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Compressed Air Illness

W. D. M. PATON

and D. N. WALDER

LONDON: HER MAJESTY'S STATIONERY OFFICE

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PREFACE

MEN engaged on tunnelling operations or other kinds of engineering construction work which have to be carried out in compressed air instead of at atmospheric pressure are exposed to certain physiological risks. To safeguard those who work under these conditions the Ministry of Labour have laid down precautionary measures in their safety regulations for the engineering industry, and in 1946 the Council were asked by the Institution of Civil Engineers to appoint a representative to serve on their Compressed Air Committee which was considering how these regulations might be revised.

It became apparent that little was known about the true distribution of compressed air illness or the causes and conditions of its appearance in particular individuals. Serious cases involving disability were notified to the authorities and received careful attention, but the milder type (commonly called "the bends"), which takes the form of temporary pain in the joints and represents by far the commonest manifestation of the disease, had never been fully studied. It was thus difficult to frame the requisite regulations, and there was clearly a need for an investigation which would provide information about the incidence and course of decompression sickness and give an opportunity for exploring new ways of reducing the incidence or relieving the condition once it was incurred.

Large-scale tunnelling operations are rare, but in 1948 work was started on a tunnel under the River Tyne between Jarrow and Howdon. With the consent and helpful co-operation of the contractors, Charles Brand and Son, Limited, Dr. W. D. M. Paton, of the Council's staff, and Dr. D. N. Walder, of the Department of Surgery, Durham University and formerly of the Department of Physiology, Bristol University, were able to make observations on the 376 men who worked in compressed air during the construction of the tunnel. Some 40,000 decompressions were performed according to standardized procedures, and out of this total there were 350 cases of decompression sickness, only three being serious. The attacks occurred almost exclusively among men working regular shifts in compressed air, and only rarely among other workers exposed to pressure at irregular intervals while engaged on lighter tasks. The most important conditioning factor appeared to be the duration of employment. Thus, the incidence of bends was high among new shift workers, giving an almost epidemic character to the disease whenever new labour was recruited, but it fell to comparatively negligible levels after some months of employment. The decline was due in part to "natural selection" among the working population, but still more to an "acclimatization" to the work. This finding has prompted the suggestion that it might be an advantage for men to be given some preliminary training on the surface in tasks of the same nature as those to be performed later in compressed air.

It is clear that, however carefully decompression is handled, temporary discomfort may frequently occur and may affect almost every shift worker. Any steps which might help to eliminate it should therefore be carefully considered.

MEDICAL RESEARCH COUNCIL,
38 Old Queen Street,
London, S.W.1

May 5th, 1954

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PLATE I

Photograph of shift workers at working face on the Howdon site, in the 10 ft. 6 in. pedestrian tunnel (Ring No. 97). Air pressure 34–37 lb. per. sq. in., on November 4, 1948. (Reproduced by kind permission of Charles

AN INVESTIGATION INTO COMPRESSED AIR ILLNESS DURING THE CONSTRUCTION OF THE TYNE TUNNEL, 1948-50

by

W. D. M. PATON, M.A., D.M. and D. N. WALDER, M.D.

Introduction

THE consequences of work in compressed air have been recognized for more than a hundred years. They consist chiefly of the condition termed "decompression sickness", the symptoms of which may range from a pain in the joints or limbs (the "bends"), causing no permanent disability and passing off either spontaneously or after recompression, to serious damage to the central nervous system. It is only cases of the latter type, however, which, by causing loss of working ability, have hitherto come to be notified. In the construction of the Tyne Tunnel in 1948–50, only 3 cases were so notified, although there were 350 cases of bends. If this ratio of roughly 1 severe case to 100 cases of the milder condition of bends holds generally, a very rough estimate of the total yearly bends incidence may be obtained from the Annual Reports of the Chief Inspector of Factories, summarized in Table 1. From these figures a yearly incidence of 2,000 to 5,000 cases of bends might be expected, but the ratio used is based on so small a number of notifications that it may well be inaccurate.

TABLE 1

Cases of compression illness notified to Chief Inspector of Factories

Year	1939	1940–7	1948	1949	1950
No. of cases	12	6	28	46	46

Another means of estimating the annual incidence is to assume that it is generally true, as it was in this investigation, that there are roughly as many cases of bends as there are men employed in compressed air. A major undertaking of this sort would absorb a large part of the compressed air workers of the country and it is unlikely that the total number involved in such work exceeds 1,000 men per year. This yields a lower figure, 1,000 bends per year, for the annual incidence. It is probable that no more accurate estimate than this can be made.

It is clear, however, that a large number of cases of bends occurs every year greatly exceeding the number of cases of compressed air illness notified. Although such bends involve little more than temporary discomfort, even this is undesirable and must obviously be a deterrent to recruitment of the labour force. Furthermore, among the severer cases a regular proportion die or suffer permanent disability. Despite these facts, the study of industrial decompression sickness has been almost entirely neglected in this country, apart from Haldane's pioneer work (see Haldane and Priestley, 1935), and the intense activity (now abandoned) resulting from the stimulus of war. Even in other countries few systematic observations have been made (Levy, 1922; Boulton, 1942).

The need for such an investigation, apart from any academic interest, was strongly felt when revision of the Regulations for Work in Compressed Air was undertaken by the Ministry of Labour (1945) conjointly with the Compressed Air Committee of the Institution of Civil Engineers; it was found that some of the simplest questions of fact about such illness in the industrial sphere could not be answered. It was particularly with this in view that the present research was undertaken; but possibilities for more fundamental investigations and for improving prevention and control of compressed air illness were also borne in mind as far as possible.

The most important deficiency in previous reports is that they have analysed not the whole population at risk but only those men who proved to be susceptible to compressed air illness, making it difficult, for instance, to draw any conclusions as to variations of susceptibility with age. Nor have they been unambiguous about the precise decompression procedure used. The chance of an investigation free from these defects was presented by the proposed construction under compressed air of two tunnels under the Tyne between Howdon and Jarrow. The consent of the contractors, Charles Brand and Son Limited, was readily secured to its initiation, and we are greatly indebted to them for their sustained co-operation, without which the investigation would have been impossible.

The details of our methods are described below, but one particular point deserves special mention. The labour force contained a substantial proportion of the individualist and unorganized workers who so often enter compressed air work as miners' labourers or in similar grades, attracted by the high wages. With such a working population, the simplest "experiment" would have met grave difficulties and required continuous supervision. Accordingly the idea of such experiments was soon abandoned, and only a few studies of the physiology of individual workers were made. Similarly only very simple measurements and records were taken, but particular care was exercised that these should be accurate and complete. The greatest part of our work was the collection and analysis of these records, relying upon the ordinary circumstances and progress of an undertaking in compressed air to provide us with the material we needed.

I. Material and Methods

THE TYNE TUNNEL PROJECT

For many years, an increasing volume of traffic has been ferried across the Tyne between Howdon and Jarrow, associated with the expanding shipbuilding trade, until it became obvious that a tunnel could more adequately deal with this traffic. Originally three tunnels were planned, for road traffic, cyclists and pedestrians respectively, but the exigencies of post-war economy have forbidden the construction of the road-traffic tunnel at present.

Construction was started on the Jarrow side, where the first sod was cut on October 4, 1947. (See Fig. 1, at the back of the Report, and photograph of working face, Plate I.) A vertical shaft was sunk through clay and shale to a depth of about 70 ft. Work on the horizontal 10 ft. 6 in. tunnel for pedestrians then proceeded in shale until June 29, 1948, but only so far as could be done without compressed air, since this site was too small for the erection of compressed air plant. On the Howdon side, where there were waterbearing sands and gravels overlying sandstone, a similar vertical shaft was started in October 1947. After some delay in manufacturing the air-locks, compressed air was first used in the Howdon shaft on June 2, 1948, and the shaft was completed on July 15. Horizontal tunnelling then began from this side at a pressure varying with tidal and other conditions from 32 to 42 lb. per sq. in. Junction with the Jarrow boring was made on May 14, 1949, the air pressure being maintained by means of a bulkhead previously erected in the Jarrow end of the tunnel. An air-lock was also constructed in this tunnel near the Howdon shaft to regulate the air pressure until caulking was completed. Pressure was gradually lowered and was finally released on January 13, 1950.

As soon as the 10 ft. 6 in. tunnel was well started, the boring of the larger 12 ft. 0 in. tunnel for cyclists began in October, 1948. This tunnel proceeded more slowly, and work was held up between March and June, 1949, during which time a shield was erected, on account of the difficult nature of the ground encountered. During the following period, except towards the end when the small tunnel was being tested for leaks, the pressure was the same in the large as in the small tunnel. On January 12 pressure fell below 15 lb. per sq. in., and the following day the large tunnel borings from the two sides were joined and pressure was finally released.

The pedestrians' tunnel is reached by escalators at either side of the river and for these inclined tunnels were constructed. The escalator tunnel on the Jarrow side was completed without the use of compressed air. At Howdon, work on the escalator tunnel began in April, 1948 and compressed air was used from December 9, 1948, onwards, starting at 8 lb. per sq. in.; it was not until March 10, 1949, that pressures exceeding 15 lb. per sq. in. were required. Thereafter the pressure gradually rose as the tunnel was driven deeper, reaching the same pressure as in the horizontal tunnels on June 24, 1949.

Work in compressed air, therefore, took place in four phases:

1. Sinking the Howdon shaft.
2. Driving the 10 ft. 6 in. tunnel from the Howdon side, with later locking off and caulking at a lower pressure than the rest of the working.
3. Driving the 12 ft. tunnel starting later than the 10 ft. 6 in. tunnel, but proceeding simultaneously with reduction of pressure during the last few weeks.
4. Sinking the Howdon escalator tunnel.

POPULATION AT RISK AND WORKING SHIFTS

Altogether a total of 376 individuals were exposed to compressed air during the construction of the tunnels. This population can be divided into two main groups, those working in shifts (177), and those entering and leaving the tunnels to perform tasks, the duration of which did not coincide with that of the regular shifts (199). The shift workers varied in number according to the number of working faces, the amount of caulking being carried out, etc. But, as a rule, there were at each face:

1 leading miner,
2 miners,
3 labourers,
1 caulker,
1 runner.

The shift duration (i.e. the time spent at the working face and excluding decompression time) was 6 hours until October 3, 1948, when it was lengthened to 8 hours. During a period of difficult working on the 12 ft. face (from March to June, 1949), the shift duration was temporarily shortened to 4 hours.

TABLE 2

Decompression times for varying periods of exposure in compressed air (reproduced from the Report of the Institution of Civil Engineers' Committee on Regulations for the Guidance of Engineers and Contractors for Work carried out in Compressed Air, 1936)

(1) Pressure when entering man-lock from working chamber (More than (*a*) to not more than (*b*), in lbs. per square inch)	(2) Lowest permissible pressure in first two minutes after starting decompression (lbs. per square inch)	(3) Fastest permissible reduction of pressure from figure, if any, in column (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 ranges A. to F.											
		A More than 6 hours		B More than 4 but not more than 6 hours		C More than 3 but not more than 4 hours		D More than 2 but not more than 3 hours		E More than 1 but not more than 2 hours		F Not more than one hour	
		Minutes	Minutes per lb.	Minutes	Minutes per lb.	Minutes	Minutes per lb.	Minutes	Minutes per lb.	Minutes	Minutes per lb.	Minutes	Minutes per lb.
(1) (*a*) to (*b*)	(2)	T	R	T	R	T	R	T	R	T	R	T	R
0–22													
22–24	4	10	2½	8	2	4	1	—	—	—	—	—	—
24–25	5	20	4	15	3	8	1½	5	1	—	—	—	—
25–26	5	—	—	15	3	8	1½	5	1	—	—	—	—
26–28	6	—	—	27	4½	21	3½	12	2	4½	¾	—	—
28–30	7	—	—	35	5	28	4	21	3	7	1	—	—
30–32	8	—	—	44	5½	36	4½	28	3½	12	1½	—	—
32–34	9	—	—	50	5½	45	5	36	4	18	2	4	½
34–36	10	—	—	60	6	55	5½	40	4	20	2	5	½
36–38	11	—	—	72	6½	66	6	50	4½	27	2½	8	¾
38–40	12	—	—	84	7	78	6½	60	5	30	2½	12	1
40–42	13	—	—	—	—	85	6½	65	5	33	2½	13	1
42–44	14	—	—	—	—	98	7	77	5½	42	3	14	1
44–46	15	—	—	—	—	165	7	82	5½	45	3	15	1
46–48	16	—	—	—	—	120	7½	88	5½	48	3	20	1¼
48–50	17	—	—	—	—	127	7½	102	6	59	3½	25	1½

The remainder of the population at work included the engineers, contractor's agents, foremen, electricians, and others, who were normally exposed for considerably briefer periods than the shift workers, but who often entered the compressed air several times a day. This portion of the population did not change very much as the work proceeded; but there was an appreciable, steady turnover among the shift workers, which will be discussed in some detail later.

DECOMPRESSION PROCEDURES

At the very beginning of the work, decompression was carried out in accordance with the table published in 1936 for the Institution of Civil Engineers (Table 2). As soon, however, as the proposed revised table (compiled by G. C. C. Damant and W. D. M. Paton for the Compressed Air Committee of the Institution of Civil Engineers and Ministry of Labour) became available, this

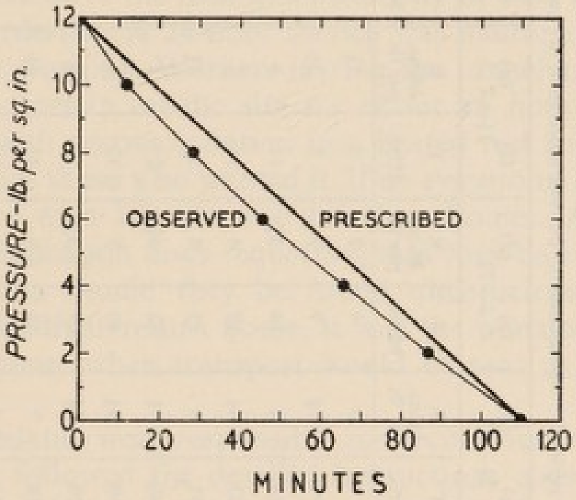

FIG. 2. Comparison between rate of fall of pressure within the decompression chamber, using an orifice of fixed size, and the rate of fall prescribed in the Regulations (Ministry of Labour and National Service, 1951).

procedure was followed (Table 3). No special allowance was made for the fluctuations of working pressure necessitated by the tidal rise and fall of the river level. These fluctuations were sometimes of the order of 6 to 8 lb. The decompression was always done as though the workers concerned had spent the whole of their exposure at the pressure prevailing at the end of the exposure.

The decompression was always under the control of a full-time lock-keeper. Since the technique of decompression was unusual, the following brief description is given. The initial rapid reduction of pressure, required by the decompression tables mentioned above, was obtained in the usual way by widely opening the outlet tap of the man-lock. Instead of then regulating the succeeding slow fall of pressure by manual manipulation of the outlet tap, a disc with a fixed orifice was screwed into its mouth by the lock-keeper, thus limiting the rate of fall of pressure. Several discs were made and calibrated to give the necessary range of rates of fall. The advantages of this method were that the occupants of this decompression chamber were unable to speed the rate of decompression, although they could slow it if required, and a less degree of skill and integrity was required of the lock-keeper. This device was suggested by H. E. Whyte (Contractor's Engineer). The rate of fall of pressure is not precisely linear by such an arrangement (Fig. 2), is liable to slight alterations by changing temperature and humidity, is affected slightly by the number of men in the lock,

TABLE 3

Decompression Table (reproduced from the Revised Preliminary Draft of Regulations as to Safety, Health and Welfare in Work of Engineering Construction, Ministry of Labour and National Service, 1951)

Section 1	Section 2	Section 3																
" *Basic pressure* " more than (*a*) to not more than (*b*) lbs. per square inch	Lowest permissible pressure in first two mins. after starting decompression (lbs. per square inch)	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*) 3½—4 (*d*)		(*c*) 3—3½ (*d*)		(*c*) 2½—3 (*d*)		(*c*) 2—2½ (*d*)		(*c*) 1½—2 (*d*)		(*c*) 1—1½ (*d*)		(*c*) ½—1 (*d*)		(*c*) 0—½ (*d*)
(*a*) (*b*)		T Mins.	R Mins. per lb.	T Mins.	R Mins. per lb.	T Mins.	R Mins. per lb.	T Mins.	R Mins. per lb.	T Mins.	R Mins. per lb.	T Mins.	R Mins. per lb.	T Mins.	R Mins. per lb.	T Mins.	R Mins. per lb.	T Mins.	R Mins. per lb.
18—20	2	13	6½	6	3	5	2½	4	2	4	2	3	1½	2	1	2	1	1	½
20—22	3	24	8	14	4½	11	3½	10	3½	9	3	7	2½	6	2	4	1	2	½
22—24	4	35	9	22	5½	18	4½	16	4	14	3½	11	3	9	2	6	1½	3	1
24—26	5	46	9	32	6½	28	5½	23	4½	19	4	16	3	12	2	8	1½	4	1
26—28	6	56	9½	42	7	38	6½	31	5	25	4	22	3½	15	2½	11	2	5	1
28—30	7	65	9½	52	7½	48	7	40	5½	32	4½	27	4	20	3	14	2	7	1
30—32	8	74	9½	61	7½	57	7	50	6½	40	5	32	4	25	3	16	2	8	1
32—34	9	83	9	70	8	65	7	59	6½	49	5½	37	4	29	3	18	2	10	1
34—36	10	91	9	78	8	74	7½	68	7	58	6	43	4½	34	3½	21	2	11	1
36—38	11	98	9	87	8	82	7½	76	7	67	6	53	5	39	3½	26	2½	13	1
38—40	12	105	9	95	8	90	7½	84	7	75	6	62	5	44	3½	31	2½	16	1½
40—42	13	113	9	102	8	98	7½	92	7	83	6½	70	5½	49	4	35	2½	18	1½
42—44	14	120	8½	109	8	105	7½	99	7	91	6½	77	5½	55	4	39	3	20	1½
44—46	15	127	8½	116	8	112	7½	107	7	99	6½	85	5½	63	4	44	3	22	1½
46—48	16	133	8½	123	8	120	7½	115	7	106	6½	93	6	72	4½	48	3	24	1½
48—50	17	139	8	130	8	126	7½	122	7	114	6½	101	6	80	4½	52	3	26	1½

and is usually too slow over the last few pounds of pressure. In general, however, it appeared to be a satisfactory method. A recording barograph enabled errors of decompression to be investigated in retrospect.

Each lock-keeper kept a log of names of men entering or leaving the tunnel through his lock, together with the working pressure at the time of leaving, the duration of their stay in the "air" and the total time taken for decompression. His only other task was to organize the food and hot drinks supplied to the men about to be decompressed.

RECOMPRESSION PROCEDURES

A medical recompression chamber (or medical lock) was available on the Howdon site for the treatment of workmen suffering from bends. This lock consisted of two compartments separated by a bulkhead and door. This enabled workmen to enter and leave the lock independently of each other. It was in the charge of medical orderlies. A 24-hour service was maintained throughout the duration of pressure working. Workers leaving the tunnel at the end of a shift were encouraged to remain on the site for about an hour. During this time they were provided with accommodation in a heated rest room, where tea and food were available for those who wanted it. If no symptoms of bends developed during this hour the men left the site for their homes. All compressed air workers carried identification discs requesting that they be sent back to the site as quickly as possible should they be found unconscious. When workmen developed bends after their return home, it was the practice for them to send a message by telephone, when transport would be sent to bring them to the medical lock.

The medical attendants were responsible for recompressing the bends cases, and in general they followed the detailed instructions given them by us. The pressure in the medical lock was recorded on a barograph, so that a close check could be kept and assurance made that they followed our instructions.

At first it was the practice to treat cases by rapidly increasing the medical-lock pressure until the symptoms disappeared, and then to lower the pressure gradually without any initial rapid fall. The procedure used was much the same as the special procedure for serious cases which will be mentioned later (p. 8). Since this method seemed unnecessarily long for treatment of ordinary cases of bends, two other more rapid methods of recompression for such cases were substituted which differed from each other only in that, with one method, compression to just above the working pressure was maintained twice as long as with the other method. These procedures were used alternatively. They were as follows:

Method A Compress to working pressure + 3 lb.

Hold 10 minutes.

Decompress rapidly to pressure laid down in decompression tables and then slowly as laid down in tables for exposure of more than 4 hours to the working pressure (usually for 90 to 100 minutes).

Method B Compress to working pressure + 3 lb.

Hold 20 minutes.

Decompress rapidly to pressure laid down in decompression tables and then slowly as laid down in tables for exposure of more than 4 hours to the working pressure (usually for 90 to 100 minutes).

TABLE 4

Rules for treatment of severe cases of decompression sickness

(1) Any case in which there is loss of consciousness, inability to walk, numbness, pains in chest or abdomen, or other serious symptoms must be treated by the *Special Procedure* below.

(2) Only those cases which are typical "bends" should be treated by the usual recompression methods. Other cases, if in doubt, must be treated by the *Special Procedure*.

(3) The *Special Procedure* must be used repeatedly on a case for so long as he is relieved by pressure. Only if a case does not recover after exposure to full pressure for an hour can attempts to cure him be abandoned. He should then be very carefully decompressed (see para. 3 of *Special Procedure*) to avoid making him any worse. Under no circumstances must the pressure be lowered while a case still has symptoms which are removable by raising the pressure.

(4) Care must be taken that the case has really recovered, and that numbness, for example, does not return without its being noticed. The case should walk about at intervals during the decompression to make sure of his being normal.

SPECIAL PROCEDURE

(1) Compress to working pressure, and hold at this until 10 minutes after the case has recovered from his symptoms.

(2) Lower the pressure at the following rates:

between 40 and 30 lb. per sq. in., 1 lb. per sq. in. in 3 minutes;
between 30 and 15 lb. per sq. in., 1 lb. per sq. in. in 5 minutes;
between 15 and 0 lb. per sq. in., 1 lb. per sq. in. in 8 minutes.

(3) If symptoms return, compress immediately to working pressure again, hold this for 10 minutes, and lower the pressure at the following rates:

between 40 and 30 lb. per sq. in., 1 lb. per sq. in. in 4 minutes;
between 30 and 15 lb. per sq. in., 1 lb. per sq. in. in 6 minutes;
between 15 and 0 lb. per sq. in., 1 lb. per sq. in. in 10 minutes.

4) If symptoms still return, compress again to working pressure for 10 minutes longer and repeat (3). Continue this process as long as necessary, making the decompression still slower if need be.

For severe cases the orderlies were instructed to use the special procedure of Table 4; the table explains the circumstances under which it was to be employed.

Results. In ordinary bends, all three methods proved equally effective, relieving 75 per cent of subjects with one recompression and 90 per cent with two recompressions. Since Method A is the most economical in time, it is probably the best for general use.

THE LOCKS

The main locks were situated at the top of the Howdon shaft, one for the entry and exit of men, and one on the opposite side of the shaft for "muck". The "muck-lock" was not used for decompression of men except on rare (and unauthorized) occasions. The man-lock was fitted with seats to hold about 15 men, and measured 6 ft. 3 in. in diameter by 21 ft. in length (total volume, 615 cu. ft.). We have calculated that, even during the longest decompression with 15 occupants, the amount of carbon dioxide in the air of the lock can never have risen above 0·3 per cent of an atmosphere.

During the rapid phase of decompression there was a temperature drop of approximately 15° C. with 100 per cent relative humidity (as measured with a whirling psychrometer) accompanied by intense mist formation; this gave rise to severe chilling of the occupants, which it was thought might predispose to bends. Consequently electric heaters of a total wattage of 2,000 were installed in the chamber in an attempt to minimize this sudden fall in temperature; on September 29, 1948, the total wattage was increased to 4,000. These measures were not required during the summer, when, indeed, it was sometimes necessary to play hoses on the lock to maintain some degree of temperature control.

A second pair of locks was installed and operated during the construction of the Howdon escalator, and here again one was used as a man-lock and one as a muck-lock. The same procedure and precautions were observed in regard to this man-lock as with the main man-lock.

An inter-tunnel lock was constructed at the Howdon end of the 10 ft. 6 in. tunnel when the completion of this part of the project made it convenient to reduce the pressure there. Men working in this part of the tunnel spent the major proportion of their shift at the lower pressure, although they were exposed for a brief time to the higher pressure.

SOURCES OF DATA

Compression books. These contained records of the times of every occasion that any man entered compressed air, the time he left it and the time taken for decompression.

Barograph charts. These were available for the pressures of the main tunnel, the pressures of the decompression chamber, and the pressures of the medical lock (or recompression chamber). These records contained a complete description of all the pressure changes at these three points.

Decompression sickness case records. Every case of bends was interviewed by the medical orderly, and in addition cases of special interest were interviewed by one of us. Details about the attack were recorded on a special proforma (Table 5).

Employment sheets of the working force. Ages were noted on the employment sheets.

Miscellaneous. Certain miscellaneous and unsystematic information was available about weights, physical health and fluid intake of certain men, and some information about humidity and temperature in the shaft, tunnels and decompression locks.

TABLE 5

Decompression sickness case record

No.

Name *Age* *Wt.* *Occupation*

Date of attack *Working pressure* lb. per sq. in.

Duration of exposure to full pressure: from a.m. to a.m.
p.m. p.m.

Time taken to decompress: from a.m. to a.m.
p.m. p.m.

Symptoms: Pain, aching, burning, gripping, stabbing, tingling, in hand, wrist, forearm, elbow, upper arm, shoulder, foot, ankle, leg, thigh, hip. {Cross out words that do not apply. Insert L. or R. to indicate left or right side of body.}

Other symptoms:

When did pain begin? at a.m.
p.m.

First recompression: Started at: a.m. Complete a.m.
p.m. p.m.

At full pressure:	lb. per sq. in. for	min.
Then pressure lowered to:	lb. per sq. in. for	min.
” ” ” ”	lb. per sq. in. for	min.

At what pressure during recompression did relief (if any) begin to be felt? lb. sq. in.

At what pressure during recompression was relief complete? lb. per sq. in.

Details of subsequent recompressions (if necessary for this attack).

For each recompression, record (1) time when symptoms returned and what the symptoms were; (2) time when recompressions took place; (3) how the recompression was done; (4) time when relief was felt.

II. Analysis of the Overall Sickness Rate

TOTAL AND AVERAGE BENDS INCIDENCE

By the overall sickness rate is meant the ratio of attacks of bends sufficiently severe to require recompression to all compressions carried out during the period when the working pressure in the tunnel was greater than 18 lb. per sq. in. In this time a total of 40,000 compressions were performed, involving

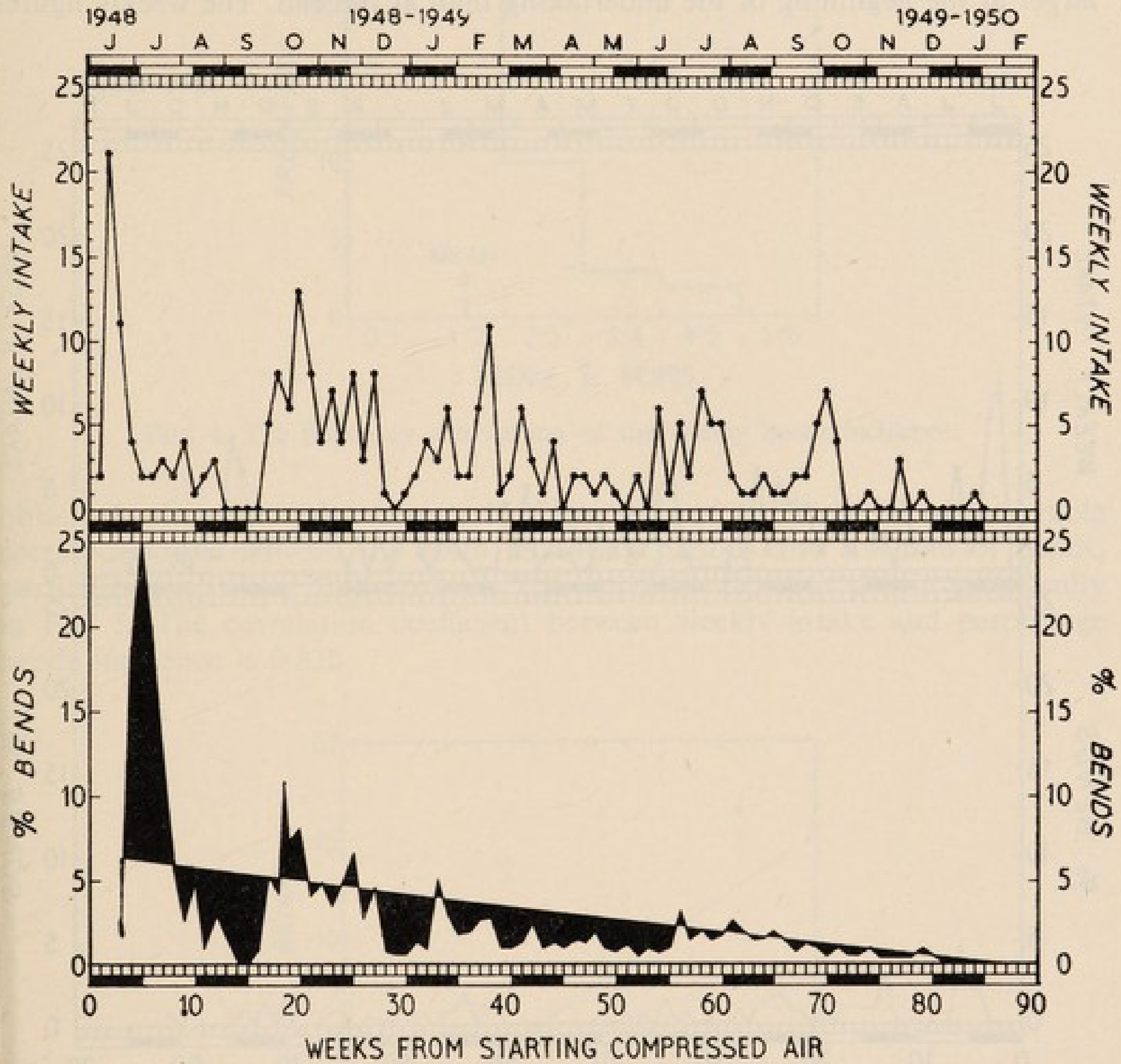

FIG. 3a. Weekly intake of shift workers (above), and bends incidence (below), related to time in weeks from beginning operations in compressed air. The line in the lower graph represents the calculated regression line of bends incidence on time. (Bends incidence = 2·806–0·0759 × (weeks–46·79)

376 men. There was a total number of 350 cases of decompression sickness in 187 of these men. This yields an overall rate of 0·87 per cent. This is a very satisfactory record; 2 per cent bends is generally regarded as the upper limit of permissible bends incidence.

In the whole period, three serious cases of bends occurred, of which two resulted in permanent spinal paralysis. The latter will be described later (p. 39).

WEEKLY INCIDENCE

Fig. 3a (for shift workers) and Fig. 3b (for other workers) show the weekly incidence of these cases of bends. It is marked by two features: a considerable fluctuation from week to week and a tendency to diminish as the work progressed. In Fig. 3a the gradual fall in the incidence of bends is significant; the regression line of bends incidence on time has been drawn, and shows that the incidence fell roughly by 0·3 per cent every month.

The fluctuations of incidence of bends round this steady fall continue throughout the period during which compressed air was used, although they were much larger at the beginning of the undertaking than at the end. The weekly figures

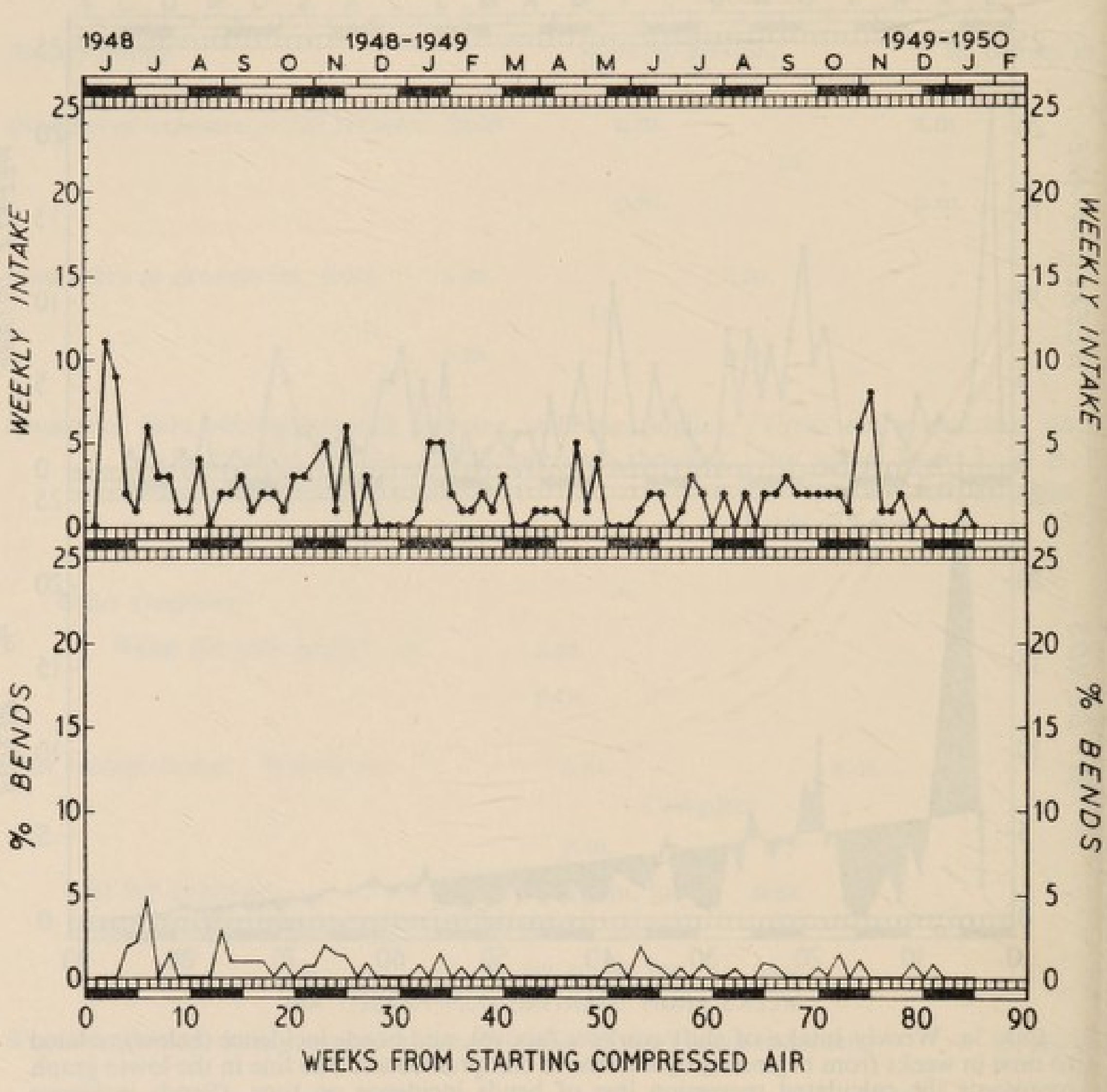

Fig. 3b. As Fig. 3a, substituting non-shift workers in place of shift workers.

for shift workers have been analysed from January, 1949, with respect to the frequency with which the incidence fell in the ranges 0–1, 1–2, 2–3, 3–4 or 4–5 per cent, and the resulting frequency distribution is shown in Fig. 4. These fluctuations can be shown to be largely due to chance, so that over this period the variations in incidence from week to week are attributable chiefly to the random operation of the innumerable factors partaking to some degree in the genesis of bends. But random variations alone are highly unlikely to give rise, for an overall mean of 2 per cent bends in 100 to 300 exposures per week, to fluctuations higher than 6 per cent. We have therefore sought other explanations for the much larger changes occurring earlier in the undertaking.

Factors influencing Fluctuations in Incidence

Influx of new labour. It was noticed that many cases of bends occurred in recent recruits. Accordingly figures for the weekly intake of new labour were

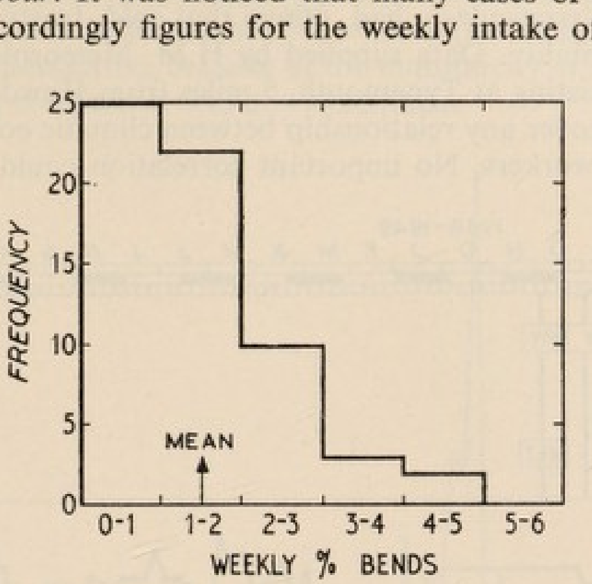

FIG. 4. The frequency distribution of the weekly bends incidence.

obtained; these are also shown in Figs. 3a and b. There is a remarkable correspondence between the main recruiting periods and the rate of bends, particularly with the shift workers. This correspondence is shown graphically in Fig. 5. The correlation coefficient between weekly intake and percentage bends incidence is 0·836.

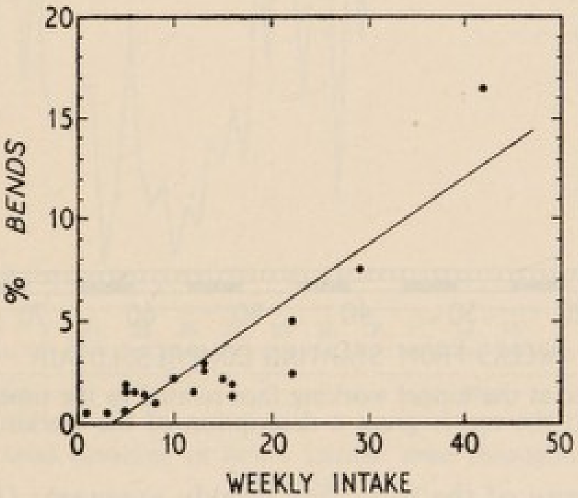

FIG. 5. The relation of weekly bends incidence among shift workers to the weekly intake; the line represents the regression of bends incidence on intake. (Percentage of bends = 0·308 × (weekly intake) — 1·011, r = 0·836)

Average working pressure. Considerable fluctuations in pressure occurred over the whole course of the project. We have related the weekly bends incidence with the average working pressure. Fig. 6 shows the course of the average pressure each week. Apart from the usual observation that bends did not occur unless the pressure was over 18 lb. per sq. in., there was no correspondence between fluctuations in bends incidence and fluctuations in working pressure.

The prevailing weather. Many of the miners expressed the belief that local weather conditions affected their susceptibility to bends, some claiming that damp weather was particularly bad, others that cold, frosty weather caused an increase in susceptibility. Data supplied by H.M. Meteorological Office of the daily conditions existing at Tynemouth, 5 miles from Howdon, have been used in an effort to discover any relationship between climatic conditions and bends incidence in shift workers. No important correlation could be found between

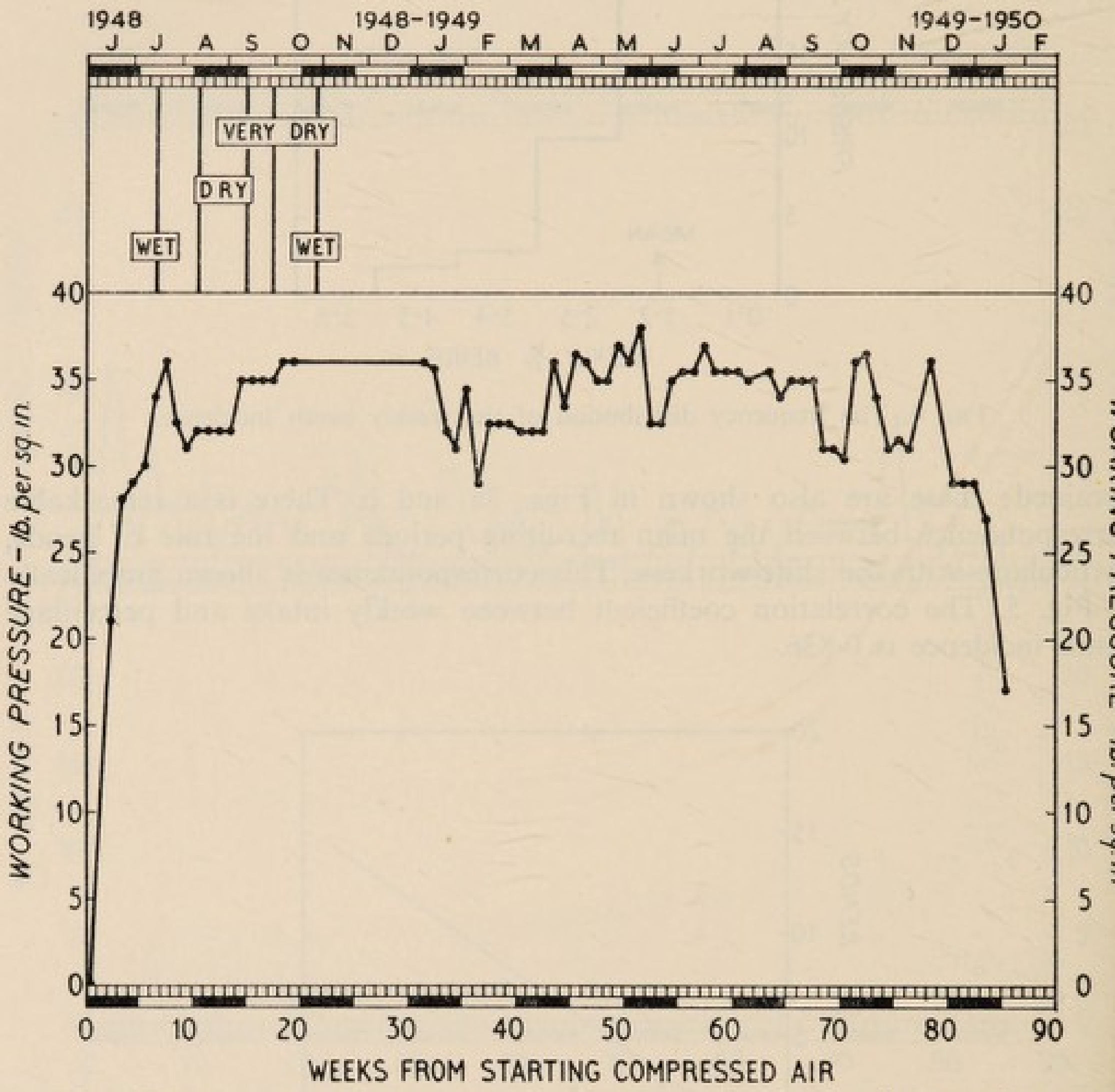

FIG. 6. The pressure at the tunnel working face related to the time from starting work in compressed air. At the top is given a description of the working conditions during the earlier months.

the bends rate and any of the following weekly averages: (1) rainfall; (2) sunshine; (3) humidity; (4) wind velocity; (5) barometric pressure; (6) maximum temperature; (7) minimum temperature. The data obtained are represented graphically in Figs. 7, 8 and 9, and should be compared with the bends incidence figures of Fig. 3a.

Conditions of work. At times, working conditions were far worse than at other periods. Sometimes the working face was dry, at other times the men worked in 9 to 12 in. of water (see Fig. 6). Similarly, the awkwardness and laboriousness varied considerably. From Fig. 1 (at the back of the Report) an indication of the rate of progress of the construction of the tunnel can be obtained. If the rate of progress or the times of dry or wet working in Fig. 6

are compared with the weekly incidence of bends in Fig. 3a it can be seen that there is no obvious relationship between the slower periods, marked by difficult conditions, and the bends rate. No statistical analysis has been attempted since it proved impracticable, because of the multiplicity of factors involved, to define the working conditions with any exactitude.

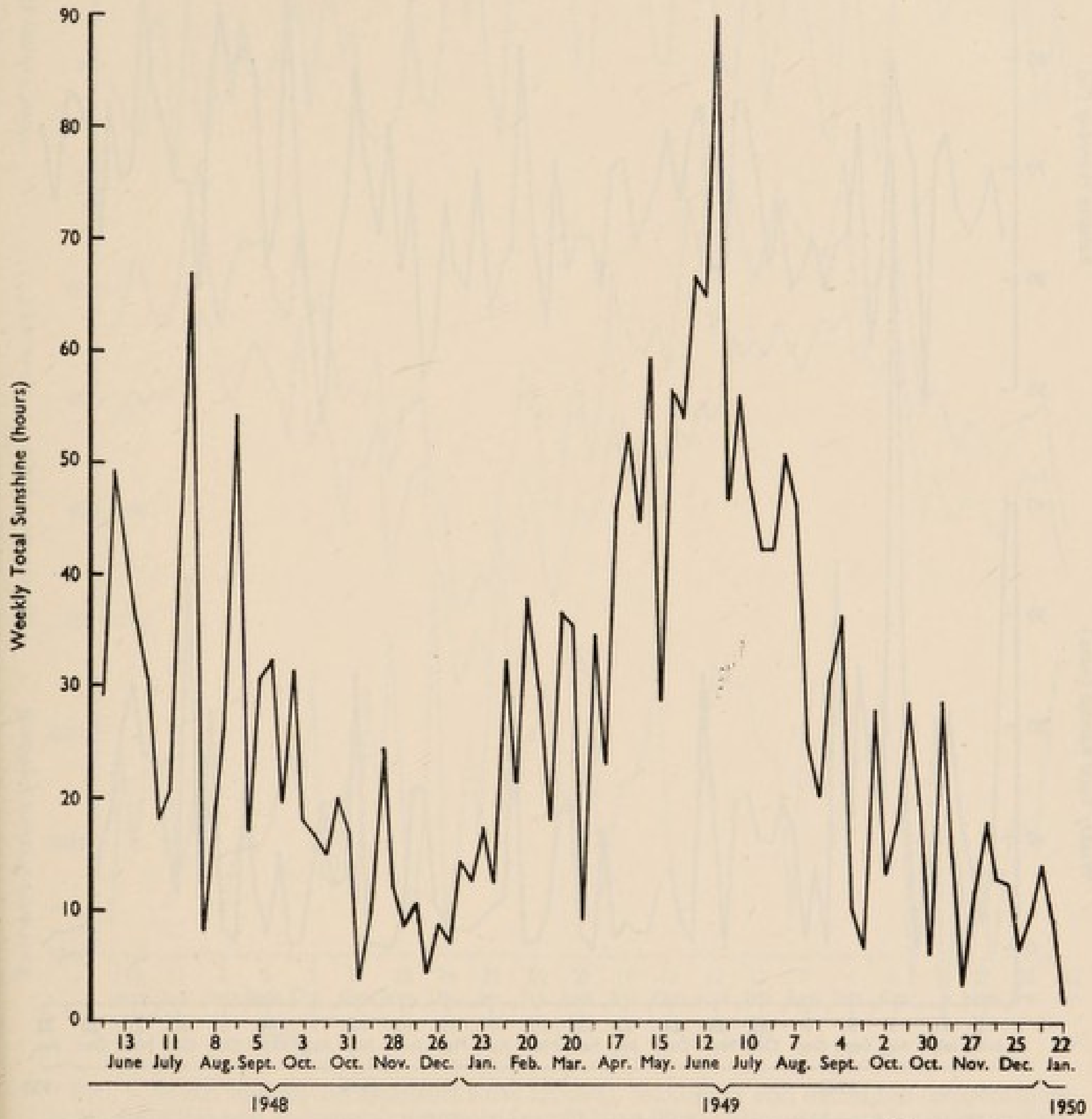

FIG. 7. Weekly total sunshine in hours against time throughout the investigation (Tynemouth).

Faulty decompression procedure. We tested the possibility that the incidence of bends may be related to the accuracy with which the decompression was carried out. This investigation was limited to the shift workers. It is not sufficient to know the total time of decompression; the precision with which the fall in pressure followed that laid down in the regulations also influences the effectiveness of the procedure. Accordingly, by means of a transparent template, the contour of the barograph record of every shift decompression was compared with the calculated contour for a perfect decompression according to the tables in use. Divergences were recorded as positive or negative according to whether the pressure during decompression was greater or less than it should have been.

The maximum values of the divergences were then grouped, as shown in Fig. 10a, p. 18 and Table 6a, where they are related to the bends incidence for each group. A similar analysis was made for deviations from the prescribed decompression time (Table 6b).

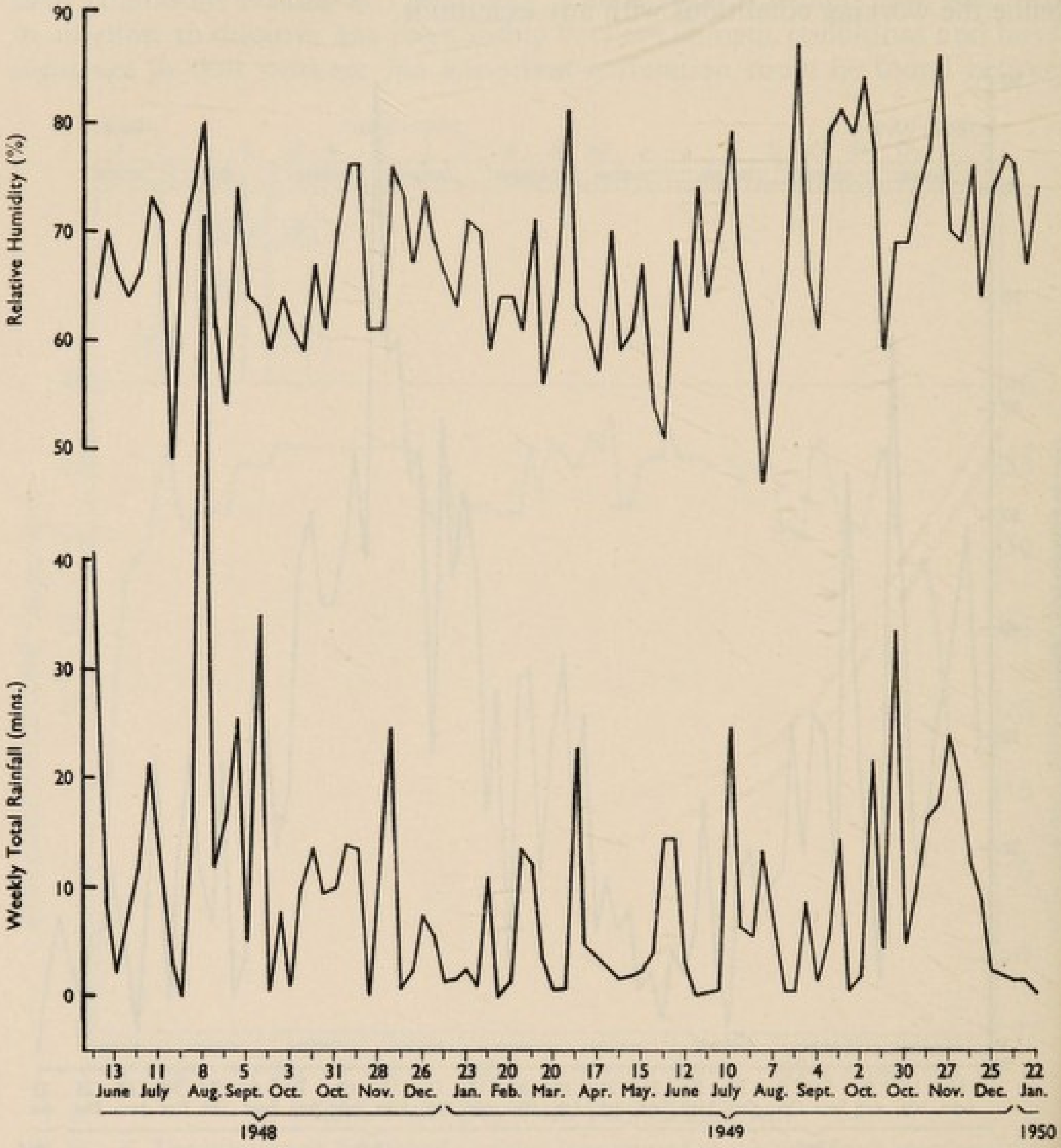

FIG. 8. Relative humidity (above) and weekly total rainfall in minutes (below) throughout the investigation (Tynemouth).

TABLE 6a

Effect of faulty decompression on bends rate

(*a*) *Divergence from prescribed rate of fall of pressure*

Divergence	More than 2·5 lb. negative	0·5–2·5 lb. negative	0·5 lb. negative–0·5 lb. positive	0·5–2·5 lb. positive
No. of exposures	626	4,486	2,291	1,572
No. of bends ..	18	84	32	18
Bends % ..	2·87	1·87	1·39	1·14

$\chi^2 = 10{\cdot}17, P<0{\cdot}01$

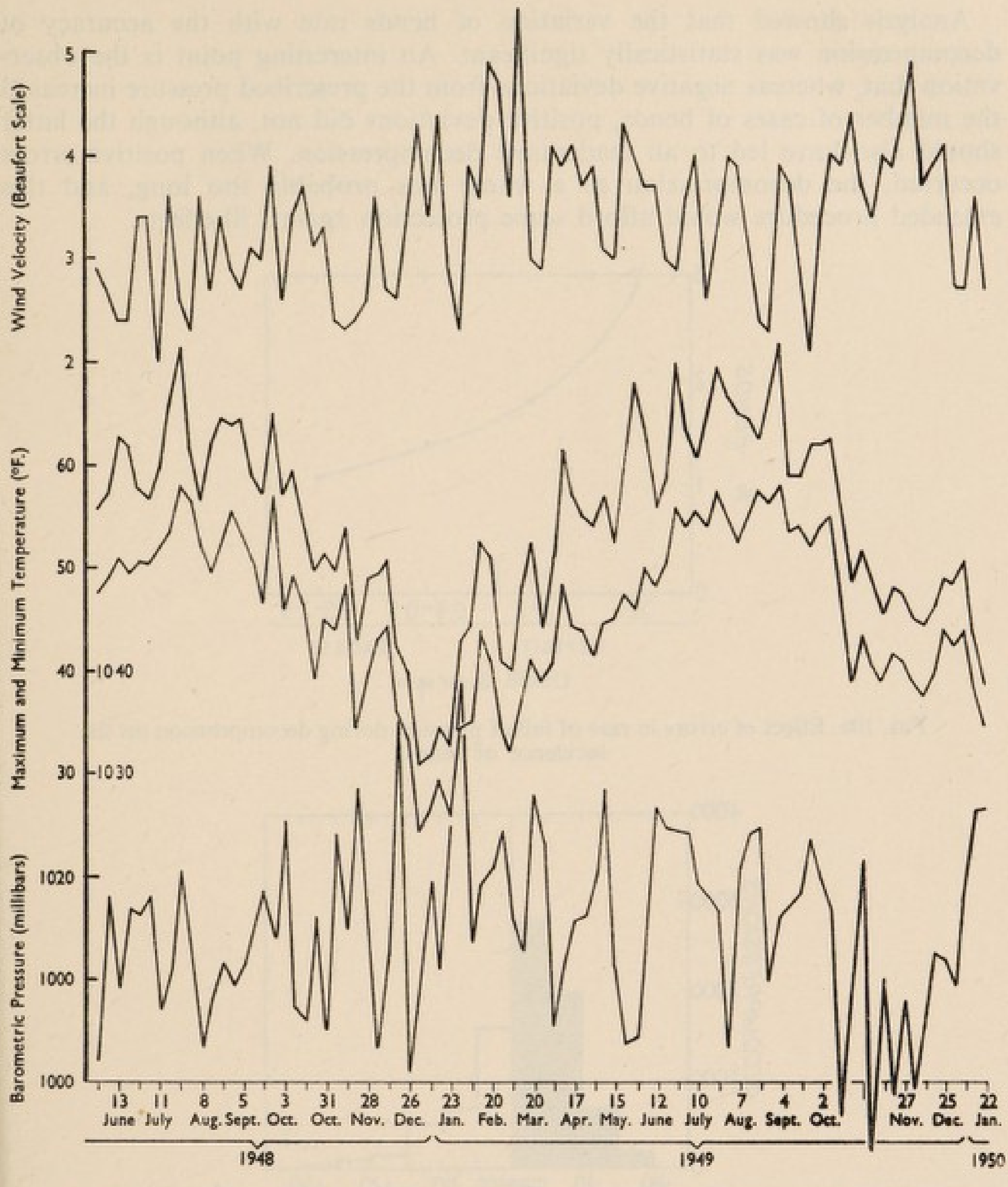

FIG. 9. Wind velocity on Beaufort scale (above), maximum and minimum temperatures in °F. (middle) and barometric pressure in millibars (below) throughout the investigation (Tynemouth).

TABLE 6b

Effect of faulty decompression on bends rate
(*b*) *Divergence from prescribed decompression time*

	15–20 min. short	10–15 min. short	5–10 min. short	Correct ± 5 min.	5–10 min. long	10–15 min. long	>15 min. long
No. of exposures	204	717	2,000	4,429	729	500	396
No. of bends ..	7	13	35	65	16	11	5
Bends % ..	3·43	1·81	1·75	1·46	2·19	2·20	1·26

Comparing 15–20 min. short with remainder: $\chi^2 = 3{\cdot}79$, $P<0{\cdot}05$

Analysis showed that the variation of bends rate with the accuracy of decompression was statistically significant. An interesting point is the observation that, whereas negative deviations from the prescribed pressure increased the number of cases of bends, positive deviations did not, although the latter should also have led to an inadequate decompression. When positive errors occurred, the decompression as a whole was probably too long, and this extended procedure would afford some protection against ill-effects.

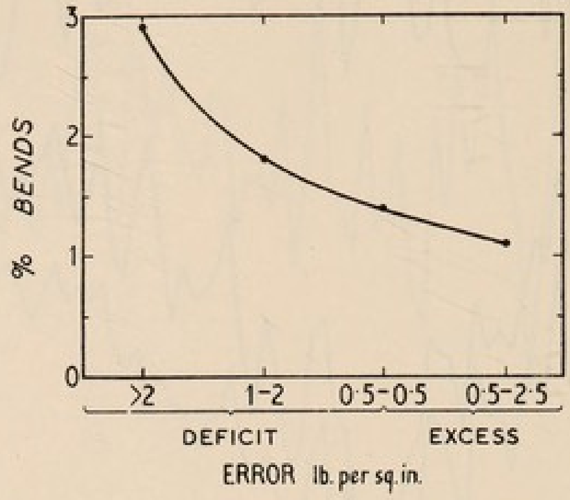

Fig. 10a. Effect of errors in rate of fall of pressure during decompression on the incidence of bends.

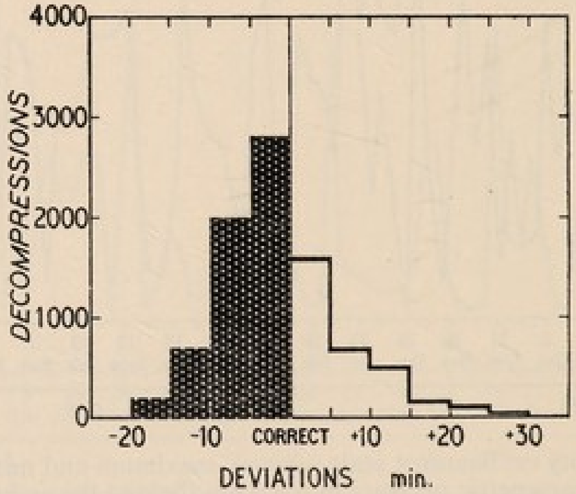

Fig. 10b. Frequency of distribution of errors in decompression time.

Fig. 10b shows the distribution of the errors in time of decompression. From this, and from Table 6a, it is clear that the large majority of decompressions are within 10 minutes of the correct time (usually about 90 minutes) but that the pressure tended to fall too rapidly in many of them in the earlier stages of decompression.

SUMMARY

The bends rate was therefore influenced principally by the influx of new labour. Significant, but less important, factors were the gradual falling-off in the number of cases as the work proceeded, and the correctness of the decompression procedure. Variations in weather conditions, working pressure or working conditions did not appear to affect bends incidence.

FIG. 11. Scatter diagram of the bends-history of all 180 workers having one or more attacks of bends. Abscissa gives the number of compressions experienced. The men are arranged on the ordinates in order of total number of compressions before leaving work in compressed air. ● = attack of bends, | = stopped work in compressed air. To the left of the vertical scale is shown the total number of bends experienced by each man.

III. Acclimatization and Selection in the Working Population

In the last section it was shown that there was a significant tendency for the bends incidence to increase with every influx of new labour, and at the same time a gradual fall in the bends rate with the passage of the weeks. From this follows the probability that the bends incidence of a working force, if all members of it started working at the same time and there were no additions, would steadily fall from a fairly high initial value. Although such an artificial state of affairs does not occur in practice, an approximation, which permits of more exact analysis than the ordinary week-by-week incidence, can be obtained if a complete history of each man is known. Using this information, collected as we have described (p. 9), we were able to adjust the working-histories of each of 180 men to start all on the same day, so that the bends

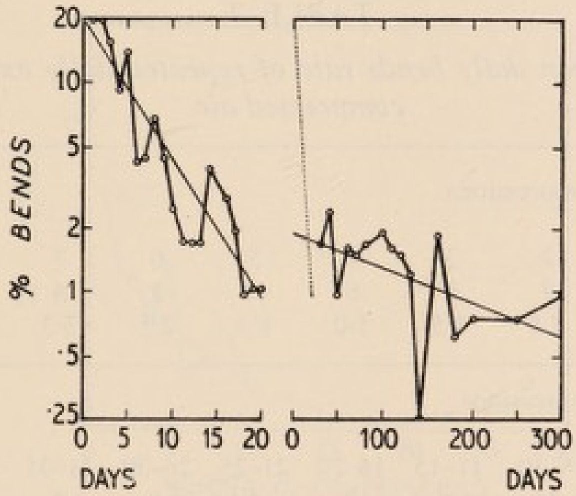

Fig. 12. Decline of bends incidence with time for all workers shown in Fig. 11. Left-hand graph 0–20 days, with regression line ($\log_{10}$ bends incidence = 1·265 — 0·06278 × time in days; r = —0·976, $P<0{\cdot}05$). Right-hand graph 20–300 days, with regression line ($\log_{10}$ bends incidence = 0·2962 — 0·001721 × time in days; r = —0·4794, $P<0{\cdot}05$). The dotted line represents the 0–20 days regression line from the left-hand graph.

incidence of all the workers at various times after starting work could be directly compared. The resulting chart is given in Fig. 11. The various workers are arranged in order of duration of employment, and the time when each man suffered a bend is marked with a black dot. Cessation of work is marked by a vertical line. For this analysis we have used only those men who suffered bends at least once. This represents in fact a fairly homogeneous group, since it includes 95 per cent of the shift workers and only 8 per cent of the non-shift workers (see Table 10, p. 26). The non-shift workers concerned were men such as foremen. Thus the whole group represents virtually all those, and only those, regularly employed in compressed air.

From Fig. 11 it was now possible to obtain the bends rate for successive days of exposure to compression for the whole working population by simply counting the number of bends and the number of men exposed on each day and expressing the former as a percentage of the latter. The results are illustrated in Fig. 12, and show that the deductions of the last paragraph are fulfilled. The incidence of bends in the first 1–2 days of employment was extremely high, more than 20 per cent, but it then began to fall, quite rapidly at first and then decreasing more slowly but continuously for as long as the task lasted, to 1 per cent or less.

Such a decline in bends rate can only be due to a lessening susceptibility of those employed, or to elimination of the susceptible members of the population, or to both of these factors. Without enquiring at this stage into the details of the factors determining the individual degree of susceptibility, we can attempt to analyse the two factors, acclimatization and natural selection, in rather greater detail.

ACCLIMATIZATION

To test whether susceptibility to bends decreased with continued experience of work in compressed air, the data of Fig. 11 were again used. A group of men was chosen such that none of them was "shed" over the period of time chosen.

TABLE 7

The effect on the mean daily bends rate of repeated daily exposures to work in compressed air

(A) 120 men, first 10 compressions

Compression no.	1	2	3	4	5	6	7	8	9	10
No. of bends	14	9	9	6	10	3	4	6	5	2
Bends %	11·7	7·5	7·5	5·0	8·3	2·5	3·3	5·0	4·2	1·7

(B) 90 men, first 50 compressions

Compression no.	1–5	6–10	11–15	16–20	21–25	26–30	31–35	36–40	41–45	46–50
No. of bends	33	16	6	2	4	6	8	8	2	3
Bends %	7·3	3·6	1·3	0·44	0·89	1·3	1·8	1·8	0·44	0·67

(C) 80 men, first 100 compressions

Compression no.	1–10	11–20	21–30	31–40	41–50	51–60	61–70	71–80	81–90	91–100
No. of bends	36	5	5	11	1	8	9	8	12	12
Bends %	4·5	0·63	0·63	1·4	0·1	1·0	1·1	1·0	1·5	1·5

(D) 20 men, first 300 compressions

Compression no.	1–50	51–100	101–150	151–200	201–250	251–300
No. of bends	6	8	4	4	3	6
Bends %	0·6	0·8	0·4	0·4	0·3	0·6

This implied, of course, that a large group (say 140 men) could only be followed for a very short time, 5 days; whereas a test over a long period of time (say 300 days) could be applied only to a group of 20 men. For each group and period chosen, the average daily bends rate per man was then obtained (either for single days or for longer periods with smaller groups). Table 7 gives the results so obtained and some of these are shown graphically in Fig. 13. (It must be remembered that the smaller groups are composed of men surviving more compressions and thus tend, as described below, to have had fewer attacks of bends; the overall bends incidence therefore differs among the different groups of Table 7).

Table 7 and Fig. 13 indicate that initially there is a steady decline in bends rate, beginning after the first compression. (The detailed picture is obscured by the large fluctuations, bigger than can be attributed to random variation, on the 5th and 8th to 9th days). This decline is continued up to the 10th to 15th day (Table 7, B) but thereafter the variations in incidence are no greater than random. The rate of decline for the first 10 to 15 days can be roughly described by saying that the bends rate halves every 5 days. The bends rate is thus reduced to between a quarter and an eighth of its initial value by acclimatization. Whether the rate of decline is really constant over this period cannot be stated for certain, in view of the other irregularities in bends incidence; but the fact that the first day had, with any group, the highest bends incidence suggests that at least there is no important delay before the acclimatization starts.

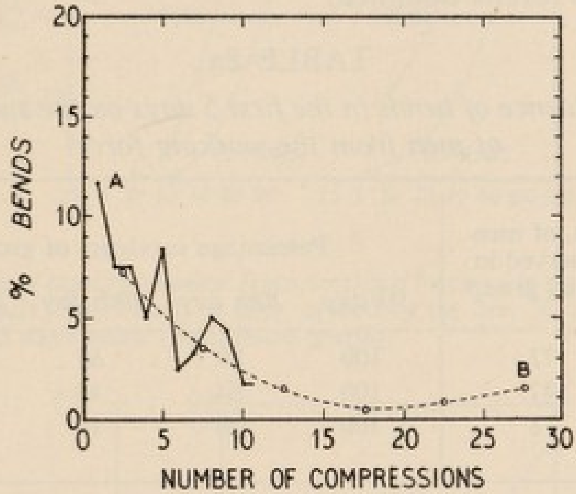

FIG. 13. Decline of bends rate due to acclimatization in a group of 120 men over 10 days (continuous line) and in a group of 90 men over 30 days (broken line).

These results are interesting, since it has been suggested by previous investigators that adaptation of this sort does not occur, but rather that sensitivity increases with successive exposures. On the other hand, compressed air workers themselves often comment on their strong impression that men get used to the work, and that, if they have the "guts" to endure the initial discomfort of a few attacks of bends, they will subsequently be relatively immune. Our results undoubtedly confirm, and render partially quantitative, the industry's experience.

Such acclimatization is clearly of practical importance. A great deal of "wastage" could be prevented if susceptible individuals were successfully reassured that perseverance in their employment would be rewarded by less trouble rather than more. Another practical point is suggested by the nature of the acclimatization itself. Its course in time has similarities to that of getting into training, and corresponds roughly to the period taken by subjects, unused to a certain type of physical exercise, before they stop becoming "stiff" after that exercise. It is plausible to suppose that unaccustomed exercise may lead to minor local ruptures of muscle fibres or their sheaths, giving rise simultaneously to a nucleus suitable for bubble-initiation (and so to bends) as well as to a point of localized discomfort recognized as stiffness. If this is the case it should be possible to produce the acclimatization by surface work of the same kind as that to be done under pressure. This might, indeed, be an economically satisfactory procedure, depending on whether the saving in wastage of labour and in morale and comfort of the working population justified the employment of all new labour on surface tasks for the first week of employment.

SELECTION

Our first approach to the question of selection among the workers was an attempt to determine whether duration of employment depended on apparent susceptibility. Two criteria of apparent susceptibility were taken:

(a) the number of bends in the first 5 days of work, and

(b) the number of bends in the first 50 days of work.

These figures are termed, respectively, the 5-day rating and the 50-day rating. The men of Fig. 11 were grouped according to these ratings, and the proportion of them still employed at arbitrary times thereafter was determined. Tables 8a and 8b show the results obtained.

TABLE 8a

The effect of the incidence of bends in the first 5 days on the subsequent elimination of men from the working force

Apparent initial susceptibility (No. of bends in 1st 5 days)	No. of men observed in initial group	Percentage survivors of group				Mean survival time (days)
		1st day	20th day	80th day	320th day	
0	72	100	89	65	17	156
1	47	100	64	43	0	82
>1	8	100	38	13	0	30

TABLE 8b

The effect of the incidence of bends in the first 50 days on the subsequent elimination of men from the working force

Apparent susceptibility (No. of bends in 1st 50 days)	No. of men observed in initial group	Percentage survivors of group			Mean survival time (days)
		1st day	50th day	150th day	
0	24	100	92	67	171
1–2	37	100	70	24	108
3–4	9	100	67	22	160
>4	7	100	71	0	—

Comparing these figures one sees, for instance, that of those free from bends in the first 5 days, 65 per cent are still at work 80 days later; whereas, among those who had more than one attack of bends initially, only 13 per cent survive to 80 days. Similar contrasts are seen with the 50-day rating. Corresponding to these results, the mean survival time of the various groups diminishes rapidly as the apparent susceptibility to bends increases.

The behaviour of the various groups can conveniently be summarized by a graph such as Fig. 14. This shows smoothed curves (obtained by the use of probits), in which the ordinate gives the percentage of the initial group at risk who left work, against duration of employment on the abscissa. Such a graph shows the whole time-course of the selective process of the group. The construction of this curve depends on the fact that the distribution of survival times proves to be approximately normal if the logarithm of the number of days is taken rather than the number of days itself; thus the results can be plotted as probits against log-time (Fig. 15). From these lines the smooth curves in Fig. 14 were drawn.

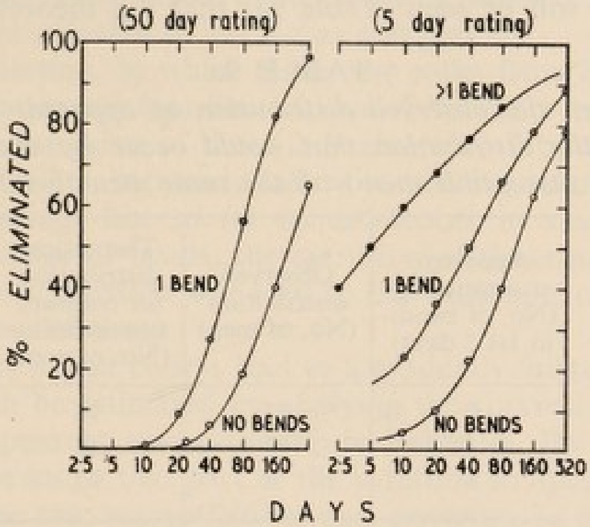

Fig. 14. Percentage of men eliminated from working force with lapse of time according to the number of bends experienced in their preceding (a) first 50 days work (left-hand graph) and (b) first 5 days work (right-hand graph).

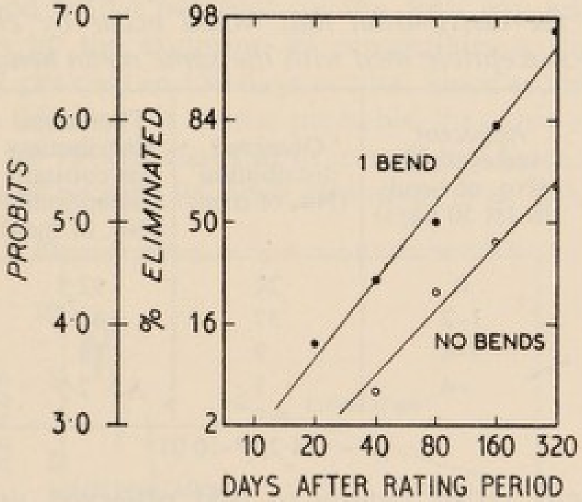

Fig. 15. Percentage of men eliminated from working force according to the number of bends experienced in their first 50 days work. The percentage eliminated has been expressed in probits.

It is clear from these facts that selection of some sort takes place, and those who experience bends early in their employment tend to leave early. But it is not permissible to conclude at once that the apparent susceptibility in fact corresponds to the real susceptibility to bends of the different subjects. An attack of bends appears to be an almost unpredictable phenomenon occurring at random within a given individual's experience. If then we have a given average incidence of bends in a group exposed for a certain time, we must expect to find, not a uniform frequency of attack, but considerable variations in frequency, even if all the men were, on the average, of the same susceptibility. These variations should, in fact, (if completely random) follow a binomial distribution, comparable to that obtained, for example, by throwing dice.

Accordingly, the expected distribution of bends incidence has been calculated for the figures of Tables 8a and 8b. For the 5-day rating group, this means that we calculated the proportion of the population at risk who, for a mean bends incidence of 9·8 per cent (the mean incidence over this period) and for five successive trials, will experience either no bends, one bend, or (in this case) more than one bend. It will be seen (Table 9a) that the theoretical distribution so

TABLE 9a

Comparison between the observed distribution of apparent susceptibility in the first 5 days with the distribution that would occur by chance in a group of uniformly susceptible men with the same mean bends incidence

Apparent susceptibility (No. of bends in 1st 5 days)	Observed distribution (No. of men)	Theoretical distribution for constant susceptibility (No. of men)
0	72	76
1	47	41
>1	8	10

$\chi^2 = 1{\cdot}49,\ P \simeq 0{\cdot}5$

TABLE 9b

Comparison between the observed distribution of apparent susceptibility in the first 50 days with the distribution that would occur by chance in a group of uniformly susceptible men with the same mean bends incidence

Apparent susceptibility (No. of bends in 1st 50 days)	Observed distribution (No. of men)	Theoretical distribution for constant susceptibility (No. of men)
0	24	12·5
1–2	37	44
3–4	9	18
>4	7	2·5

$\chi^2 = 24{\cdot}2,\ P < 0{\cdot}01$

obtained corresponds rather closely to that observed, and does not in fact differ from it significantly. The differences in apparent susceptibility, therefore, as judged by the 5-day rating, can be completely explained as due to the random incidence of bends. There is here no evidence for any variation in the actual liability of the different individuals to bends, and the distribution of bends incidence would be quite compatible with the existence of a uniform susceptibility in all the population concerned.

For the 50-day rating (Table 9b) the position is somewhat different. The theoretical distribution is, again, not unlike that observed. But it differs in that there are more individuals free from bends, and more who get them frequently than expected by random incidence. This difference is highly significant. It provides evidence that individuals do in fact differ in their liability to suffer from bends.

Two factors can thus be distinguished in the incidence of bends; one random by which some individuals come purely by chance to suffer more or fewer bends than their companions; the other constitutional, by which some individuals are, on the average, more or less prone to bends. The constitutional factor is hard to disentangle from the effects of chance, and it seems unlikely that any selection procedure using a preliminary test period would be of much practical use in eliminating the constitutionally susceptible; Table 9a illustrates how a test period of 5 days fails to reveal the presence of differences in susceptibility, and it would be impracticable to use longer test periods.

The process of selection, by which those who suffer from bends tend to leave work, will not, so far as random fluctuations of incidence are concerned, alter the bends rate. The extrusion of those individuals who, by chance rather than by particular susceptibility, happen to suffer bends, cannot diminish the incidence among those remaining. But so far as differences in susceptibility lead to differences in experience of bends, the extrusion of those prone to bends and the retention of those resistant will lead to the evolution of a more resistant population with lapse of time.

Such an evolution will of course lead to a gradually falling bends incidence. This rate of fall can be estimated by applying the survival rates of Table 8b to the figures for apparent susceptibilities in Table 9b. But an error is introduced here, since we know that part of the variation in apparent susceptibility is quite random. The true susceptibilities can, however, be estimated by fitting a negative binomial to the data of Table 9b, following the methods of accident theory.* Combining these with the survival rates of Table 8b, it is found that the bends rate would fall from an initial value of 3·6 per cent on the 1st day after the rating period to 3·4 per cent on the 50th day and 2·4 per cent on the 150th day. Thus by the exclusion of susceptibles a slow gradual fall in bends rate of about 1 per cent in 150 days occurs. Since acclimatization appears to cease after 10 to 15 days, it seems probable that this slower decrease in bends rate accounts for the gradual fall in overall incidence already described, which continues almost as long as work continues (Fig. 16).

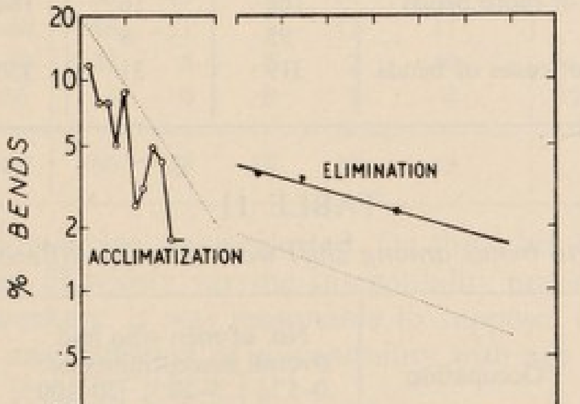

FIG. 16. Comparison of the fall in overall bends incidence (dotted line) with the estimated rates of fall due (1) to acclimatization (open circles) and (2) to the elimination of susceptible individuals (closed circles).

* The negative binomial has the equation $\left(1+\frac{m}{k}-\frac{mA}{k}\right)^{-k}$ where A is the generating symbol. The values of m and k estimated from the data are 1·8117, 1·2673 respectively. If x is the apparent susceptibility, the corresponding expected true susceptibility is given by $\lambda = m(k+x)/(k+m)$. The mean values of x in the four groups of Table 8b have been taken as 0, 1·5, 3·5, 7·5. The corresponding values of λ are 0·75, 1·63, 2·81, 5·16.

The actual mechanism of selection is probably fairly simple. No one had bends more than nine times, although apparent susceptibility varied from 0 to 100 per cent and the periods at risk from 1 day to over 1,000 days. The vast majority of those liable to bends incurred an attack only one to three times. This implies that in general a man would stay in employment until he had suffered from one to three attacks of bends. Such a process fits the data of Fig. 11 excellently with one minor qualification—that the more resistant individuals put up with one or two more attacks, on the average, than the susceptibles. This is, of course, understandable, for attacks spaced weeks or months apart must be much more tolerable than those closely following one another.

If such a process were operating, we would expect a close relation between the dates of the final bend and of stopping work. In fact this was the case; out of 180 men who experienced one or more bends, the final day of employment of 44 of them was itself marked by a bend; from the overall incidence of bends in the group, only about 4 to 5 final days would have been expected by chance to be so marked.

We may conclude, in short, that, as a rule, men remain at work until they have had one to three attacks of bends, and then leave soon after the last attack. To an important extent, these attacks are quite random, but there is also an element of constitutional susceptibility.

TABLE 10

Liability to bends of shift workers and non-shift workers

Type of worker	Shift workers	Non-shift workers	Total
No. of men exposed	177	199	376
No. of men who had one or more bends	168	16	184
%	95	8	
No. of cases of bends	319	31	350

TABLE 11

Liability to bends among shift workers with different tasks

Occupation	No. of men who had overall susceptibility of: 0–5% bends	5–20% bends	20–100% bends
Miner	10	2	3
Miner's labourer	54	20	38
Caulker ..	15	8	6
Others	14	1	2

IV. Factors Affecting Susceptibility to Bends

OCCUPATION

One of the outstanding facts about the incidence of bends is that it is almost wholly borne by the shift workers (Table 10). Out of 350 cases of bends only 31 occurred in non-shift workers. This difference will be discussed later.

It was further enquired whether the incidence in shift workers varied with the task on which they were engaged, but no significant difference was found between the susceptibility of the various groups (Table 11).

AGE

Our most reliable and complete information about the ages of the working population referred to those men who suffered from bends; so that for this analysis we restricted ourselves to this group. This means, of course, that about

TABLE 12a

The relationship between age and initial susceptibility to bends

Age (yr.)	No. of men	Bends rate in first 2 days (%)
20–30	89	14
30–40	60	14
40–50	24	23
>50	5	40

TABLE 12b

The relationship between age and overall susceptibility to bends

Age (yr.)	No. of men with susceptibility of:					Group bends rate (%)
	0–1%	1–2%	2–5%	5–20%	20–100%	
20–30	85	49	16	17	20	6
30–40	46	21	8	12	11	6·8
40–50	32	8	5	2	10	8·5
>50	3	0	0	1	4	23
Total	166	78	29	32	45	

half the working population was neglected. On the other hand, those that got bends included men of widely varying susceptibility and ages and almost the bulk of the shift workers. It was reasonable to suppose, therefore, that, even within this group, any variation of susceptibility with age would readily make itself apparent.

Two comparisons were made: one between the initial susceptibilities and age (Table 12a), and the other between the overall susceptibilities at various ages (Table 12b). (By "overall susceptibility", or, later, by "susceptibility" without qualification, is meant the number of bends suffered by an individual as a percentage of the total number of his exposures to compressed air.) For (a), the bends in the first 2 days were observed for the different age groups (Table 12a). The table shows how, in the first 2 days of employment, the bends rate is steady until the age of 40, when it begins to rise, and then increases sharply at the age of 50.

The same phenomenon is seen with the overall susceptibility (Table 12b). Again, the average bends rate for the different age groups increases from the age of 40, and rises steeply at the age of 50. Very similar results were obtained by Snell (1896).

Quantitative comparisons can be made, although no great weight can be laid on them: i.e. men aged from 40 to 50 have a bends rate about 30 per cent higher, and those over 50 about 150 per cent higher than those aged from 20 to 40 years.

A corollary of these conclusions is, of course, that the date of the first bend will tend to be earlier the older the man concerned. These dates have been obtained for the same men (Tables 12c, d) and show that this corollary is in fact fulfilled.

TABLE 12c

Date of first bend (i)

Age (yr.)	No. of men with first bend in: 0–10 days	10–30 days	>30 days
20–30	44	8	32
30–40	34	12	12
40–50	16	2	7
>50	5	0	0

TABLE 12d

Date of first bend (ii)

Age (yr.)	No. of men with first bend in: 0–5 days	>5 days
20–45	83	79
>45	11	2

WEIGHT

In view of the common statement that obesity renders subjects liable to decompression sickness, the susceptibility of the men was compared with their weight (Table 13). There was no significant correlation between these two variables, however.

It must not be inferred, however, that the relation sought does not exist. Weight is a poor index of obesity, and some of the largest men did not look particularly fat, sometimes the reverse. It is probable, too, that the initial selection by medical examination would exclude the grosser degrees of fatness. At the same time, our results suggest that perhaps too much importance may be attached to excessive weight in this connexion, since it cannot be a conditioning factor of any great strength.

TABLE 13

Relationship between weight and susceptibility to bends

Weight (lb.)	No. of men with susceptibility of: 0–1% bends	1–5% bends	5–20% bends	20–100% bends
100–120	1	0	0	0
120–140	5	12	5	3
140–160	11	20	9	27
160–180	12	9	10	8
180–200	1	6	3	3
>200	1	0	0	3

$r = 0{\cdot}0824$, $P = 0{\cdot}10$

V. Relationship of the Circumstances of the Bend to the Effectiveness of Recompression

It might be supposed that certain cases of bends, for example, those of rapid onset or in particular sites or in old people, or those where recompression is delayed, might be more difficult to relieve than the average case. With this in mind, we have analysed the cases of bends which occurred, taking the number of recompressions needed for cure (i.e. resistance to recompression) as an indication of the severity of the bend and the ease with which it could be relieved (Tables 14, 15 and 16).

There was significant correlation between the ease of relief of the bend and the time of onset, the bend being more easily relieved the later it occurred. The actual times after decompression when bends occur are interesting, and

TABLE 14

Relation of time of onset of bend to its resistance to recompression

Time of onset (hr.)	No. of cases of bends in which no. of recompressions required was: 1	2	3	4	5	6	7	8	9	Total no. of cases
0	51	21	8	1	2	—	—	—	—	83
1	59	18	1	4	1	1	—	—	—	84
2	61	10	3	2	—	—	—	—	1	77
3	30	7	2	1	—	—	—	—	—	40
4	19	4	1	—	—	—	—	—	—	24
5	14	—	—	—	—	—	—	—	—	14
6	8	—	—	—	—	—	—	—	—	8
7	—	—	—	—	—	—	—	—	—	—
8	7	—	—	—	—	—	—	—	—	7
9	4	—	—	—	—	—	—	—	—	4
10	1	2	—	—	—	—	—	—	—	3
Total	254	62	15	8	3	1	—	—	1	344

$r = -0{\cdot}1550$, $P = 0{\cdot}004$

the data of Table 14 have been represented graphically in Fig. 17. There was no correlation between the ease of relief and the site of the bend, although there was a suggestion here that the more numerous the sites at which pain is felt in a given case, the more resistant it will be to recompression (Table 15). But any practically important differences between the resistance of bends in different sites certainly appears to be lacking. There is no reason to suppose, for instance, that recompression for an arm bend should differ in any way from that for a leg bend.

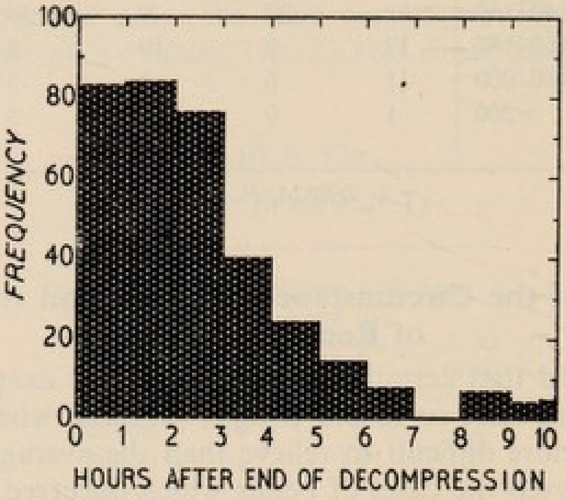

FIG. 17. The frequency of distribution of the time of onset of bends after the end of decompression.

TABLE 15

Relation of the site of a bend to its resistance to recompression

Site	No. of cases of bends in which no. of recompressions required was: 1	2	3	4	5	6	7	8	9	Total no. of cases
Leg	146	29	6	2	—	—	—	—	—	183
Arm	32	9	1	1	—	—	—	—	—	43
More than one limb	81	23	9	5	3	1	—	—	1	123
Head, chest, back, stomach, etc. ..	9	5	—	—	—	—	—	—	—	14
Total	268	66	16	8	3	1	—	—	1	363

The fact that relief is obtained more rapidly (Table 16) with delay in recompression was unexpected. It is certainly not true with really serious cases of decompression sickness. But with mild cases, it may well be that the untreated subject will in any case recover spontaneously in 24 to 36 hours. If this were so, the later treatment is started, the more effective it would appear to be. We may, indeed, sometimes be doing little more than measuring the time for the soreness of the original bend to disappear long after the causative bubble has been absorbed.

TABLE 16

Relation of the delay before treatment of a bend to its resistance to recompression

Delay (hr.)	No. of cases of bends in which no. of recompressions required was: 1	2	3	4	5	6	7	8	9	Total no. of cases
0	28	11	3	2	1	—	—	—	—	45
1	35	9	3	2	1	1	—	—	1	52
2	41	8	3	—	—	—	—	—	—	52
3	29	10	3	—	—	—	—	—	—	42
4	30	5	1	—	—	—	—	—	—	36
5	20	1	—	—	—	—	—	—	—	21
6	13	5	—	1	—	—	—	—	—	19
7	10	3	—	—	—	—	—	—	—	13
8	8	—	—	—	—	—	—	—	—	8
9	10	—	—	—	—	—	—	—	—	10
10	1	—	—	—	—	—	—	—	—	1
11	3	—	—	—	—	—	—	—	—	3
12	—	—	—	—	—	—	—	—	—	—
13	1	—	—	—	—	—	—	—	—	1
Total	229	52	13	5	2	1	—	—	1	303

$r = -0{\cdot}2046, P < 0{\cdot}05$

TABLE 17

Relation of age of the subject of a bend to its resistance to recompression

Age (yr.)	No. of cases of bends in which no. of recompressions required was: 1	2	3	4	5	6	7	8	9	Total no. of cases
18–22	11	5	1	1	—	—	—	—	—	18
22–26	59	17	2	—	—	1	—	—	—	79
26–30	63	7	5	3	1	—	—	—	—	79
30–34	37	14	3	2	1	—	—	—	—	57
34–38	36	8	—	—	1	—	—	—	—	45
38–42	18	1	1	—	—	—	—	—	—	20
42–46	16	8	2	1	—	—	—	—	—	27
46–50	5	1	—	—	—	—	—	—	—	6
50–54	5	1	—	—	—	—	—	—	—	6
54–58	1	1	—	1	—	—	—	—	1	4
Total	251	63	14	8	3	1	—	—	1	341

$r = 0{\cdot}0862, P > 0{\cdot}10$

Although we have already described the evidence for increased susceptibility bends with advancing years, there was no sign that the attacks of bends hich occurred in older men were any more refractory than usual (Table 17).

VI. Pathogenesis of Decompression Sickness

e have examined the case histories for information which may throw ne light on the factors which produce bends. It might be, for instance, t (1) occupation, (2) age or (3) weight might influence the site of election of bubbles (Tables 18, 19, 20), or (4) that bubbles in different sites might develop at different rates (Table 21). Again, if bubbles take a definite time to grow, and if their size, once it has passed the threshold for producing pain, could be measured by the pressure at which relief could be obtained, then such growth might be related to (5) the site of the bend, (6) the time of onset of the bend or (7) the delay before recompression (Tables 22, 23, 24). The tables which follow show that, in fact, correlations of this sort cannot be detected.

TABLE 18
Relation of the site of the bend to occupation

Site	No. of cases of bends in men whose occupations were: labourer	miner	caulker	others	Total no. of cases
Leg	118	22	28	11	179
Arm	26	4	5	8	43
More than one limb	80	15	17	13	125
Chest, head, back, etc.	12	—	—	2	14
Total	236	41	50	34	361

TABLE 19
Relation of the site of the bend to age

Site	No. of cases of bends in men whose ages were: 18–22	23–26	27–30	31–34	35–38	39–42	43–46	47–50	51–58	Total no. of cases
Leg ..	2	53	42	26	24	13	10	5	4	179
Arm ..	1	7	9	7	9	3	3	—	1	40
More than one limb	1	12	33	17	24	12	12	2	6	119
Chest, head, back, etc.	—	4	1	4	—	3	—	—	—	12
Total	4	76	85	54	57	31	25	7	11	350

TABLE 20
Relation of the site of the bend to weight

Site	No. of cases of bends in men whose weights (lb.) were: 100–120	121–140	141–160	161–180	181–200	>200	Total no. of cases
Leg	2	16	62	64	16	1	161
Arm	—	5	14	16	4	—	39
More than one limb	—	15	50	31	13	3	112
Chest, head, back, etc.	—	2	3	—	4	—	9
Total	2	38	129	111	37	4	321

TABLE 21

Relation of the site of the bend to time of onset

Site	No. of cases of bends in which time of onset (hr. after decompression) was within: 1st	2nd	3rd	4th	5th	6th	7th	>7th	Total no. of cases
Leg	37	42	44	24	13	6	2	9	177
Arm	16	12	4	2	3	1	1	1	40
More than one limb	27	29	32	15	8	7	4	2	124
Chest, head, back, etc.	4	7	2	—	—	—	—	—	13
Total	84	90	82	41	24	14	7	12	354

TABLE 22

Relation of the relief pressure to the site of the bend

Site	No. of cases of bends in which relief pressure (lb./sq. in.) was: 1–15	16–20	21–25	26–30	31–35	36–40	41–45	>45	Total no. of cases
Leg	2	2	3	2	5	134	36	—	184
Arm	—	1	—	2	3	29	11	—	46
More than one limb	1	1	—	1	3	79	39	1	125
Chest, head, back, etc.	—	—	—	—	—	11	3	—	14
Total	3	4	3	5	11	253	89	1	369

TABLE 23

Relation of the relief pressure to the time of onset of the bend

Time of onset (hr.)	No. of cases of bends in which the relief pressure (lb./sq. in.) was: 10–15	16–20	21–25	26–30	31–35	36–40	41–45	46–50	Total no. of cases
0–1	1	3	2	2	1	55	19	—	83
1–2	2	—	—	1	5	56	21	1	86
2–3	—	—	—	2	4	55	18	—	79
3–4	1	—	—	—	1	26	12	—	40
4–5	—	—	—	—	1	16	7	—	24
5–6	—	1	1	—	—	10	5	—	17
6–7	—	—	—	—	—	7	1	—	8
7–8	—	—	—	—	—	—	—	—	—
8–9	—	—	—	—	—	6	1	—	7
>9	—	—	—	—	—	4	3	—	7
Total	4	4	3	5	12	235	87	1	351

$r = 0{\cdot}0818$, $P > 0{\cdot}10$

TABLE 24

Relation of the relief pressure to the delay in recompression

Delay in recompression (hr.)	No. of cases of bends in which the relief pressure (lb./sq. in.) was:								Total no. of cases
	10–15	16–20	21–25	26–30	31–35	36–40	41–45	46–50	
0–1	—	3	—	—	—	30	15	—	48
1–2	1	—	1	1	1	36	12	1	53
2–3	—	—	1	—	1	40	10	—	52
3–4	—	—	—	3	1	29	11	—	44
4–5	1	—	1	—	3	26	6	—	37
5–6	—	1	—	—	1	17	4	—	23
6–7	—	—	—	1	1	11	7	—	20
7–8	1	—	—	—	1	10	2	—	14
8–9	—	—	—	—	—	5	3	—	8
9–10	—	—	—	—	—	6	3	—	9
>10	—	—	—	—	—	4	3	—	7
Total	3	4	3	5	9	214	76	1	315

$r = 0{\cdot}0310, P > 0{\cdot}10$

It follows, therefore, (a) that the site of a bend did not depend on the occupation, age or weight of the man concerned; (b) that there was no difference in the rapidity of onset of symptoms according to where the bend appeared; (c) that whatever the site of the bend, the time of its appearance or the delay in its treatment, in most cases a full return to the working pressure was needed by the sufferer for relief. With any bend there was usually a residual soreness, even after full recompression. It is probable that relief was not recorded until the patient was sure that no further benefit would follow, and, since the pressure during recompression was never raised above the working pressure, it was this pressure that came to represent the relief pressure as a rule. The records do not supply, therefore, any very sensitive index of changes in bubble size.

VII. Discussion

The chief aim of this investigation was to obtain more information about decompression sickness in civil engineering practice in order to answer certain practical questions.

SOME QUESTIONS OF PRACTICAL IMPORTANCE

How Accurate should Decompression be?

In practice it is difficult to conform exactly to a decompression table. The question arises how large may be the permitted deviation from the prescribed decompression. The principal danger is from too rapid a decompression (such as 3 or 4 in Fig. 18). This fault can be recognized on a barograph tracing because either the procedure is too short in total time (3), or the pressure during some part of the decompression is below that prescribed even though the total time is correct, (4). It appeared that deviations of 10 minutes in time or of 0·5 lb. per sq. in. in pressure were acceptable, but that greater deviations led to significant increases in bends rate.

In general, occasions when the pressure curve deviated upwards from that prescribed were associated with still lower bends rates. This was because such decompressions were usually longer than prescribed (Fig. 18, 2) and were thus correspondingly safe. But it is possible that decompressions might be of the right total time, yet deviate upwards as 1 in the figure, and these would, of course, tend to cause decompression sickness.

It may be said, therefore, that it was in practice safe for the prescribed times or pressure curve to be exceeded; but it is difficult to be certain that this would be so in all undertakings, and it would be wiser to apply similar limits of error on this side of the prescribed decompression as on the other. As a working

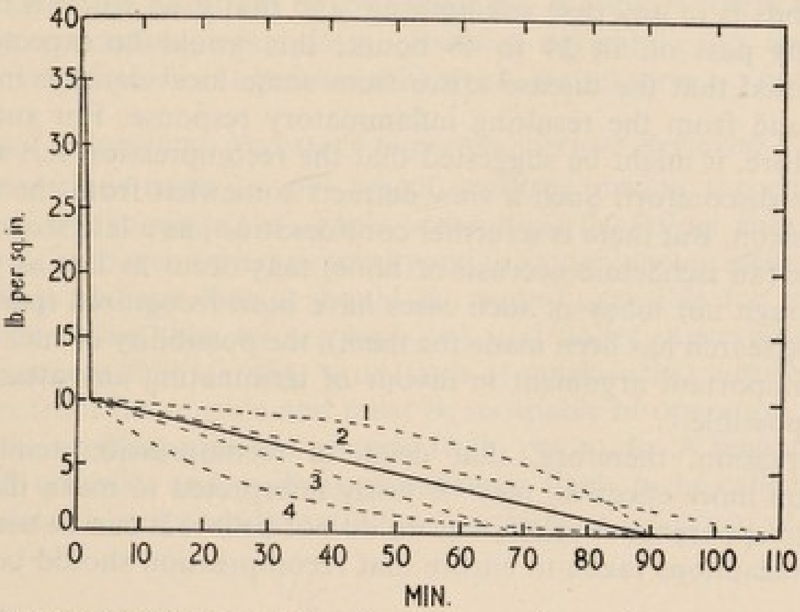

FIG. 18. Types of error in decompression. The continuous line represents the rate of fall of pressure prescribed after an exposure to 35 lb. per sq. in. for 6 hours; the dotted lines show the main types of deviation from this.

ıle we suggest that, for a decompression from a pressure of 35 lb. per sq. in. fter a shift of 4 hours or more, the decompression curve prescribed should e adhered to within ±0·5 lb. per sq. in. and the total time prescribed (91 inutes) within 5 minutes. From the experience of this particular undertaking, seems likely that accuracies of this degree could be readily achieved.

ow Quickly after Decompression do Symptoms appear in a Case of Bends?

Although pain or discomfort sometimes occurred 30 minutes or 1 hour after ıving the decompression chamber, it usually took longer than this to develop. ıly 50 per cent of cases had declared themselves 2 hours after decompression ig. 17, p. 30). To collect 95 per cent of cases, it would be necessary to wait 10 urs. These results are similar to those of other investigators, although the de-mpression procedure used here was different. The inference is that it is not ıcticable to keep men on the site after work long enough to be confident that bends will develop after leaving. This does not mean, however, that the usual iting period should be abandoned. The conventional precaution that the rkers should remain for about 1 hour does not depend for its justification ne on this hope of catching ordinary attacks of bends early. It is also a caution that treatment may be prompt if a serious case arises. Although such es have been rare during this undertaking, all of them manifested themselves within 1 hour. It is probably wise therefore to retain this precautionary waiting period, although it must be borne in mind that three out of four of the mild cases will occur after it.

How Urgent is Recompression after Symptoms appear?

With serious cases of sickness, for example, those involving the spinal cord, there is no doubt that the sooner recompression takes place, the less the damage will be. With the ordinary cases of bends studied here, it appeared that, on the contrary, the later the recompression, the more effective (in the sense of not requiring to be repeated) it became. An obvious explanation for this is that an attack of bends is in any case self-limiting, and that even without treatment it would usually pass off in 24 to 48 hours; this would be expected anyway if it is supposed that the disease arises from some local damage in muscle or joint tissue and from the resulting inflammatory response. For such cases of bends, therefore, it might be suggested that the recompression serves primarily to relieve the discomfort. Such a view detracts somewhat from the importance of recompression. But there is a further consideration; as a late sequel to bends, bone damage (an ischaemic necrosis of bone) may occur as late as years afterwards. Although not many of such cases have been recognized (partly because no systematic search has been made for them), the possibility of such permanent harm is an important argument in favour of terminating any attack of bends as soon as possible.

Our observation, therefore, that delay in recompression tends to make recompression more effective, may be justly interpreted to mean that ordinary bends tend to spontaneous relief; but we do not believe it can be used to justify easing the precautions taken to ensure that recompression should be as prompt as possible.

Can Recompression Procedure be improved?

In general, recompression procedures as applied to bends appear to be rather inefficient. Sometimes a particular case demanded as many as seven recompressions before declaring relief. But it was significant that no difference in efficiency could be detected between the two relatively rapid methods of treatment which were specially devised and the much slower method based on traditional diving technique. Were the former methods really defective in failing to compress and dissolve the causative bubble, it is highly probable that the more prolonged method would have been more successful. The fact that all three methods work equally well suggests rather that something is being expected of recompression procedure which it cannot do—namely, remove all the discomfort of a bend entirely. There is always some residual soreness, and it seems likely, as well as being in accordance with the judgment of the medical orderlies, that frequently this residual soreness is confused with the bend itself, so that further (and useless) recompressions are demanded to get rid of it.

Our results show, then, that by prolonging recompression procedure nothing would be gained and the usefulness of the recompression chamber would be diminished; they also suggest that a certain number of recompressions are wasted, since they may be futile attempts to remove not the cause of the bend but the after-effects (e.g. local oedema, etc.). If this is so, a determined effort at symptomatic relief of the residual soreness by radiant heat or aspirin might be more effective than repeated and tedious recompressions.

Can the Incidence of Bends be lessened by Pre-selection of the Working Population?

No important single factor could be isolated which tended to increase the liability to bends, with the possible exception of age. We obtained no evidence that weight was correlated with bends susceptibility, and if in fact obesity predisposes to bends, some subtler index of it than mere weight is necessary. There appeared to be some variations in susceptibility between individuals, and a belief that these exist is common in the industry. But our results in the analysis of the 5-day "apparent susceptibility" rating showed that a test period of this length would be too short to allow the susceptibles to be identified. A longer period of trial would no doubt be impracticable. It appears, therefore, that any pre-selection procedure, apart from checking normal health and excluding those men over 45 years of age from shift work, would serve no useful purpose.

Are additional Precautions Necessary to prevent Serious Accidents?

The three serious cases (p. 39) which occurred during the course of this work were all due to neglect of simple precautions, by failure either to observe the regulations or to recompress promptly and thoroughly when serious symptoms appeared. It is obvious that it should be made impossible for men to leave compressed air other than by the man-lock and under supervision of a lock-keeper. This means that all other exits (such as muck-locks) must be controlled by operators from the outside and must be incapable of operation from inside, so long as the working pressure exceeds 18 lb. per sq. in. A second essential is that the staff orderlies and medical practitioners likely to be called upon in an emergency should understand clearly the principles of treatment of compressed air illness.

Is there a Functional Element in Bends?

The basis of bends whether in its trivial, moderate or severe forms is the occurrence of pain during or after decompression. But this organic foundation of the disorder may sometimes be overlaid by a functional element. Our reasons for suspecting this are as follows. Firstly, attacks of bends were not always relieved by recompression, and repeated recompressions in rapid succession were sometimes sought by the subject. Secondly, we were quite unable to obtain evidence of a relationship between those factors in a case of bends which would be expected to influence or relate to the size of bubbles formed in the body and the circumstances under which pain appeared. This made it likely that the organic basis of the disease was being complicated by some additional factor. Thirdly, there were a number of cases in which both the medical orderly and one of us felt that the actual pain experienced was fairly mild, but had come to represent in the patient's mind a threat of some more severe disorder and hence to assume an undeserved prominence. Fourthly, the situation is one in which excessive attention to a mild pain could almost reasonably occur, for it is well known that in its severe form decompression sickness can be disabling or even fatal. The development of symptoms is sufficiently slow for there to be an abundance of time to think about them, and the mildest symptoms may sometimes occur spontaneously from quite different causes, such as rheumatism. All these factors make it reasonable that a functional element should be present, although the prospect of re-entering pressure and remaining in a confined and inevitably not very comfortable chamber for some hours must always act as a deterrent to an over-ready demand for recompression.

Despite this, the only basis for treatment is that the attack is in fact wholly of organic origin. It is, in any case, extremely difficult to assess the intensity of pain suffered by another individual. Were an attempt made to exclude from treatment those diagnosed in some way as mostly functional, it would surely lead, sooner or later, to the neglect of a serious case, quite apart from the possibility of allowing early and mild bone damage to go unchecked.

FACTORS CONTROLLING THE INCIDENCE OF DECOMPRESSION SICKNESS

A principal aim of this investigation was to obtain such information as might help to throw light on the pathogenesis of bends, with respect to such problems as the factor determining the site of bubble-formation, the rate of growth of the bubbles, their rate of disappearance on recompression, and their relation to the production of pain. But the conditions of the investigation, the random incidence of bends and the functional element in bends introduced too many confusing factors to allow such an analysis.

Four important elements in the incidence of bends were, however, brought to light. In the first place there was the evidence that acclimatization took place. This acclimatization was rapid and substantial and its nature has already been discussed. But the question arises whether it is likely to be generally observed, or whether it was present to a greater extent than usual in this particular investigation. A possible reason for this might be, for instance, that the Tyne Tunnel was the first major compressed air undertaking since the war, so that much more inexperienced labour would be recruited to it than usual, and these men would need to learn to distinguish trivial aches and pains from bends proper. It must not be forgotten, however, that recompression is a tedious process, and we doubt whether many men would be led by minor discomfort to ask for it, whether inexperienced or not. Further, the supposition that the working population was especially liable to exaggerate trivial symptoms should have led to a high overall bends incidence. But, on the contrary, this rate was 0·87 per cent, well below the 2 per cent normally taken as a working limit, and gratifyingly small even when allowance is made for the use of somewhat more rigorous decompression tables than previously. We believe, therefore, that acclimatization of this sort will always be seen at the initiation of a compressed air working, and will constitute an important element in the decline of the bends incidence.

Secondly, we obtained some evidence of a selection of resistant workers and an extrusion of the susceptibles from the working population, and to this we have attributed the progressive fall in bends rate which continues, though at a diminishing rate, probably as long as the work proceeds.

Thirdly, the random nature of many of the features of bends incidence must be stressed. Although this is sufficiently obvious on reflection, there is often in practice, a tendency to attach undeserved significance to a rise or fall in bends rate or to a high or low apparent susceptibility of an individual; such changes may be in fact within the range of random variation, and reflect neither a change in working conditions nor a constitutional disposition of an individual.

Finally, it is remarkable that by far the greatest part of the bends incidence is borne by the shift workers rather than by the equally numerous group of men exposed only occasionally and briefly to pressure. Of the shift workers nearly all suffer bends sooner or later. Decompression sickness in industry is therefore, primarily a disease of the shift worker, and it is in his direction that further study would have to be directed.

APPENDIX OF CASE REPORTS

Case 1. F. D.

This man was a foreman aged 45 years with considerable experience of compressed air work in which he had been employed for about 15 years. He had recently come to the Tyne Tunnel scheme from similar work in the south of England and had been working at Howdon for 3 weeks on alternating weekly day and night shifts. In the course of a shift it was usual for him to enter and leave the shaft several times so that he was in high pressure for frequent short periods. At various times in the past he had experienced minor attacks of bends without any serious results. On July 6, 1948, he had spent a period of about 2 hours underground at a pressure of 34 lb. per sq. in. for which a decompression time of 40 minutes is necessary after the first reduction of pressure to about 9 lb. per sq. in. For some reason, however, he wished to see the chief engineer urgently and, instead of entering the man-lock to be decompressed in the ordinary way, he let himself out through the muck-lock, taking probably only a few minutes.

About a quarter of an hour later his legs became numb and weak and he had to be assisted to the medical lock where the pressure was at once raised to 40 lb. per sq. in. Altogether five attempts at recompression and decompression were made with no beneficial effect. Retention of urine necessitated catheterization by the works' doctor, and the patient was admitted to hospital 16 hours after the onset of paralysis when it seemed evident to the works' doctor that further compression would not make him any better.

On physical examination there was paralysis of both legs, and the bladder was distended to the level of the umbilicus. The cranial nerves were normal and the arms and upper part of the trunk appeared to be unaffected. The abdominal reflexes were absent and in the lower limbs the tendon reflexes were brisk and equal and there was left ankle clonus. In both feet the plantar reflexes were extensor, and sensation to pin prick was absent in the legs and in the thighs and abdomen up to the level of the umbilicus (T10). Vibration sense was absent in the legs and iliac crests, and he was incontinent of faeces. His pulse rate was 76 per minute, blood pressure normal and there were no abnormal signs in other systems.

Some movement had returned to the left leg and to a very slight degree in the right leg by the evening of the day of admission and from then on there was a gradual return of power and sensation.

A month after admission the patient had recovered the use of his legs sufficiently to move about the ward with assistance but, although there was partial control of bladder function, he was still incontinent of faeces. The right leg was wasted and relatively weak; co-ordination of the lower limbs was poor and vibration sense absent. Right patellar clonus and up-going toes were still present.

One year after the incident he reported that his condition was much the same and that defective control of defaecation resulted in periods of constipation followed by diarrhoea. Urinary incontinence made it necessary to continue wearing the absorbent bag and he was now using a motor-propelled invalid chair.

Case 2. J. D.

This man was a fitter's mate, 29 years old, who had worked for 4½ months at Howdon; this was his first experience of compressed air work. He had previously been quite healthy, but since starting this work he had experienced two or three minor attacks of bends.

On November 11, 1948, he worked a 3¾ hours shift at a pressure of 34 lb. per sq. in., and was being decompressed in the man-lock together with some others. At the end of the phase of rapid reduction he complained of numbness in the left elbow region and of feeling faint. His companions signalled for decompression to be hastened. Atmospheric pressure was reached in about 30 minutes instead of 76 minutes according to the schedule. At first he moved about a little and was thought to be dozing, but on completion of decompression it was evident that he was unconscious.

He was taken immediately to the medical lock and recompressed to 38 lb. per sq. in. with the result that he recovered consciousness. He vomited and was able to move his legs a little although he still complained of a numb feeling in them. A doctor, not the practitioner who usually supervised the works, was summoned, and advised decompression which was performed over about 30 minutes. The patient was then sent to his home by ambulance although he lived on the other side of the river, and, after a sleepless night, was admitted to the Royal Victoria Infirmary, Newcastle, the following morning.

On examination he was pale and slightly cyanosed and the extremities were cold. His pulse was regular but weak and its rate was 120 per minute; the temperature was 97·6° F., and B.P. 90/60. His bladder was distended and palpable 2 inches above the pubic symphysis. There were moist sounds at both lung bases posteriorly.

In addition to the paralysis of the legs there was weakness of the arms and the lower intercostal muscles appeared to be immobile. Sensation was present, and the tendon reflexes were also all present and equal in the upper limbs, but there was complete anaesthesia to all stimuli in the legs and in the trunk below the level of the seventh thoracic vertebral spine behind, and the third intercostal space in front. Above this was an area of hyperaesthesia. Abdominal reflexes were just present on the left side and absent on the right. On stimulation of the soles of the feet there was flexion withdrawal on both lower limbs and priapism.

Two days after admission the patient began to have pins and needles in his arms and a left ankle jerk was obtained. Acute bronchitis with pyrexia of 100·7° F. developed. The extent of sensory loss appeared unaltered.

The condition of his chest gave rise to some anxiety over the course of the next 2 weeks and he had a small haemoptysis. X-ray of the chest revealed a small opacity in the left lower zone and he was still febrile. By now the level of sensory loss had fallen several inches and the anaesthetic level was at the fifth intercostal space in front. His bladder was functioning automatically, and there was flexion withdrawal on stimulation of the left leg but not the right.

Four weeks after admission he had much improved generally but was becoming spastic with bilateral extensor responses. The upper border of anaesthesia was now at the level of the sixth intercostal space in front.

Sensation now began to return fairly quickly over the abdomen though discrimination between pin prick and light touch remained poor. Physiotherapy was commenced and exercises to arms and legs were given with the aid of a frame and springs.

Ten weeks after his mishap he had regained a little voluntary power in his legs, the arms appeared normal, knee and ankle jerks were present and there were extensor plantar responses with occasional spontaneous extensor spasms in the legs. He remained in hospital until August, 1949, 9 months after the accident, without any marked improvement in the use of his legs although walking calipers were of considerable help, and he was able to get about with the aid of crutches; he was still incontinent of urine.

Case 3. L. L.

This patient, aged 28, claimed to have some experience of compressed air work and was taken on as a miner in January, 1949. He first went into the tunnel on January 17 and worked in a pressure of up to 39 lb. per sq. in. at the face. During compression he complained of pain in his ears and when in the tunnel said he had a numb feeling in his legs, and from the waist downwards; he also felt sick and had a headache. After decompression he felt slightly better, but the numbness in his legs persisted and he had a crackling sensation in his ears for which he was sent to the Royal Victoria Infirmary, Newcastle, where wax was removed from his ears.

The next day he stayed off work with a severe headache and vomiting. His egs still felt weak, but there was no pain. He stated that he was stopped when valking in the street by the police, who thought he was drunk. The next day e again entered the tunnel at 7 a.m. and stayed for 6 hours instead of the ustomary 4 for new workers, as he missed the outgoing shift. He claimed to have een decompressed in less than 1 hour instead of the required 1 hour 50 minutes. fter decompression his legs again became numb and he felt faint and dizzy; here was an aching pain in the right leg from the ankle to the groin, and ubsequently a similar pain came in the left leg. One hour after decompression e went into the tunnel again and remained there for 3 hours, after which he as again decompressed, this time in 1 hour 50 minutes. His symptoms had not nproved and he stated that he tried to go home but collapsed on the way; he as sent in a police ambulance back to the medical lock on the contractor's te where he remained for 7 hours in all. On decompression from the medical ck he had a severe ache over the precordium, a sensation of bursting and gging pains in both legs—worse in the left—a severe headache, dizziness, zy eyesight, pains behind the eyes, but there was no vomiting. This was at proximately 6.30 a.m. At 7 a.m. he entered the tunnel again, but stayed only ours as he was unable to stand. Decompression was completed in 1½ hours. cause of the severe pains in his left leg the works' doctor gave him an injection morphia and sent him to the Royal Victoria Infirmary, Newcastle. He states t earlier on this day he knocked his left knee.

On examination in the Royal Victoria Infirmary he was found to be conscious, ional, but very verbose. His general condition was excellent and the only ormal findings reported were as follows. The left leg was held stiffly with no ive movement; passive movement was possible but painful. Tone in the right was normal, and in the left leg did not seem to be increased. Co-ordination normal. There was some impairment of sensation to light touch and pain he whole of the left leg, and temperature and vibration senses were absent. scle joint sensation was normal and there was no anaesthesia. Ankle jerks knee jerks were present. The impression formed by the doctor who saw was that this was a mild case of Caisson disease with an overlay of hysteria. patient discharged himself from the ward after 6 days.

COMMENT

Cases 1 and 2 serve to illustrate the fact that decompression sickness, although theoretically preventable, may still occur in a severe and crippling form. In Case 1, the accident arose by the disregard of the regulations, through over-confidence, and it is probable that similar risks had been taken before. It is difficult to know how to ensure that the muck-lock is not used for anything but the passage of materials, and no doubt safety in this respect must lie in the choice of reliable men for responsible jobs and a high standard of discipline. Case 2 was very unusual in that symptoms developed *during* a normal decompression, and this atypical onset may well have contributed to the unfortunate occurrences which followed, by making it hard to recognize the attack for what it was. It is possible that if this man had been returned to the working pressure as soon as he became ill in the decompression chamber, serious results might have been avoided. Again, it is possible that, had the doctor been aware that he could examine the patient under pressure with little delay and no risk to himself, and in addition had been familiar with the proper treatment of decompression sickness, further deterioration in the subject might have been avoided.

A third serious case which does not call for additional comment was notified.

Case 3 described in this Appendix is of quite a different type from the three serious cases just referred to. We do not believe it to represent more than a mild attack of bends (at most), in view of his knowledge of the existence of bends, his unsatisfactory financial position and his clinical story. But it serves to illustrate some details of the way in which the picture of decompression sickness may be overlaid and embroidered.

SUMMARY

1. An investigation has been made into compressed air illness as it occurred during the construction of the Tyne Tunnel (June, 1948–July, 1950). The whole population at risk has been taken into account.

2. A total of 40,000 compressions are reviewed, involving 376 men. Of these, 187 suffered from bends on one or more occasions and a total of 350 cases of decompression sickness occurred. Three cases were serious, two resulting in permanent spinal paralysis; in all three some normal precaution had been neglected.

3. There was a considerable fluctuation in the bends rate from week to week, from zero to as much as 20 per cent among shift workers.

4. Part of the fluctuation in bends rate was due to random variations, but this could not account for fluctuations greater than about 6 per cent.

5. The bends rate bore no close relation to the working pressure, apart from he general observation that bends did not occur with pressures less than 8 to 20 lb. per sq. in. Variations in meteorological conditions did not influence he bends incidence, nor, in general, did working conditions.

6. There was a very important correlation of weekly bends rate with the ecruitment of new labour. In addition, the bends rate appeared to decline ith lapse of time.

7. An analysis of the relation of bends rate in the working population to the ration of employment, adjusting all the workers' records to the same day of st employment, was done for those who had at least one bend (95 per cent the shift workers, 8 per cent of the non-shift workers). It was found that the nds rate fell from an initial level of about 20 per cent to almost negligible lues after months of employment. The rate of fall was rapid in the first few ys, and thereafter slower but still sustained.

8. This decline in bends rate is due mainly to acclimatization but also, ugh to a much less degree, to elimination of susceptibles by "natural ection". The rate of acclimatization is such that, in a group in which no nination took place, the incidence fell from about 12 per cent on the 1st to about 5 per cent on the 5th, and 3 per cent on the 10th. The elimination susceptibles is such as to lower the bends rate slowly by about 1 per cent 50 days.

. There is, in addition to and obscuring the elimination of susceptibles, a dom selection of workers. Men who have experienced one to three attacks bends tend to leave work thereafter, although in many cases there was no ence that they differed in susceptibility from their companions. The date eaving work was often the same as or close to the date of the last bend.

). Consequently the labour force, which at the start contained many eptibles, consisted at the end of well-acclimatized individuals from whom, ddition, susceptibles had been partially eliminated.

. It is suggested that the initially high bends rate associated with the influx ew labour could be lessened by preliminary training of new workers, re compression, at tasks similar to those to be performed later.

. The incidence of bends was largely borne by shift workers, of whom 95 per had one or more attacks of bends; of all other workers, only 8 per cent had s, although numbers of compressions were roughly equal for the two groups. thin the group of shift workers, there was no significant difference of ptibility between the different occupations.

13. While the bends rate for correctly performed decompressions was 1·4 per cent (32 out of 2,291 compressions), it rose to 2·9 per cent when the decompression was accelerated so far that the pressure in the lock was at some time $2\frac{1}{2}$ lb. per sq. in. or more below that laid down in the tables. Decompressions over-rapid to this degree occurred about once in every ten exposures.

14. Between 20 and 50 years of age there was little difference in either initial susceptibility to bends or overall bends rate, but above this age, bends incidence increased sharply. Body weight was not significantly correlated with susceptibility.

15. Two new shorter methods of recompression were compared with the usual method derived from diving practice. They both gave results as good as the usual method for ordinary cases of bends, in spite of using shorter compression times. No reason was found for abandoning the use of a single standard recompression procedure for all subjects, independent of the type of bend.

16. The success of recompression varied directly with the latency of onset of the bend, but was not related to its site, the delay before treatment started, or the age of the subject.

17. The pressure at which relief from a bend was obtained during recompression bore no relation to the site, time of onset, or delay before recompression. In most cases the full working pressure had to be applied.

18. The commonest site for bends was in the leg (183 cases), a good number occurred in the arm (43 cases), and a few (14) in miscellaneous sites, such as the head, chest, abdomen, etc. The site was not related to the nature of the job, weight, age or time of onset.

19. Three illustrative cases of decompression sickness are described in an Appendix.

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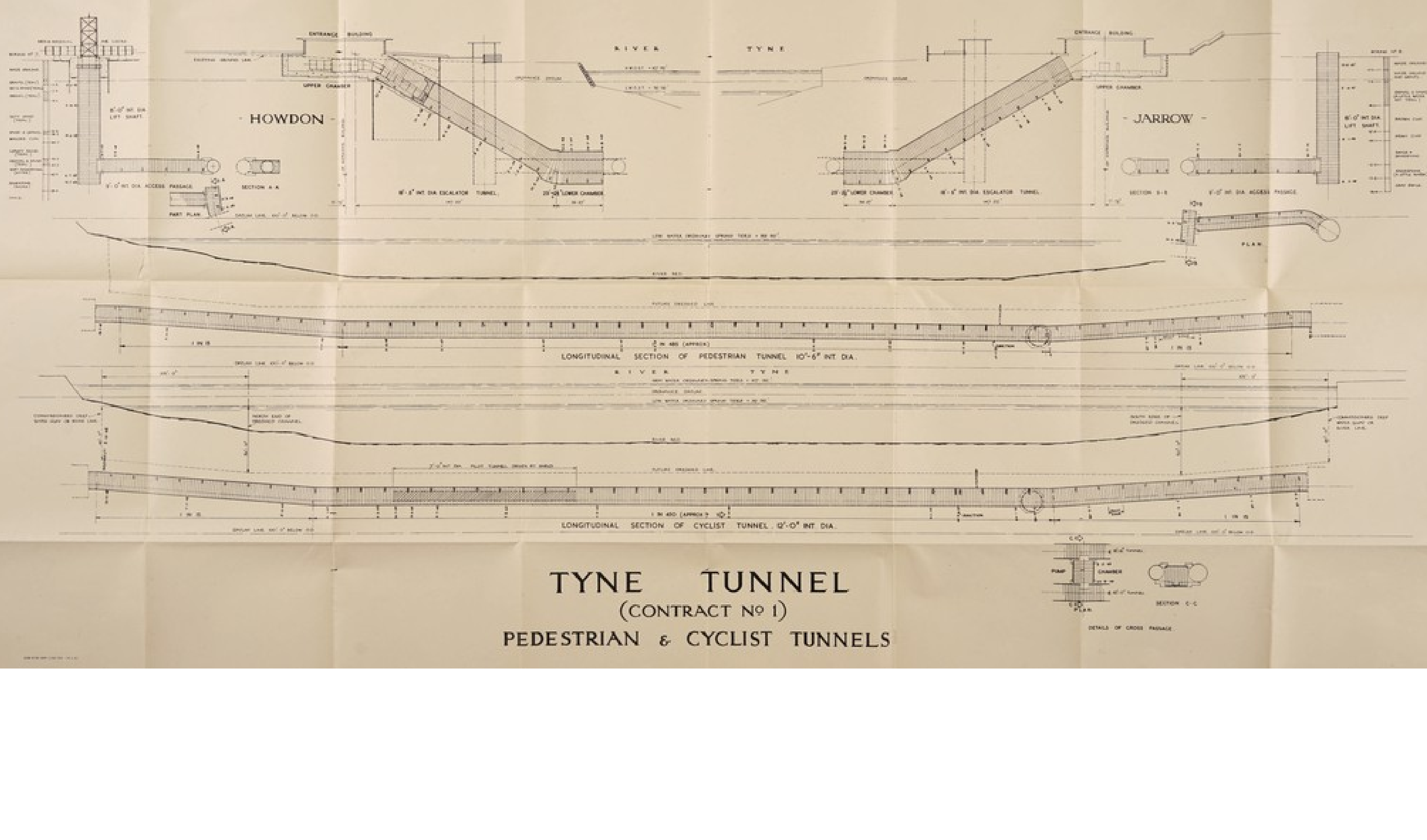

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FIG. 1. General plan of shafts and tunnels, showing times at which the various parts were completed. (Reproduced by kind permission of Charles Brand and Son, Limited.)

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