 40 minutes' duration in 150 feet of water. Hills, from experimental evidence, postulates an inherent unsaturation of normal tissues, random nucleation for gas phase separation, and random cavitations at liquid-liquid interfaces. Further experimental work based on his theories is being carried out, but at present the implications for deep diving and, in particular, for work in tunnels and caissons remain to be assessed.

One desirable change which might follow these developments is the replacement of the present casual and unstable labour force by a relatively small but highly trained group of specialist miners similar to the professional divers, capable of using mechanized equipment rather than muscular force, and employed under close medical and engineering supervision.

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