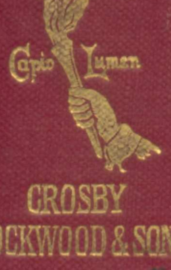
COMPRESSED
AIR WORK
AND
DIVING

Boycott



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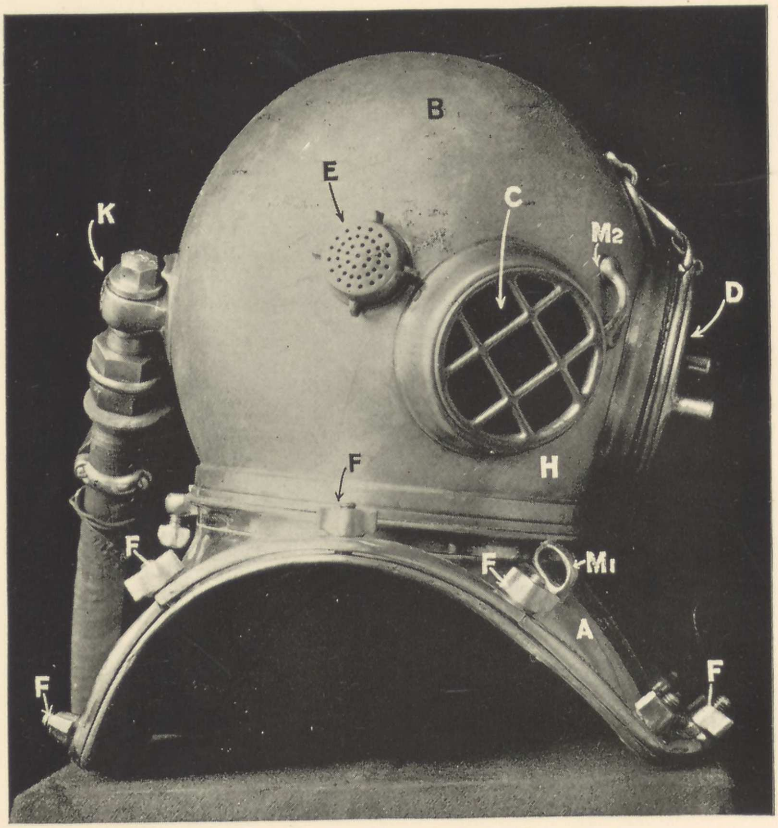
COMPRESSED AIR WORK AND DIVING

G. W. M. Boycott

COMPRESSED AIR WORK AND DIVING



Frontispiece.

DIVING HELMET.
(C. E. HEINKE & Co.)

A. Breastplate.
B. Helmet.
C. Porthole or Window.
D. Face-Plate.
E. Escape Valve.
F. Butterfly Nuts.
K. Inlet Valve.
H. Position of Supplementary Valve when fitted.

M_1. Lug, or eye, to which the life line is fastened. A similar lug on the other side is used for the air pipe.

M_2. A second Lug to which the life line may be fastened, but this is rarely used. There is a similar lug on the other side for the air pipe.

COMPRESSED AIR WORK AND DIVING

A HANDBOOK FOR ENGINEERS

COMPRISING

DEEP WATER DIVING AND THE USE OF COMPRESSED
AIR FOR SINKING CAISSONS AND CYLINDERS AND
FOR DRIVING SUBAQUEOUS TUNNELS

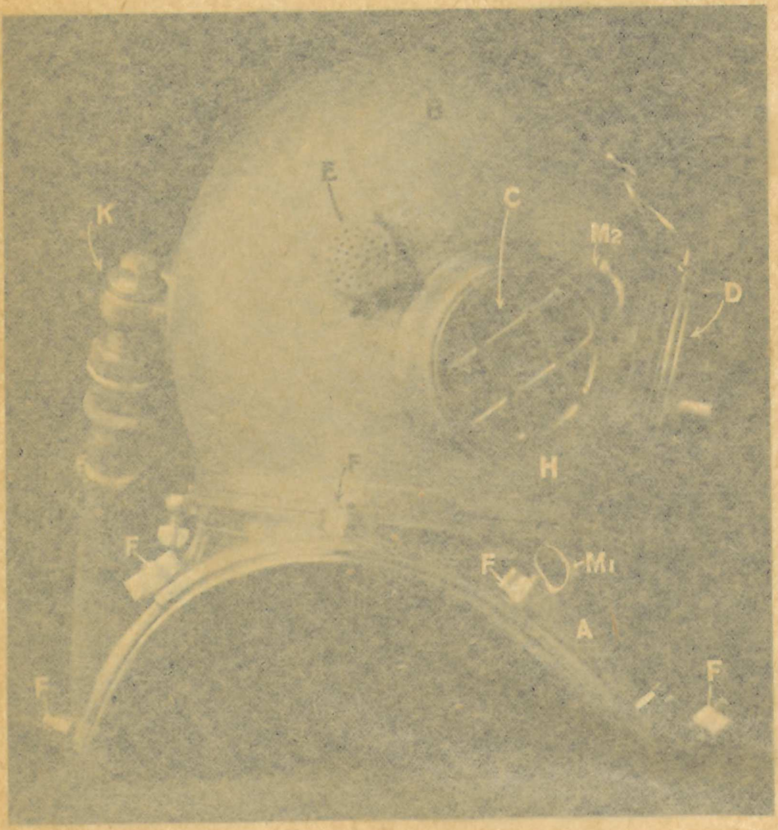
BY

G. W. M. BOYCOTT

ASSOC. M. INST. C.E.

With Numerous Plates and other Illustrations

LONDON
CROSBY LOCKWOOD AND SON
7 STATIONERS' HALL COURT, LUDGATE HILL
1909



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Capio Lumen

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PREFACE.

THIS book has been written with the intention of giving the main principles of compressed air work and diving rather than that it should be a historical review; for in this respect, so far as tunnelling is concerned, the ground has already been to a great extent covered.

More particularly I have been desirous of emphasising the importance of the work of the recent Admiralty Committee on Deep Water Diving, and of Dr J. S. Haldane, F.R.S., Dr A. E. Boycott, and Lieut. G. C. C. Damant, R.N., at the Lister Institute of Preventive Medicine, which has made necessary a revision in our rules and regulations for compressed air work and diving. Accordingly, a set of rules for stage decompression are given in Chapters I. and II., and as, I believe, up to the present, no similar set of rules and regulations has been given in any book on engineering, they will, I trust, be found useful.

Tables I. and II. for diving, and Table IV. for caisson and tunnel work, have been very kindly placed at my disposal by Drs Haldane and Boycott and Lieut. Damant. Further information may be found in the "Report of the Committee on Deep Water Diving," Wyman & Son, Fetter Lane, E.C., and in "Prevention of Compressed Air Illness," Vol. VIII., No. 3, June 1908, *The Journal of Hygiene*, Cambridge Press. These two treatises contain information quite invaluable to the engineer in charge of compressed air work.

I should like to take this opportunity of saying that I feel, and I am sure that every other engineer professionally interested in compressed air work must feel also, that we are deeply indebted to Dr Haldane, Dr Boycott, and Lieut. Damant, and also to Dr Leonard Hill and his colleagues, for the work they have done during the last few years, with the result of adding so much to our knowledge of the preventive treatment of caisson sickness.

Others who have also been good enough to help me, by supplying plans, giving permission to make extracts from their writings, and in other ways, are:—The Institution of Civil Engineers; Mr Maurice Fitzmaurice, C.M.G., who supplied the drawings of Rotherhithe Tunnel; Mr Alfred Noble, who supplied the drawings of the East River Tunnels; Mr F. W. Davis, who supplied the drawings of Barmouth Air-lock and Cylinders, Conway Cylinders, and Davis Air-lock; Mr E. W. Moir, who supplied the drawings of the East River Tunnels Shield and Moir's Medical Lock; Mr John Price, who supplied the drawings of Rotherhithe Tunnel Shield; Mr David Hay; Mr Charles A. Harrison; Mr E. B. Thornhill; Mr Francis Fox; Mr A. J. Collin; Mr E. H. Tabor; Mr J. H. Walker; Mr A. H. Smith; *The Engineer;* Messrs Walker Bros., of Wigan;

Messrs Fraser & Chalmers; Messrs C. E. Heinke & Co.; Messrs Schram Harker & Co.; Messrs Vuibert & Nony; Messrs The Nobel's Explosives Co.; Messrs The Ingersoll-Rand Co. To all these I would express my indebtedness.

G. W. M. BOYCOTT.

25 Lee Terrace,
Blackheath, S.E.,
January 1909.

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COMPRESSED AIR WORK AND DIVING.

CHAPTER I.

Stage Decompression.

Introductory.—The tables in this book have been worked out according to the method originated as the result of the work of a Committee appointed by the British Admiralty in August 1905, to report upon the conditions of deep water diving, and of the investigations of Dr J. S. Haldane, Dr A. E. Boycott, and Lieutenant Damant, R.N., at the Lister Institute of Preventive Medicine.

The principle of this method is, that the diver, or worker in compressed air, is brought rapidly to about half the absolute pressure, stopped there for a time, then decompressed a little further after a sufficient time has elapsed to allow the maximum nitrogen pressure in any part of his body to become not more than about twice the nitrogen pressure of the air at the lower stage. He is then brought on by further stages on the same principle until he reaches atmospheric pressure. The name usually given to this method is that of "stage decompression." Its distinctive feature, however, is not that the decompression is in stages, but that the decompression is rapid for the first part and slow afterwards. Stages are usually adopted because they are found to be the most convenient way of timing the decompression in practical working.

Stage decompression has several great advantages over uniform decompression. One is that the nitrogen in the blood is kept at a maximum safe pressure in excess of the air breathed, and therefore the rate of desaturation is also at a maximum. In this way the greatest economy possible in the time spent in decompression is obtained. Thus to decompress from 213 ft., or a pressure of 95 lbs., would take 309 minutes, or about five hours, whereas to obtain the same standard of safety by uniform decompression would take ten hours, showing an advantage of 50 per cent. in favour of the stage method. Then, when decompressing from great depths or high pressures after short exposures, the saturation, which would otherwise be going on during decompression, is obviated by the first rapid drop in pressure, so that after such short exposures the rate of decompression can be kept within reasonable limits.

Again, the rate of decompression is slowest when most needed, whereas uniform decompression is either unnecessarily slow at the beginning, or dangerously quick at the end.

To those accustomed to uniform decompression, a sudden drop from 45 to 15 lbs., or to half the absolute pressure, might appear dangerous. This, however, is not the case; it is as safe to decompress quickly from 45 to 15 lbs. as it is from 15 lbs. to atmosphere, since in each instance the volume of gas (not the mass) tending to be liberated will be the same. In other words it is the relative, and not the absolute, drop in pressure which has to be considered.

Lastly, this method has been tested by a large number of experimental dives carried out under the direction of the Admiralty Committee, and has been adopted for use in the British Navy.

Note.—Throughout this book pressures are +, or by gauge, unless otherwise stated.

Choice of the Worker.—All divers and caisson workers who have to work at a greater pressure than 18 lbs. should undergo a strict medical examination before being admitted to work, and this examination should be periodically repeated.

All men suffering from chronic disease, alcoholic excess, ear troubles, &c., should be excluded, as well as men who are at all fat or who have ever had any serious symptoms after a reasonably slow decompression, since such an occurrence points strongly towards excessive susceptibility to compressed air illness. For high pressures the skinniest men available should be selected.

Compression.—The rate of compression should be so regulated as not to cause any discomfort or pain in the ears owing to incomplete opening of the Eustachian tubes. A too rapid descent, or compression, might cause mechanical injury followed by middle ear inflammation.

In the Royal Navy divers can descend to 30 fathoms in two or three minutes, and when the exposure is to be at great depths, the descent should be as rapid as possible in order to limit the time of virtual exposure.

In the case of tunnel and caisson workers it is recommended that the compression should be rather slower than with divers. This is because the diver has the rate of compression under his own control, whereas with caisson workers several men are in the air-lock together and amongst them may be one or two who find a little difficulty in inflating their Eustachian tubes quickly. A rate of 5 lbs. in one minute for the first 15 lbs., and 10 lbs. every minute afterwards, will be quite slow enough under ordinary circumstances, and a man who cannot compress comfortably at this rate should be rejected for compressed air work. Sometimes, when a worker is suffering from a cold, considerable discomfort is experienced during compression. Under these circumstances a longer time may be required, and a man with a bad cold should not attempt to pass through the air-lock with others.

If a man experiences any pain he should turn back, and similarly a diver should reascend to the surface.

Air Supply.—It has been found (Haldane and Priestley, *Journal of Physiology*, vol. 32) that the partial pressure of CO_2 in the lung air is about 5·6 per cent. of an atmosphere, and remains constant whatever the pressure of the air breathed may be. Thus at two atmospheres absolute pressure the percentage of CO_2 in the lung air will be $\frac{5 \cdot 6}{2} = 2.8$ per cent., and at three atmospheres $\frac{5 \cdot 6}{3} = 1.9$ per cent. And since the percentage of CO_2 in the air breathed must not be allowed to rise above that normal to the lung air, it follows that when the air supply, with the diver's head just below water, is the minimum required, it must be increased with the depth. Thus a diver who will require at atmospheric pressure a minimum of about 1.5 cub. ft. of free air per minute, at a depth of 33 ft., or two atmospheres' absolute pressure, will want 3 cub. ft. of free air per minute, and at 66 ft. 4.5 cub. ft. of free air per minute.

Or, to put it another way, starting with a minimum supply at atmospheric pressure, the volume of air, measured at the given pressure, supplied him must remain constant whatever the pressure.

In caisson or tunnel work the supply should be at least 5 cub. ft. per man per minute, measured at the existing pressure, or 300 cub. ft. per man per hour. This larger air supply is to allow for fumes generated by blasting and other impurities; but if these impurities are at all excessive, a larger air supply will be needed.

Table I. For Diving.—This table has been arranged with exposures sufficiently short to keep the time, which must be spent in decompression, within reasonable limits.

As an example of its use we may take the case of a diver who is going to do some work at a depth of 96 ft. He would descend as rapidly as possible to the bottom, taking say two minutes in doing so. At the end of $55-2=53$ minutes at the bottom, or fifty-five minutes from the surface, he would start coming up, and would do so quickly (the ears can always follow any rate of decompression), until he reached a depth of 30 ft., when he would stop three minutes. At the end of three minutes he would ascend to 20 ft., and stop there ten minutes, and at the end of the ten minutes he would ascend to a depth of 10 ft. and stop there fifteen minutes. He would then ascend the remainder of the way to the surface. The time taken in ascending to the first stopping place might be about two minutes, and a half minute or so for each 10 ft. of ascent between the stoppages and for the last 10 ft. He should move his arms and legs during each stoppage in order to hasten desaturation. The stoppages are regulated by signal from surface according to the readings of the pressure gauge.

A diver has sometimes to descend twice or oftener at short intervals. When this happens the more slowly desaturating parts of his body will not have become desaturated at the time the second descent begins. To meet the increased risk the two periods at the bottom should be added together, and the proper stoppages for such an exposure used during the second ascent.

With an interval of one hour between the exposures these precautions may be halved, or with two hours' interval may be altogether omitted, if the duration of exposure during the first dive has not exceeded that shown in the table.

Table II.—This table is for use when a diver has been detained at the bottom beyond the ordinary limit of time by reason of some accidental circumstance, such as getting his life line or air pipe entangled.

These two tables for diving have been so arranged, by a slight modification in the spacing of the stoppages demanded by theoretical considerations, as to prevent any danger of "bends" in the water. It should be noted that "bends," which are caused by the more slowly desaturating tissues, although painful, are not so dangerous as other symptoms, such as paralysis. For this reason, if the diver is in a collapsed condition after a long exposure in cold water, the last stop at 10 ft. might be omitted, since the stoppage at 20 ft. will already have got rid of most of the harmful excess of gas. If decompression symptoms are feared, and no medical lock is available, the diver should be kept on the ladder for about ten minutes, so that he can be lowered into the water if necessary. And when he has been brought on board he might sit for another twenty minutes before undressing, still wearing his boots, helmet, &c., and merely having his front and back lead weights removed, so that he can be sent below again at once on the appearance of symptoms.

It will not usually be necessary for him to go to a greater depth than that for the first stoppage, and generally a depth of 20 ft. will be sufficient.

TABLE I.

[A. E. BOYCOTT, G. C. C. DAMANT, AND J. S. HALDANE.]

Stoppages during the Ascent of a Diver after Ordinary Limits of Time from Surface.

Depth.		Pressure. Pounds per sq. in.	Time from Surface to Beginning of Ascent.	Approx. Time to First Stop.	Stoppages in Minutes at different Depths.*						Total Timefor Ascent in mins.
Feet.	Fathoms.				60 ft.	50 ft.	40 ft.	30 ft.	20 ft.	10 ft.	
0-36	0-6	0-16	No limit -	...	...	...	...	...	...	...	0-1
36-42	6-7	16-18½	Over 3 hours -	1	...	...	...	...	...	5	6
42-48	7-8	18½-21	Up to 1 hour -	...	...	...	...	...	...	...	1½
			1 to 3 hours -	1½	...	...	...	...	...	5	6½
			Over 3 hours -	1½	...	...	...	...	...	10	11½
48-54	8-9	21-24	Up to ½ hour -	...	...	...	...	...	...	...	2
			½ to 1½ hours -	2	...	...	...	...	...	5	7
			1½ to 3 hours -	2	...	...	...	...	...	10	12
			Over 3 hours -	2	...	...	...	...	...	20	22
54-60	9-10	24-26½	Up to 20 mins.	...	...	...	...	...	...	...	2
			20 to 45 mins. -	2	...	...	...	...	...	5	7
			¾ to 1½ hours -	2	...	...	...	...	...	10	12
			1½ to 3 hours -	2	...	...	...	...	5	15	22
			Over 3 hours -	2	...	...	...	...	10	20	32
60-66	10-11	26½-29½	Up to ¼ hour -	2	...	...	...	...	...	...	2
			¼ to ½ hour -	2	...	...	...	...	...	5	7
			½ to 1 hour -	2	...	...	...	...	3	10	15
			1 to 2 hours -	2	...	...	...	...	5	15	22
			2 to 3 hours -	2	...	...	...	...	10	20	32
66-72	11-12	29½-32	Up to ¼ hour -	2	...	...	...	...	...	2	4
			¼ to ½ hour -	2	...	...	...	...	3	5	10
			½ to 1 hour -	2	...	...	...	...	5	12	19
			1 to 2 hours -	2	...	...	...	...	10	20	32
72-78	12-13	32-34½	Up to 20 mins.	2	...	...	...	...	...	5	7
			20 to 45 mins. -	2	...	...	...	...	5	10	17
			¾ to 1½ hours -	2	...	...	...	...	10	20	32
78-84	13-14	34½-37	Up to 20 mins.	2	...	...	...	...	...	5	7
			20 to 45 mins. -	2	...	...	...	...	5	15	22
			¾ to 1¼ hours -	2	...	...	...	...	10	20	32
84-90	14-15	37-40	Up to 10 mins.	2	...	...	...	...	...	3	5
			10 to 20 mins. -	2	...	...	...	...	3	5	10
			20 to 40 mins. -	2	...	...	...	...	5	15	22
			40 to 60 mins. -	2	...	...	...	3	10	15	30
90-96	15-16	40-42½	Up to 10 mins.	3	...	...	...	...	...	3	6
			10 to 20 mins. -	2	...	...	...	...	3	5	10
			20 to 35 mins. -	2	...	...	...	...	5	15	22
			35 to 55 mins. -	2	...	...	...	3	10	15	30
96-108	16-18	42½-48	Up to 15 mins.	3	...	...	...	...	3	5	11
			15 to 30 mins. -	3	...	...	...	3	7	10	23
			30 to 40 mins. -	3	...	...	...	5	10	15	33
108-120	18-20	48-53½	Up to 15 mins.	3	...	...	...	2	3	7	15
			15 to 25 mins. -	3	...	...	...	5	5	10	23
			25 to 35 mins. -	3	...	...	...	5	10	15	33
120-132	20-22	53½-59	Up to 15 mins.	3	...	...	...	2	5	7	17
			15 to 30 mins. -	3	...	...	...	5	10	15	33
132-144	22-24	59-64½	Up to 12 mins.	3	...	...	...	3	5	5	16
			12 to 25 mins. -	3	...	...	2	5	10	12	32
144-156	24-26	64½-70	Up to 10 mins.	3	...	...	...	3	5	5	16
			10 to 20 mins. -	3	...	...	2	5	10	12	32
156-168	26-28	70-75	Up to 10 mins.	3	...	...	2	3	5	5	18
			10 to 16 mins. -	3	...	2	3	5	7	10	30
168-180	28-30	75-80½	Up to 9 mins. -	3	...	...	2	3	5	5	18
			9 to 14 mins. -	3	...	2	3	5	7	10	30
180-192	30-32	80½-86	Up to 13 mins.	3	...	2	3	5	7	10	30
192-204	32-34	86-91½	Up to 12 mins.	3	2	2	3	5	7	10	32

* During each stoppage the diver should continue to move his arms and legs.

TABLE II.

[A. E. Boycott, G. C. C. Damant, and J. S. Haldane.]

Stoppages during the Ascent of a Diver after Delay beyond the Ordinary Limits of Time from Surface.

Depth.		Pressure. Pounds per sq. in.	Time from Surface to Beginning of Ascent.	Approx. Time to First Stop.	Stoppages in Minutes at different Depths.								Total Time for Ascent in mins.
Feet.	Fathoms.				80 ft.	70 ft.	60 ft.	50 ft.	40 ft.	30 ft.	20 ft.	10 ft.	
60-66	10-11	26½-29½	Over 3 hours	2	...	...	...	...	...	...	10	30	42
66-72	11-12	29½-32	2 to 3 hours	2	...	...	...	...	...	...	10	30	42
			Over 3 hours	2	...	...	...	...	...	...	20	30	52
72-78	12-13	32-34½	1½ to 2½ hours	2	...	...	...	...	...	...	20	25	47
			Over 2½ hours	2	...	...	...	...	...	...	30	30	62
78-84	13-14	34½-37	1¼ to 2 hours	2	...	...	...	...	...	...	15	30	47
			2 to 3 hours	2	...	...	...	...	...	5	30	30	67
			Over 3 hours	2	...	...	...	...	...	10	30	35	77
84-90	14-15	37-40	1 to 1½ hours	2	...	...	...	...	...	5	15	25	47
			1½ to 2½ hours	2	...	...	...	...	...	5	30	35	72
			Over 2½ hours	2	...	...	...	...	...	20	35	35	92
90-96	15-16	40-42½	1 to 1½ hours	2	...	...	...	...	...	5	15	30	52
			1½ to 2½ hours	2	...	...	...	...	...	10	30	35	77
			Over 2½ hours	2	...	...	...	...	...	30	35	35	102
96-108	16-18	42½-48	40 to 60 mins.	2	...	...	...	...	...	10	15	20	47
			1 to 2 hours	2	...	...	...	...	5	15	25	35	82
			Over 2 hours	2	...	...	...	...	15	30	35	40	122
108-120	18-20	48-53½	35 to 60 mins.	2	...	...	...	...	5	10	15	25	57
			1 to 2 hours	2	...	...	...	...	10	20	30	35	97
			Over 2 hours	2	...	...	...	...	30	35	35	40	142
120-132	20-22	53½-59	30 to 45 mins.	3	...	...	...	...	5	10	15	20	53
			¾ to 1½ hours	3	...	...	...	5	10	20	30	30	98
			Over 1½ hours	3	...	...	...	15	30	35	40	40	163
132-144	22-24	59-64½	25 to 45 mins.	3	...	...	...	3	5	10	15	25	61
			¾ to 1½ hours	3	...	...	...	10	10	20	30	35	108
			Over 1½ hours	3	...	...	...	30	30	35	40	40	178
144-156	24-26	64½-70	20 to 35 mins.	3	...	...	...	3	5	10	15	20	56
			35 to 60 mins.	3	...	...	...	7	10	15	30	30	95
			Over 1 hour	3	...	...	20	25	30	35	40	40	193
156-168	26-28	70-75	16 to 30 mins.	3	...	...	...	3	5	10	15	20	56
			30 to 60 mins.	3	...	...	3	10	10	15	30	30	101
			Over 1 hour	3	...	5	25	25	30	35	40	40	203
168-182	28-30	75-80½	14 to 20 mins.	3	...	...	...	3	3	7	10	15	41
			20 to 30 mins.	3	...	...	2	2	3	10	15	25	60
			30 to 60 mins.	3	...	3	3	7	10	20	30	35	111
			Over 1 hour	3	...	15	25	30	30	35	40	40	218
182-194	30-32	80½-86	13 to 20 mins.	3	...	...	...	3	3	7	15	15	46
			20 to 30 mins.	3	...	...	3	3	5	10	15	25	64
			30 to 60 mins.	3	...	3	5	10	12	20	30	35	118
			Over 1 hour	3	5	20	25	30	30	35	40	40	228
194-206	32-34	86-91½	12 to 20 mins.	3	...	...	3	3	5	7	10	20	51
			20 to 30 mins.	3	...	3	3	3	5	10	20	20	67
			30 to 60 mins.	3	3	3	5	10	15	20	30	35	124
			Over 1 hour	3	15	20	25	30	30	35	40	40	238

Sometimes, however, if the symptoms are severe, it may be necessary to send him to a greater depth for a few minutes in order to relieve the pain and to cause any bubbles which may have formed to go into solution again more quickly than they would otherwise do.

TABLE III.

Showing MINIMUM *Air Supply required by Divers.*

Depth.		Pressure in Pounds per square inch due to Head of Salt Water.	Cubic Feet of Free Air per Man per Minute.
Feet.	Fathoms.		
33	5½	15	3·0
66	11	29	4·5
99	16½	44	6·0
132	22	59	7·5
165	27½	74	9·0
198	33	88	10·5
231	38½	103	12·0

In salt water at a depth of 1 foot pressure = 0·445 pound per square inch nearly.
In fresh ,, ,, ,, 0·434 ,, ,,

CHAPTER II.

Stage Decompression (*continued*).

Table IV.—This table is for use in caisson or tunnel work where long shifts may be employed by reason of the comparatively low pressure usually necessary for this class of work.

With such long shifts and low pressures the calculated theoretical rate of decompression is nearly uniform after the first rapid drop in pressure, and the rules for decompression are greatly simplified by adopting uniform decompression. The table gives the number of minutes for each pound of decompression after a first rapid drop in the proportion of two to one in absolute pressure.

Suppose, for instance, that men working at a pressure of 30 lbs. came out for a meal after three hours' exposure, they would first decompress rapidly to $\frac{30+15}{2} = 22\frac{1}{2}$ lbs. absolute pressure, or $7\frac{1}{2}$ lbs. by gauge. They would then lower the pressure 1 lb. every six minutes, taking $6 \times 7\frac{1}{2} = 45$ minutes to pass through the air-lock. After a second or third exposure the time required would be $7 \times 7\frac{1}{2} = 52\frac{1}{2}$ minutes. After six hours or more continuous exposure $8 \times 7\frac{1}{2} = 60$ minutes would be required. It is clear that in order to economise time spent in the air-lock it will be better for pressures over 25 lbs. to keep the men continuously under pressure during each shift, and such an arrangement is usually preferred by the men themselves.

Rule.—Decompress to half the absolute pressure rapidly, and then at the rates given in the table.

Table V.—In tunnel work or in caisson sinking, where the space is available, it is recommended that a section of tunnel or large air-lock should be provided where the pressure should be constantly maintained at a little less than half the absolute pressure. With such an arrangement the men would be able to pass rapidly from the working chamber or section of tunnel into the "purgatory" air-lock or section of tunnel, and after a delay, proportionate to the working pressure, would pass rapidly out. Whilst in the lock, they could occupy their time in changing their clothes and washing, or in having a meal, and the moving about thus occasioned would considerably hasten the process of desaturation.

This method is a very convenient one for tunnel work, as the ordinary air-locks are kept free for ingress and egress of material, except for the few minutes during each shift actually occupied in passing in and out.

In the table, in the first column, is given the working pressure, in the second the absolute working pressure $\div 2.2$, which is the pressure at which the air must be maintained in the purgatory lock, and in the other columns are given the time in minutes which must be spent in the lock after different lengths of exposure.

Thus, with a working pressure of 34 lbs., the pressure in the purgatory lock or section of tunnel would be $\frac{34+15}{2.2} = 22\frac{1}{2}$ lbs. nearly of absolute pressure or $7\frac{1}{2}$ lbs. by gauge. Any one coming out after three hours would have to spend fifty minutes in the purgatory lock as shown in the third column from the end.

The custom has usually been to work one and a half hours twice a day at a pressure of 45 lbs., and it will perhaps be well, until further practical experience is available, that exposures at 45 lbs. should not exceed two hours, at 40 lbs. should not exceed three hours, and at 35 lbs. should not exceed four hours.

Saturation is practically complete in six hours, so that the lengths of time to be spent in the lock after six hours' exposure will also serve for longer exposures.

Tables VI. and VII.—These two tables are for use after curative recompression in the medical lock, or after preventive recompression made necessary by some accident, such for instance as a burst dress in the case of a diver, or a cracked cast-iron cylinder in caisson work. When a worker is suddenly decompressed by some such accident as one of these, he should immediately be placed in the air-lock, and the pressure raised as quickly as possible up to, or very nearly up to, the pressure he has just been working at. If no symptoms appear, or when those which have appeared have disappeared, the pressure should be slowly and cautiously lowered to about half the absolute working pressure. It should then be lowered in stages, with stoppages every 5 lbs. as given in the tables. After recompression in the air-lock, decompression should be very slow and cautious, as the bubbles may not have become completely dissolved during the recompression.

It is inadvisable to keep a patient long at pressures above 45 lbs., so that if at any time it is necessary to recompress at pressures higher than this a start should be made in lowering the pressure very soon after the patient has entered the air-lock.

The two tables have been calculated for three hours' and six hours' added exposure respectively. To find the value of this exposure the time spent in the medical lock before the half absolute pressure is reached should be added to the working exposure.

As a general rule it is not wise to hurry decompression after curative treatment, and the six hour table will therefore be the safest one to use. If the patient is, however, only being treated for a mild case of bends which has come on an hour or so after leaving work, these excessive precautions need not be taken, provided the pressure in the medical air-lock is not raised above about 15 lbs., which will usually be sufficient for treatment of cases such as these.

The medical lock should be fitted with a couch, on which a patient may recline, and should also have double doors like those of an ordinary working air-lock, so that a doctor may be able to enter and attend to a patient without any necessity of raising or lowering the pressure in the medical lock itself.

TABLE IV.

[A. E. Boycott, G. C. C. Damant, and J. S. Haldane.]

Showing Rate of Decompression in Caisson and Tunnel Work.

Working Pressure in Pounds per Square Inch.	Number of Minutes for each Pound of Decompression after the First Rapid Stage.		
	After first three hours' exposure.	After second or third three hours' exposure following an interval for a meal.	After six hours or more of continuous exposure.
18-20 pounds	2	3	5
21-24 ,,	3	5	7
25-29 ,,	5	7	8
30-34 ,,	6	7	9
35-39 ,,	7	8	9
40-45 ,,	7	8	9

TABLE V.

For Caisson and Tunnel Work.

Working Pressure in Pounds per Square Inch.	Pressure in Purgatory Lock in Pounds per Square Inch.	Time in Minutes to be spent in Purgatory Air-Lock.						
		After 20 minutes' exposure.	After 40 minutes' exposure.	After 1 hour's exposure.	After 2 hours' exposure.	After 3 hours' exposure.	After 4 hours' exposure.	After 6 hours' exposure, or over.
21	1½	...	...	1	2	3	4	5
22	1½	...	1	2	4	5	8	10
23	2	...	2	3	5	8	11	15
24	2½	1	3	4	7	11	14	20
25	3	2	3	5	9	13	18	26
26	3½	2	4	6	11	16	22	32
27	4	2	5	7	13	19	25	38
28	4½	3	5	8	15	23	30	44
29	5	3	6	9	18	26	35	50
30	5½	4	7	11	20	30	40	56
31	6	4	8	12	23	35	45	*62*
32	6½	4	9	14	27	40	50	*68*
33	7	5	10	15	30	45	56	*74*
34	7½	5	11	17	34	50	63	*80*
35	8	6	12	19	38	56	70	*86*
36	8½	7	13	21	42	62	*76*	*92*
37	9	8	15	23	46	68	*83*	*100*
38	9½	8	17	25	50	74	*90*	*108*
39	9½	9	19	27	55	81	*96*	*114*
40	10	10	20	29	60	87	*103*	*120*
41	10½	11	22	32	66	*95*	*110*	*128*
42	11	12	24	35	72	*102*	*118*	*134*
43	11½	13	26	38	78	*110*	*126*	*142*
44	12	14	28	41	85	*120*	*134*	*150*
45	12½	15	30	45	92	*128*	*142*	*160*

The figures in italic type are for emergency use only.

TABLE VI.

Showing Rate of Decompression in Medical Lock after THREE HOURS' ADDED EXPOSURE.

Working Pressure in Pounds per Square Inch.	Half Absolute Working Pressure in Pounds per Square Inch.	Stoppages in Minutes at Different Pressures.								Total Time for Stage Decompression in Minutes.
		40 lbs.	35 lbs.	30 lbs.	25 lbs.	20 lbs.	15 lbs.	10 lbs.	5 lbs.	
18	1½	...	...	...	...	...	...	...	15	15
19	2	...	...	...	...	...	...	...	20	20
20	2½	...	...	...	...	...	...	...	20	20
21	3	...	...	...	...	...	...	...	25	25
22	3½	...	...	...	...	...	...	...	30	30
23	4	...	...	...	...	...	...	...	35	35
24	4½	...	...	...	...	...	...	...	40	40
25	5	...	...	...	...	...	...	...	45	45
26	5½	...	...	...	...	...	...	5	50	55
27	6	...	...	...	...	...	...	10	50	60
28	6½	...	...	...	...	...	...	10	55	65
29	7	...	...	...	...	...	...	15	55	70
30	7½	...	...	...	...	...	...	15	60	75
31	8	...	...	...	...	...	...	20	60	80
32	8½	...	...	...	...	...	...	20	65	85
33	9	...	...	...	...	...	...	25	65	90
34	9½	...	...	...	...	...	...	25	70	95
35	10	...	...	...	...	...	...	30	70	100
36	10½	...	...	...	...	...	5	30	70	105
37	11	...	...	...	...	...	5	30	75	110
38	11½	...	...	...	...	...	10	30	75	115
39	12	...	...	...	...	...	10	35	75	120
40	12½	...	...	...	...	...	10	35	75	120
41	13	...	...	...	...	...	10	40	75	125
42	13½	...	...	...	...	...	15	40	75	130
43	14	...	...	...	...	...	20	40	75	135
44	14½	...	...	...	...	...	20	40	75	135
45	15	...	...	...	...	...	25	40	75	140
46	15½	...	...	...	...	5	25	40	75	145
47	16	...	...	...	...	5	25	45	75	150
48	16½	...	...	...	...	10	25	45	75	155
49	17	...	...	...	...	10	25	45	75	155
50	17½	...	...	...	...	10	25	50	75	160
50-55	17½-20	...	...	...	...	20	30	55	75	180
55-60	20 -22½	...	...	...	10	20	35	55	75	195
60-65	22½-25	...	...	...	15	25	40	55	75	210
65-70	25 -27½	...	...	10	15	30	40	55	75	225
70-75	27½-30	...	...	15	20	30	40	55	75	235
75-80	30 -32½	...	5	15	25	35	40	55	75	250
80-85	32½-35	...	10	20	25	35	40	55	75	260
85-90	35 -37½	5	15	20	25	35	40	55	75	270

TABLE VII.

Showing Rate of Decompression in Medical Lock after SIX HOURS' ADDED EXPOSURE *or over.*

Working Pressure in Pounds per Square Inch.	Half Absolute Working Pressure in Pounds per Square Inch.	Stoppages in Minutes at Different Pressures.								Total Time for Stage Decompression in Minutes.
		40 lbs.	35 lbs.	30 lbs.	25 lbs.	20 lbs.	15 lbs.	10 lbs.	5 lbs.	
18	1½	...	...	...	...	...	...	...	30	30
19	2	...	...	...	...	...	...	...	35	35
20	2½	...	...	...	...	...	...	...	45	45
21	3	...	...	...	...	...	...	...	50	50
22	3½	...	...	...	...	...	...	...	55	55
23	4	...	...	...	...	...	...	...	60	60
24	4½	...	...	...	...	...	...	...	70	70
25	5	...	...	...	...	...	...	...	75	75
26	5½	...	...	...	...	...	...	5	75	80
27	6	...	...	...	...	...	...	15	75	90
28	6½	...	...	...	...	...	...	20	75	95
29	7	...	...	...	...	...	...	25	75	100
30	7½	...	...	...	...	...	...	30	75	105
31	8	...	...	...	...	...	...	35	75	110
32	8½	...	...	...	...	...	...	40	75	115
33	9	...	...	...	...	...	...	45	75	120
34	9½	...	...	...	...	...	...	50	75	125
35	10	...	...	...	...	...	...	55	75	130
36	10½	...	...	...	...	...	5	55	75	135
37	11	...	...	...	...	...	10	55	75	140
38	11½	...	...	...	...	...	15	55	75	145
39	12	...	...	...	...	...	20	55	75	150
40	12½	...	...	...	...	...	25	55	75	155
41	13	...	...	...	...	...	30	55	75	160
42	13½	...	...	...	...	...	35	55	75	165
43	14	...	...	...	...	..	35	55	75	165
44	14½	...	...	...	...	...	40	55	75	170
45	15	...	...	...	...	...	45	55	75	175
46	15½	...	...	...	...	5	45	55	75	180
47	16	...	...	...	...	10	45	55	75	185
48	16½	...	...	...	...	10	45	55	75	185
49	17	...	...	...	...	15	45	55	75	190
50	17½	...	...	...	...	20	45	55	75	195
50-55	17½-20	...	...	...	...	35	45	55	75	210
55-60	20 -22½	...	...	...	15	35	45	55	75	225
60-65	22½-25	...	...	...	30	35	45	55	75	240
65-70	25 -27½	...	...	15	30	35	45	55	75	255
70-75	27½-30	...	...	25	30	35	45	55	75	265
75-80	30 -32½	...	15	25	30	35	45	55	75	280
80-85	32½-35	...	25	25	30	35	45	55	75	290
85-90	35 -37½	10	25	25	30	35	45	55	75	300

TABLE VIII.

Showing Pounds per Square Inch and Nearest Equivalent Kilogrammes per Square Centimetre.

Pounds per Square Inch.	Kilogrammes per Square Centimetre.	Pounds per Square Inch.	Kilogrammes per Square Centimetre.	Pounds per Square Inch.	Kilogrammes per Square Centimetre.
1	0·07	35	2·46	68	4·78
2	0·14	36	2·53	69	4·85
3	0·21	37	2·60	70	4·92
4	0·28	38	2·67	71	4·99
5	0·35	39	2·74	72	5·06
6	0·42	40	2·81	73	5·13
7	0·49	41	2·88	74	5·20
8	0·56	42	2·95	75	5·27
9	0·63	43	3·02	76	5·34
10	0·70	44	3·09	77	5·41
11	0·77	45	3·16	78	5·48
12	0·84	46	3·23	79	5·55
13	0·91	47	3·30	80	5·62
14	0·98	48	3·37	81	5·70
15	1·05	49	3·45	82	5·77
16	1·12	50	3·52	83	5·84
17	1·20	51	3·59	84	5·91
18	1·27	52	3·66	85	5·98
19	1·34	53	3·73	86	6·05
20	1·41	54	3·80	87	6·12
21	1·48	55	3·87	88	6·19
22	1·55	56	3·94	89	6·26
23	1·62	57	4·01	90	6·33
24	1·69	58	4·08	91	6·40
25	1·76	59	4·15	92	6·47
26	1·83	60	4·22	93	6·54
27	1·90	61	4·29	94	6·61
28	1·97	62	4·36	95	6·68
29	2·04	63	4·43	96	6·75
30	2·11	64	4·50	97	6·82
31	2·18	65	4·57	98	6·89
32	2·25	66	4·64	99	6·96
33	2·32	67	4·71	100	7·03
34	2·39	...	...	...	...

TABLE IX.

Giving Feet and Nearest Equivalent Metres.

Feet.	Metres.	Feet.	Metres.	Feet.	Metres.
1	0·3	35	10·7	68	20·7
2	0·6	36	11·0	69	21·0
3	0·9	37	11·3	70	21·3
4	1·2	38	11·6	71	21·6
5	1·5	39	11·9	72	21·9
6	1·8	40	12·2	73	22·3
7	2·1	41	12·5	74	22·6
8	2·4	42	12·8	75	22·9
9	2·7	43	13·1	76	23·2
10	3·0	44	13·4	77	23·5
11	3·4	45	13·7	78	23·8
12	3·7	46	14·0	79	24·1
13	4·0	47	14·3	80	24·4
14	4·3	48	14·6	81	24·7
15	4·6	49	14·9	82	25·0
16	4·9	50	15·2	83	25·3
17	5·2	51	15·5	84	25·6
18	5·5	52	15·8	85	25·9
19	5·8	53	16·2	86	26·2
20	6·1	54	16·5	87	26·5
21	6·4	55	16·8	88	26·8
22	6·7	56	17·1	89	27·1
23	7·0	57	17·4	90	27·4
24	7·3	58	17·7	91	27·7
25	7·6	59	18·0	92	28·0
26	7·9	60	18·3	93	28·3
27	8·2	61	18·6	94	28·7
28	8·5	62	18·9	95	29·0
29	8·8	63	19·2	96	29·3
30	9·1	64	19·5	97	29·6
31	9·4	65	19·8	98	29·9
32	9·8	66	20·1	99	30·2
33	10·1	67	20·4	100	30·5
34	10·4	...	...	...	...

CHAPTER III.

The Common Diving Dress and Helmet.

The first practicable diving dress was invented by Mr Augustus Siebe in the year 1828, and consisted of a helmet and short jacket, coming down to the waist, below which the air escaped after the manner of a diving bell. The inconvenience of this dress is of course apparent, and lies in the fact that the diver cannot stoop to his work, but must for safety remain almost upright. As a result Mr Siebe, whilst engaged on the wreck of the "Royal George," invented, in 1839, the closed type of dress, and this dress with very few modifications has remained in use in this country ever since.

The dress is made of strong waterproofed canvas in one piece, and the only openings are at the wrists and at the neck, where the breastplate is attached. The wrist-bands are made of stout vulcanised rubber, which, when the diver has the dress on, tightly grip the wrists. The water is prevented from entering when the diver's arms are below the level of the helmet, by the fact that the pressure of the water causes the dress to cling tightly round the diver's arms, and when he raises his arms to the level of his helmet, by the pressure of the air inside the dress. When the diver lifts his arms up above his head, the sleeves fill with air, and air will escape in bubbles at his wrists. No water can, however, enter, as the pressure of air in his sleeve is greater than that of the water above his head.

The top of the dress is a flat band of vulcanised rubber about $\frac{1}{4}$ in. thick and about 2 in. wide. This band fits over the breastplate, and is secured to it by a metal plate in four pieces. This plate is fastened to the breastplate by twelve studs which pass through it. The rubber band has twelve holes corresponding to the studs. By means of butterfly nuts the plate is screwed down tight to the breastplate, squeezing the rubber band between, so that a perfect watertight joint is obtained.

The breastplate terminates in a collar which is threaded in segments—first a threaded segment and then one plain. The helmet is treated in the same manner, and is put on by applying the threaded portion of the helmet to the unthreaded portion of the breastplate. It is made secure by a one-eighth turn, and prevented from twisting open by a hinged catch. The helmet itself has two glass port-holes or windows, one on each side, protected by strong bars. The face-plate is made of strong glass with a brass rim, and is screwed on just before the diver goes over the side of the diving boat. It also is frequently protected by bars.

At the back of the helmet is the attachment for the air pipe, and this contains a valve with a spring, so that if anything happens to the air pipe it will at once close. The pressure of air inside the helmet will keep it closed so that no water can enter. The strength of the spring is sufficient to keep it thus, even though the pressure inside the helmet is slightly below that caused by the head of water at the level of the valve. The spring of the escape valve should, however, be kept screwed up sufficiently tight to prevent the pressure of air inside the helmet from falling below that caused by the head of water at a level about 3 in. below it.

On the right-hand side of the helmet, just behind the glass window, is the escape valve, fitted with a weak spring for the escape of surplus air. It is closed by a perforated plug which can be screwed in or out according as the diver wishes to raise or lower the pressure in the helmet and dress.

On the right-hand side in front of the window, and lower down than the escape valve, is a supplementary valve which is closed by the diver just before going under the water. It is not an essential part of the apparatus, but is used by professional divers for taking in water into the mouth for the purpose of washing down condensed moisture on the face-plate.

Two lead weights, back and front, weighing 36 to 40 lbs. each, and boots with thick lead soles weighing 16 lbs. each, and a belt with knife attached complete the outfit. The lead weights and lead-soled shoes are to cause the diver to sink, since in his dress and helmet he will be very much lighter than the water displaced.

When the diver is getting ready for a descent he puts on over his underclothing a white woollen jersey and a pair of woollen pants. One or two pairs of woollen stockings are then put on and drawn up over the pants. He then steps into the dress and sits down whilst the attendant pulls up the feet of the dress until the diver's feet are well into them. He then stands up, and having had the backs of his hands well soaped, with the help of the attendant works them through the tight rubber wristbands. If the diver has small wrists, it is sometimes a good plan to first wrap round them strips of washleather about 2 in. wide and about 15 in. long. These should be slightly moistened, and have a piece of string attached at one end, which can be tied round the wrists to make all secure. One or two pairs of strong elastic bands, specially made for the purpose, should then be put on over the wrist-bands of the dress.

The shoulder pad is then put on under the dress, and this is followed by the breastplate. Inside the dress will be found a loose piece folded up. This must be pulled through the ring of the breastplate and well up round the diver's face. The rubber neckband must then be fitted on to the studs and fastened down by the loose pieces of plate and the butterfly nuts. These last, after having been first tightened up with the fingers, must have a final tightening up with the spanner provided with every set of apparatus. The piece of dress, referred to as being found folded up, can then be comfortably arranged so as to be out of the way of the diver.

The helmet is then put on and screwed home by a one-eighth turn. On his head underneath the helmet the diver will wear a tightly-fitting, red woollen cap, which is supplied with the underclothing. An ordinary cap is liable to come off and get over the diver's face, so should not be used.

In the front of most breastplates will be found two studs. On these the front lead weight will be hung by means of two short chains attached to it. For additional security the two chains should be continued round the diver's neck by a piece of rope. The back weight is then hung round the neck by means of a rope which is passed over two hooks, which will be found one on each shoulder. A piece of rope attached to the back weight, and passing through a hole in the front weight, is used for lashing the weights round the diver's body, and prevents them from shifting about. In some helmets the two studs for hanging the front weight on are omitted, and then it is hung round the neck on a rope in the same way as the back weight.

The life line is then knotted securely round the diver's waist and carried up under his right arm, and fastened by a piece of twine to an eye, or lug, on the shoulder of the breastplate. The belt is then girded on, and, lastly, the air pipe is screwed into the inlet valve, brought up under the left arm, and treated in the same manner as the life line. Some professional divers, instead of fastening the life line and air pipe to the eye-pieces, secure them to the brass bars protecting the two side windows of the helmet. This plan is not, however, generally favoured, because a sudden pull on the life line by the attendant has more power to jerk the helmet back, and when the diver is in a stooping position, this may bring the helmet into painful contact with his face. When the helmet is fitted with a telephone, the wires are frequently embedded in the centre of the life line. If this is the case, the life line is screwed into the back of the helmet in a similar manner to the air pipe, before being passed under the diver's arm. Sometimes, however, the telephone wires are embedded in the air pipe, and then an ordinary life line is used.

The diver is now ready to make a descent. The pump attendants start pumping steadily, and the face-plate is screwed in. Finally, as the diver is just about to get submerged, he closes the supplementary valve. In the case of an inexperienced diver, the attendant should see that this is properly closed before he goes under. Professional divers generally have the face-plate put on at the last moment, but a beginner, who will feel very clumsy and uncomfortable at first in the unaccustomed dress and heavy weights, should preferably have his face-plate put on before getting on to the diving ladder, for fear he might stumble. When he is a few feet below water he should stop to adjust his escape valve. The proper adjustment of the valve is rather important. The valve is kept closed by a weak spring. When the valve is screwed up the power of the spring is increased so that less air can escape. If the air pressure gets too high the air will penetrate into the dress, and then the diver will be brought rapidly to the surface, or "blown up," on account of the increased displacement of water, for with the valve properly adjusted the dress clings tightly to the body. If, on the other hand, the valve is too much open, the pressure on the body will make breathing very difficult. The most comfortable adjustment will be when the air in the dress is just sufficient to take the load of the heavy lead weights off the diver's shoulders. A very interesting experiment was made by Dr Haldane upon himself, during his investigations on behalf of the Admiralty Committee, to show the effect of varying the pressure in the diving dress. The apparatus used by Dr Haldane was the ordinary dress and helmet, but in place of the ordinary escape valve, a rubber tube was fitted, about two feet long, with an ordinary valve at the end of it. During the experiment this valve was kept fully open, and Dr Haldane found that with the valve held a few inches above the helmet the pressure on the chest and abdomen was so great that breathing was quite impossible. With the valve held at the top of the helmet breathing was possible, but extremely laboured ; at the ordinary level still laboured, especially during exertion or with a short air supply ; and two or three inches lower was much easier (see "Report," page 11).

The danger of blowing up accidentally is greatest when a diver suddenly stoops down. The outflow of air is then temporarily checked, and the air will accumulate in the back of the helmet and penetrate into the legs. If this happens the diver will be brought feet uppermost to the surface. This, of course, is highly dangerous, not only on account of the sudden decompression, if from any depth, but because of the great risk the diver runs of getting caught in something or of striking his head against the keel of a boat. As the diver comes up, the air in his dress will expand, so that all the time his velocity will be increasing. The danger, therefore, of striking anything at the surface will be very great. To obviate, or at any rate minimise, this danger, a new type of dress, with tightly lacing up legs, has been introduced into use in the Royal Navy. This prevents the air from getting into the legs, so that the diver, should he fall down, runs no risk from the air accumulating, but is immediately able to right himself. If a diver for any reason wishes to blow himself up purposely, he will come to the surface in a perpendicular position.

We are assuming that the diver is making his first descent on a ladder reaching to the bottom and tightly lashed, say, to a pile. The professional diver, in open water, will usually prefer a rope held to the bottom by a weight.

The next thing for the diver to do will be to see if he can inflate his Eustachian tubes. If he cannot do so, he will feel, when he has descended a few feet, a pain in the ears. He should then try swallowing, or moving his jaw about. If this does not relieve him, he should come up a few feet. When the nose can be held, as in an air-lock, it is quite easy, by blowing, to inflate the Eustachian tubes. This cannot be done of course in a helmet, but some divers find it helpful to press the nose against the face-plate and then blow.

When the diver has once learnt to manage his air valve and inflate his Eustachian tubes, he will quickly gain confidence and soon feel quite at home in the water and enjoy the novel experience. Except in clear water the light does not penetrate very far and the diver will generally have to do his work by feel. Where electric current is available he can take an electric submarine hand lamp down with him and these are frequently used for salvage operations. They are not, however, much used for ordinary operations.

The communications between the diver and the attendant, when there is no telephone, are made by means of pulls on the rope. Divers usually make their own code of signals, but it is very usual for one pull to mean "all right," two pulls to mean "more air," and three pulls "I am in danger, pull me up." If the diver is in shallow or very clean water, he can take a small line down with him and with this line a slate can be passed up and down with messages written on it.

The position of attendant is a rather responsible one, since upon his care and vigilance the life of the diver may depend. During the descent of the diver he holds the life line and air pipe together in his left hand and pays them out with the other. When the diver reaches the bottom he holds one in each hand and must keep them sufficiently tight to be able to just feel the movements of the diver and to at once notice any signals he may make. In deep diving, or in any place where there is any fear of the air pipe becoming entangled, it will be necessary to have two attendants, one for the life line and one for the air pipe. Two men will be required for the pump, and there should always be a spare man to do anything that may be required, as it is quite impossible for the men working the pump to leave their posts, and even when there are two men in charge of the air pipe and life line it is not desirable that one should have to give up charge to the other even temporarily. With very deep dives two or more pumps coupled together will be required, and then the number of men attending upon the diver is of course very much increased.

CHAPTER IV.

Rouquayrol-Denayrouze Apparatus—Fleuss Dress—The Diving Bell—Pumps.

The Rouquayrol and Denayrouze apparatus was invented by a French mining engineer, Rouquayrol, and a French naval lieutenant, Denayrouze, in the year 1864.* It is used on the Continent with the ordinary diving dress and is carried on the diver's back. It consists of a steel cylinder of about 0.28 cub. ft. capacity, which acts as a reservoir for the air as delivered by the pump, and a smaller chamber in direct communication with the helmet by means of a pipe. The air in the reservoir is usually kept at a pressure of about 5 lbs. above that in the small chamber. The air is admitted from one chamber to the other as follows:—The small chamber is situated at the top of the reservoir, and has a diaphragm in the centre of its own top to which is attached by a rod the cone-shaped valve closing the opening between the reservoir and chamber.

When the diver breathes, the pressure in the chamber is lowered, and the water, pressing on the diaphragm, causes the valve to open, and air is admitted, until the pressure in the chamber is sufficient to press outwards the diaphragm and thus close the valve.

The chief disadvantages of this apparatus are that it

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* "La Navigation Sous-Marine," Pesce.

is complicated and therefore likely to get out of order; that it is very much in the diver's way, and might easily get caught in something; and that the pressure gauge will give no indication to the attendant of the diver's depth. In its favour is the fact that the diver when stooping down runs no risk of being "blown" to the surface. As against this he will be breathing against pressure, as the diaphragm will be above the diver's head, and the effect produced will be the same as that obtained by Dr Haldane in his experiment described in the last chapter, when the escape valve at the end of the rubber tube was held too high up.

A sudden fall would also be less dangerous, although if this were for any distance, the reservoir is so small that the air would soon be exhausted, unless it were kept at an excess pressure much above that required by the diver. This could be done with shallow diving, but to do so with deep diving would be quite impracticable.

On the whole the air reservoir appears a very useless encumbrance, and so far has not come into use in this country.

Another system is the Fleuss apparatus. With this apparatus the life line and air pipe are dispensed with, and the diver instead carries with him a steel cylinder containing oxygen at a pressure of 120 atmospheres. This is admitted to the helmet by a reducing valve, and the CO_2 (carbonic acid gas) produced by breathing is absorbed by caustic soda. This apparatus was invented by Mr Fleuss some years ago, and has been much improved by him since that date. It is chiefly used by rescue parties after explosions in mines, and enables them to go with perfect safety into parts of the mines filled with deadly gases. The apparatus when used for this purpose consists of the steel cylinder of oxygen and a knapsack containing the caustic soda. A rubber mask covers the face, and the oxygen is breathed from a reducing valve from the cylinder which communicates with the mask by a flexible pipe. It is then exhaled, and by means of another pipe and a simple system of valves circulates through the knapsack where the CO_2 is absorbed by the caustic soda. It is then breathed over again by the wearer, together with a small fresh supply of oxygen.

When this apparatus has to be used with a helmet and diving dress for work below water, and the depth is greater than 17 ft., the oxygen should be mixed with air, since oxygen at high pressure acts as a poison. For a depth of 70 ft. 60 per cent. air would be required.*

This apparatus was the one used by Messrs Siebe, Gorman & Co.'s famous diver Lambert, in his historic dive through the workings of the Severn Tunnel.† During the construction of the tunnel the water on one occasion suddenly broke in, and the workers quickly retreating forgot in their haste to shut a valve. After pumping had been tried without any effect upon the height of the water, it was decided to try and shut the sluice by means of a diver in the ordinary dress. The work to be done by the diver was as follows: to go behind an iron door in a head wall and shut down a flap valve on an 18-in. pipe, come back through the door, lift up two tram rails, and then shut the door, then screw down a 12-in. sluice valve on another pipe on the near side of the door. The distance to be walked was 1,000 yds. under a head of water of 30 ft., and this

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* See Dr Haldane's lecture before the North Staffordshire Institute of Mining and Mechanical Engineers, published in *Water*, 15th April 1908.

† "History of the Severn Tunnel," Walker.

distance was too far for one diver to drag behind him the length of air pipe required. The first attempt was made with three divers in the ordinary dress. These three went together as far as they could, dragging their air pipes behind them. Then one stopped, and the other two went on, the man who remained behind helping them by pulling forward their air pipes. Then another man stopped, and the leading diver, Lambert, went on alone, but at last he could get no further, and had to return. Mr Walker, the contractor, then telegraphed for Mr Fleuss, having heard of his apparatus, and on 8th November 1880, Lambert, after a few preliminary dives to get accustomed to the dress, made his first attempt. On this occasion he got as far as the door, and pulled up one rail. He then returned, and his failure in this first attempt can be well understood when we remember his unaccustomed apparatus; and those who have ever had a diving dress on know how after even a short exposure in water the hands become quite numb with the cold together with the stoppage of proper circulation by the tight wrist-bands.

However, on 10th November, Lambert made his second attempt, and successfully shut down the flap valve, pulled up the remaining tram rail, closed the door, and gave the sluice valve the number of turns he had been instructed, and returned after having been absent one hour twenty minutes.

The pumping was then started, and although it took much longer than had been anticipated, the water was at length low enough to enable the valves to be reached. It was then seen why so much pumping had been required. The sluice valve had a left-handed thread, and this having been forgotten when Lambert was given his instructions, he had opened the valve instead of closing it. Fortunately this valve was not so important as the other one. There were, it will be remembered, two valves and a door to shut, and it was Lambert's shutting of the other valve and the door which enabled the water to be got under.

If a glass tumbler be submerged face downwards in a basin of water, the water will be prevented from rising by the pressure of air inside the tumbler, about 14.7 lbs. per square inch, which is the same as that of the atmosphere pressing on the exposed surface of the water in the basin. As the tumbler is still pressed downwards the water gradually rises, and as it does so compresses the air inside, because the pressure of the air on the exposed surface of water is helped by the head of water from the lip of the tumbler to the surface of the water in the basin, and if the tumbler were submerged to a depth of 33 ft. in salt water, and was in shape truly cylindrical, the water would rise half way up it.

This is the principle of the earlier diving bells, and they were no doubt made bell shaped in order that the maximum compression might be obtained with a minimum rise of water level in the bell itself. The idea of using compressed air to keep down the water originated with Edm. Halley, Secretary to the Royal Society, about the year 1714,* and he adopted the following ingenious method for compressing the air. Casks were provided with a bung hole in the bottom and another hole in the top fitted with a flexible pipe. This pipe was open at the end, but had a weight fixed to it, so that when in the water this end was below the bottom bung hole. As the cask was lowered into the water, the water was admitted through the bung hole and compressed the air inside the

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* *Proc. Royal Society*, vol. xix.

cask. It could not escape through the top hole because the end of the pipe was kept below the bottom of the cask. When the bell was reached the pipe was taken hold of and lifted up underneath the bell. The water then rose in the cask and forced the air into the bell at the required pressure. Halley's bell was in the form of a truncated cone, and was made of wood, with a capacity of about 60 cub. ft. The top was fitted with a glass window, and a valve to let out the foul air.

When making a descent, Halley used to stop every 12 ft. and have casks sent down until the water which had risen in the bell had been driven out. Then he would descend another 12 ft. On one occasion, in company with four others, he descended to a depth of 54 ft., and was below one and a half hours.

In 1778 John Smeaton devised a bell with which to underpin the foundations of a bridge over the Tyne at Hexham which had been injured by a flood. This bell in some respects more resembled a caisson than a diving bell, as it was not intended to be entirely submerged. It was 4 ft. 6 in. high only, and 3 ft. 6 in. long, and had on the top a 10-in. diameter force pump for supplying air. Light was obtained from five circular glass windows at the top, Fig. 1. Smeaton afterwards used a bell at Ramsgate harbour,* and after his death, when the work was taken over by Rennie, the bell was much improved, and it was used for the whole of the construction of the East Pier, which was founded 17 ft. below water. Rennie also used his bell at Holyhead, Howth, and Sheerness harbours, and also at Plymouth dockyard. Rennie's bell was made of cast iron.

The modern diving bell is built up with mild steel

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* *Proc. Inst. C. E.*, vol. v.

plates, and is chiefly used on large harbour works for the purpose of levelling off the ground to receive the large concrete blocks used in harbour construction. The weight when ballasted is about 25 per cent. in excess of the water displaced. Air is delivered through a receiver from a steam or electrically driven air compressor.

In Chapter I., Table III., it has been pointed out that a minimum air supply will be required by the diver. For shallow depths this can be determined with sufficient accuracy by calculating, from the stroke and diameter of cylinder, the capacity of free air per revolution of each cylinder, and then multiplying by the number of cylinders and the number of revolutions per minute. As the depth increases, losses due to heating, leakage, and cushioning cease to become negligible. Loss from heating will not be serious, provided the water surrounding the cylinders in the water jacket is changed every half hour or so. Cushioning is a capacity loss chiefly, as about 75 per cent. of the power expended in compressing will be

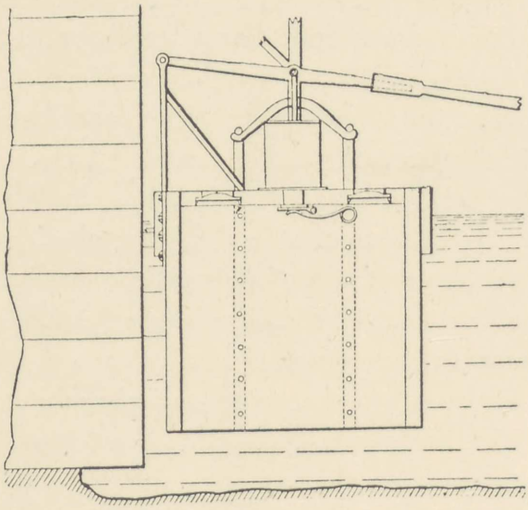

Fig. 1.—John Smeaton's Diving Machine, 1778.

returned during the second half of the stroke. In the case of single-action pumps, the work done will be entirely lost. Out of twelve ordinary service pumps tested by the Admiralty Committee,* the average loss was 11.3 per cent. at atmospheric pressure, 34.6 per cent. at a depth of 100 ft., and 57.0 per cent. at a depth of 200 ft.

Afterwards improved pumps were supplied, and gave results rather better than 25 per cent. at 200 ft.

The loss from cushioning is to a great extent inevitable, as there must always remain a small amount of highly compressed air due to the valve clearance and also in the space occupied by the springs on the pistons. This loss increases with any wear or slackness which would tend to shorten the length of the stroke.

In Table X. two columns have been worked out, one for pumps with an efficiency of 75 per cent. at a depth of 198 ft., and the other for pumps with an efficiency of 50 per cent. at a depth of 198 ft. By dividing by the capacity of one cylinder per revolution and the result by the number of revolutions per minute, the numbers of cylinders for any particular depth will be obtained.

Thus at a depth of 231 ft. and cylinders with a capacity of 0.10 cub. ft. per minute, and the number of revolutions thirty per minute, the number of cylinders required would be $\frac{17.0}{0.10 \times 30} = 5.7$. This necessitates three two-cylinder pumps and the number of men required will be six to a pump, and in order that they may be able to work them comfortably the handles of the pumps will have to be made rather longer than is usual. From the last column it will be seen that the work that will have to be done is rather beyond the ordinary

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* "Diving Report," p. 25.

powers of a man, which are generally considered to be about 3,000 ft.-lbs. per minute. It would probably be better for very deep dives to use a larger number of pumps with smaller capacity and also with a rather longer stroke than is customary. The increase in length of stroke would lessen the percentage loss due to cushioning. Another way to get over the difficulty is to fasten a rope in the middle of its length to both handles at the ends nearest the pump. As many men as necessary can then get hold of the four ends and help those who have hold of the handles. The work of the latter will then be reduced by about one-half, and they will also have to do most work when the pump handles are in the most favourable position for force to be exerted by them. When three pumps are used they should be connected to a four-way junction piece with valves so that any one pump can be shut off or detached if necessary. When the diver reaches the first stopping place one pump will be sufficient, as a little excess of CO_2 will be an advantage rather than otherwise as it will tend to stimulate the diver's circulation, and thus help him to get rid of his surplus nitrogen.* When the diver has nearly reached his first stopping place the pumps should be stopped for a moment, and the gauge tapped in order to accurately find his position, and to stop him by signal at exactly the right place.

Pumps used for deep diving should be frequently tested for leakage and other losses.

The method adopted by the Admiralty Committee was to connect up to a dry gas meter, and then by compressing the outside of the pipe any pressure required could be obtained. It then only remained to

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* "Diving Report," p. 45.

compare the calculated air delivery with that shown by the meter.

Another way, and one for which the necessary gear will be more generally likely to be available, is to pump up into a receiver of known capacity. The pressure is obtained by compressing the pipe as with the dry gas meter, and the number of revolutions required to raise the pressure in the receiver to the gauge pressure on the pump is compared with the calculated number.

Still another way would be to use two receivers connected together, and pump into one until the required pressure is obtained and then open the valve communicating with the other and fill that, the number of revolutions being counted from the time the valve is opened. The valve must be opened in such a way as to maintain the pressure in the first receiver at the pressure for which the test is being made.

TABLE X.

Depth.		Cubic Feet of Free Air per Minute.	Cubic Feet of Cylinder Capacity per Minute.		Work in Compressing + Friction in foot-lbs. per Minute.
Fathoms.	Feet.		Efficiency = 75 per cent. at 198 ft.	Efficiency = 50 per cent. at 198 ft.	
0	0	1·5	1·5	1·5	...
5½	33	3·0	3·2	3·3	5,500
11	66	4·5	5·0	5·4	13,000
16½	99	6·0	7·0	8·0	22,000
22	132	7·5	9·0	11·3	32,000
27½	165	9·0	11·5	15·5	43,000
33	198	10·5	14·0	21·0	55,000
38½	231	12·0	17·0	29·0	66,000

TABLE XI.

For Pumps with a Capacity of 0·10 *cub. ft. per Cylinder per Revolution and an Efficiency of* 75 *per cent. at a depth of* 198 *ft.*

Depth.		Number of Cylinders required at 1 Revolution per Minute.	Practical Number of Cylinders required.	Number of Revolutions per Minute.
Fathoms.	Feet.			
0	0	15	1	15
5½	33	32	1	32
11	66	50	2	25
16½	99	70	2	35
22	132	90	4	23
27½	165	115	4	29
33	198	140	6	24
38½	231	170	6	28

CHAPTER V.

Pneumatic Caissons and Cylinders.

COMPRESSED air is employed in the sinking of cylinders and caissons, for the foundations of bridges, dock walls, and other structures in water-bearing strata. It is also employed for the shafts of sub-aqueous tunnels and for mine shafts.

The principle of the caisson is that of the diving bell. The caisson or cylinder is open at the bottom, and the water is kept from entering by pumping in compressed air at a pressure equal to that due to the head of water at the level of the bottom of the caisson.

The caisson may be compared to a box, open at the bottom, closed at the top above high water level, and filled with compressed air.

Under actual working conditions the caisson usually has a strong roof about 9 ft. from the bottom, dividing off the lower part of the caisson from the upper, and forming what is known as the working chamber. From the roof extend one or more shafts up to above high water. These are closed at the top by the air-locks which allow ingress and egress of men and material without any loss of air.

The caisson is made to sink by the material being excavated all over the bottom of the working chamber and passed out through the shafts by means of buckets. A few types of air-lock are described in the next chapter, but the principle is much the same in all. The bucket, on reaching the top of the shaft when being sent out full, is passed into a chamber which has a door opening outwards (*i.e.*, outwards with reference to the bucket chamber, but inwards with reference to the caisson). The door is then closed and the air inside the chamber is allowed to escape until the pressure inside is the same as that of the ordinary atmosphere. The result is that the door described as opening outwards is pressed tightly against the bucket chamber by the pressure of the air inside the working chamber and the shaft, and since it is lined with a rubber gasket all round the edge, a perfect air-tight closure is effected so that no air can escape from inside the caisson. On the other hand, the outer door, which opens inwards towards the bucket chamber, and which has been kept tightly closed by the pressure which is that of the working chamber and shaft, will now open quite easily and allow the bucket to be removed. The method of closing the material lock on the inside is practically the same in every type of lock, but that of closing the outside opening is different in various locks. In some locks sliding doors are used on the outside, and in the Davis lock the door is carried away on the top of the bucket each time it is taken away to be tipped. Doors of this sort are of course not kept closed by the air pressure, but have to be screwed down or kept shut in some other way.

The entrance chamber for men is worked on the same principle, but the doors are nearly always of the ordinary type kept closed by the air pressure.

Merely excavating the inside of the caisson will not, however, be sufficient to make it sink, since there will be the buoyancy of the caisson and the skin friction to overcome.

In open water-bearing strata the buoyancy of the caisson will be obtained from the amount of water which would be displaced by the caisson measured from high water level, the bottom of the chamber being taken as closed in, which it actually is by the pressure of the air. If the caisson has vertical sides, the buoyancy, or upward reaction, can be obtained by multiplying the area it stands upon, or cross-sectional area, by the head of water at the level of the cutting edge.

In actual practice there are, however, many modifications of these rules. In salt water, as at Barmouth Bridge, described in the next chapter, a fresh water spring may necessitate the air pressure being raised to a point much higher than that required by the head of salt water in order to keep the water from rising in the working chamber. It very often happens, on the other hand, that the working chamber can be kept quite dry by a pressure of air lower than that due to the head of water measured from water level to cutting edge.

It is rather difficult to determine beforehand what the skin friction will amount to, but it is usually from about $2\frac{1}{2}$ to 6 cwt. per sq. ft.

To overcome skin friction and upward reaction of air, or buoyancy, it will be necessary in almost every case to add to the weight of the caisson itself. With large caissons such weight is usually added in the form of concrete which is put in above the roof of the working chamber, which will have consequently to be made strong enough to bear it. When the caisson has reached the bottom intended for it, the working chamber and shafts will also be filled up with concrete, so that the whole will become a huge monolith which will form the foundation for the bridge pier, wall, or whatever it is that is to come on the top of it.

If it is to be a bridge pier, the concrete usually stops at ground level, and then the pier is continued upwards in masonry or brickwork inside the outer skin of the caisson. When the pier is above high water, this outer skin can be taken off by divers down to ground level. Although concrete is undoubtedly the most convenient material to use for filling up caissons, other materials are sometimes employed. For small cylinders, for instance, many engineers prefer blue brick.

The regulation of the air supply is an important matter. There must be sufficient to keep the pressure at the necessary height, and also to make up for any losses through leakages and for what will be lost every time the bucket chamber or entrance chamber for men is emptied. There must also be sufficient to insure the health of the workers. If there is too much air, what are called "blows" will be produced. Blows are caused by too large a volume of air escaping at one point. The result will be that the water mixed with the air will be lighter than a column of water of the same height; the solid water will be banked up on each side forming a sort of shaft through which the air will escape; a dense fog will form inside the working chamber due to the drop in temperature caused by the work done by the air in expanding, and eventually, when the water has closed in again and the escape of air stopped, the water will come pouring in at the weak spot and perhaps all round the cutting edge. A blow like this will be very serious, especially if the cutting edge of the caisson is only a little way into the ground, and the reduction in pressure may cause the caisson to sink, and perhaps more on one side than the other, or even to topple over. The actual danger to the workers is not great if nothing happens to the caisson, since the water coming in will compress the air in the chamber so that it rarely rises more than about 2 ft. above the cutting edge. Sometimes, however, the excavation is carried some way below the cutting edge, and then the danger will be greater, especially if the workers are unable to swim.

When a blow such as this occurs, the escaping air will make a noise like thunder. When the caisson is some way into the ground, blows will only be noticed by a slight fog and the water trickling in at one or two places.

Blows cannot be prevented by regulating or governing the pressure only. The volume of air passed into the working chamber must also be controlled.

The author has found the most satisfactory method is to run the air engines at constant speed and to govern the pressure merely by having a governor worked by the air so that when the pressure rises above a certain point the valves will be lifted and the air engine run light. In this way the volume of air can never rise above a certain point. If the pressure alone is governed, there is no definite limit to the volume of air pumped into the caisson. The same pressure can be obtained with exceedingly varying quantities of air.

For a similar reason no attempt should be made to sink two caissons off one main by means of a reducing valve.

A caisson, when it is to be sunk in deep water, is either floated into position, as was done at the Forth Bridge, or else built *in situ* on staging, as was done at the King Edward VII. Bridge at Newcastle, and then lowered into the water by jacks. When a caisson is floated out, the shafts must be closed at the top, if, as is usually the case, only a few lengths are added at first, in order to keep the water out from above the roof of the working chamber, and so give the necessary floating power. It is important that a caisson should be pitched level; if this is done in the first instance, there will be no trouble afterwards with it getting out of position or level.

When a caisson has to be started below low water level, careful soundings must be taken, and if the site is not level, the high ground must be dredged away or the low ground levelled up.

The King Edward Bridge caissons were sunk in deep water by being gradually filled up with concrete, and as the cutting edge touched the bottom at each low water, it was observed which part of the cutting edge was sinking deepest into the mud, then, as the rising tide lifted the caisson, ballast was shovelled in at the soft places, so that eventually when the caisson ceased to rise with the tide it was practically level.

If the diameter of the caisson is small in proportion to the height, it is best to gauge the level by means of hanging plumb bobs, but if the diameter is large in proportion to the height, this should be done by levelling with the ordinary level and staff.

The author has found it a good plan with rectangular caissons, when they are surrounded by staging, to have wooden blocks at each corner with coach screws screwed into them. By placing a few washers underneath each and then adding to them or taking one or two away, the four heads can be easily brought to the same level. The levels can then be taken with reference to a horizontal joint on the caisson by levelling out to the skin of the caisson by means of an ordinary carpenter's level about 2 ft. 6 in. long. This enables the levels to be taken at any moment by a foreman, and also saves the expense of having a chainman constantly in attendance. These points should be checked by reference to a more permanent bench mark once or twice a week, and more often if the staging shows any signs of sinking, as it very frequently does. The reduced level of the cutting edge is easily obtained, as the height of the various horizontal joints can be taken from the working drawings. If there are no suitable horizontal joints, the four corners of the caisson should be clearly marked every foot in height.

It is of importance that the caisson should be pitched, not only level, but in the correct position. If it should get out of position and is not too far in the ground, it may be brought back by fixing wooden struts against the walls of the working chamber in the direction in which it is required that the caisson shall move (Fig. 2). As the caisson sinks, the tops of the struts will move in the arc of a circle, and thus the caisson will be forced to move in the required direction. This method must, however, be used with great caution, or else the walls of the working chamber may be injured.

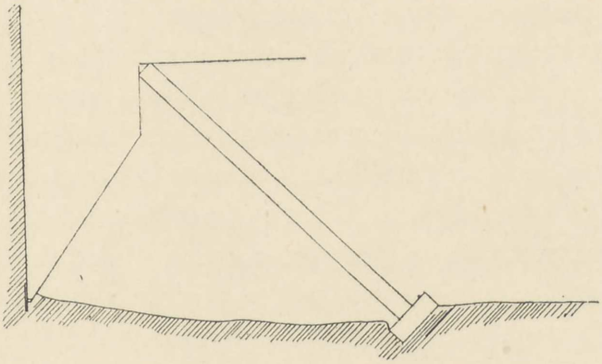

Fig. 2.—Method of Strutting Caisson.

If the caisson is in rock, it will be necessary each time it is lowered to clear well behind the cutting edge along the side which is to move outwards, or else it will be stopped at the line of excavation. When the caisson is out of position or level, the clearing away round the cutting edge must always be made with reference to the final position which the caisson will occupy.

It sometimes happens, as for instance in sloping ground, that the caisson will move a little, even though correctly pitched. Under such circumstances it will be a good plan to use one or two light struts as a preventive measure to prevent the caisson getting further out of position. As a general rule with very large caissons an inch or two out of position is not of great moment, and under such circumstances it is best not to risk any injury to the caisson by using too much force.

Another matter to which attention must be paid is the protection of the cutting edge, which will very easily get bent if it comes into contact with some hard substance. Some caissons are fitted with one or two big girders with a wide bottom flange. A bank of earth, or of the strata being passed through, is left under each of these, and this is gradually cut away, or the girders are allowed to crush through them so that in this way they act as a brake on the descent of the caisson and prevent injury to the cutting edge. Brackets bolted to the sides of the working chamber and packed underneath with timber may also be used. In hard rock the cutting edge should not be allowed to take any of the weight, and the rock should be well cleared all round and behind the cutting edge before each lowering of the caisson. The caisson will be held up by skin friction and is lowered by reducing the pressure of the air. If there is a large range of tide, and the brake girders are unable to take the difference in weight due to the alteration in the water level, some of the kentledge must be in a movable form so that at low tide some of it may be taken off. In caissons with double skins which do not require to be concreted up, this can be most conveniently applied in the form of water, which can be pumped in or out as the circumstances of tide level may demand.

In soft ground the caisson may be allowed to sink gradually into the ground without any lowering of the air unless the skin friction becomes too great, but a look-out must be kept for large boulders and old piles or pile heads. The two latter are often found at a considerable depth below ground level, and will often do a good deal of damage if not noticed in time.

If the cutting edge should get bent in at all, it will be necessary to keep the line of excavation some distance behind it in order to prevent the caisson jambing as it descends.

Pipes are fitted for blowing out any water that may get into the working chamber when the excavation has been carried below the cutting edge. Air should be allowed to mix with the water, and then it can be blown out over the sides of the caisson considerably above the level of the water outside. If this is not done, the water in the pipes will only rise to outside water level. A convenient method is to introduce a pipe of smaller diameter into the mouth of the blow-out pipe, so that the latter can be kept below the water in the caisson, and will not require adjustment as the level of water is reduced. The other end of such a small pipe will be merely left open so that the air in the working chamber can enter it.

In the diagram, Fig. 3, which has been introduced to illustrate this chapter, the concrete is shown at the top of the roof girders, but in actual practice the air-tight ceiling will come at the bottom of the girders and the space between them will be filled with concrete. The sloping walls at the sides may either be filled with concrete or left open in the form of brackets. If the former method is adopted, the cutting edge will be considerably strengthened, both by the plating connecting the brackets together and also by the concrete filling inside. If the latter, there will be more head room for the workers and enable them better to get close up to the cutting edge and to work under and behind it. The timber framing starts immediately above the ceiling and is knocked out

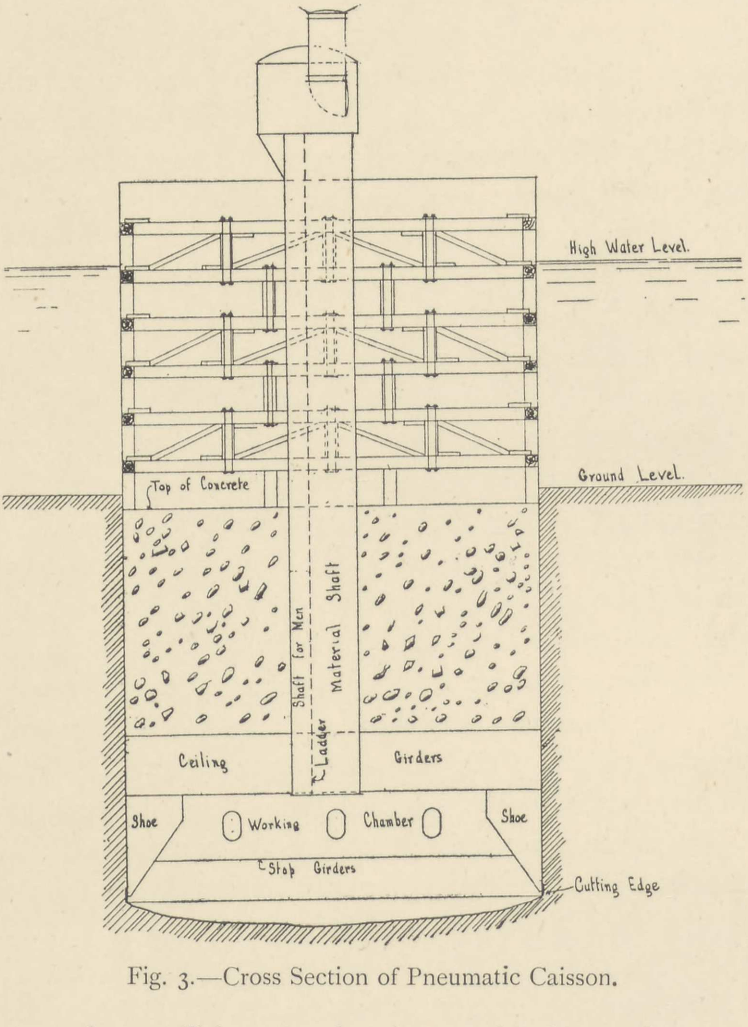

Fig. 3.—Cross Section of Pneumatic Caisson.

one frame at a time as the concrete is brought up. In the King Edward Bridge caissons the first 26 ft. from the cutting edge was strutted with steel girders which were concreted in; the timber framing started above this level.

Below low water the timbers will be kept in position by the pressure of the water on the outside of the caisson, but above low water there will be a tendency for the shell to open a little. It will therefore be necessary to have a few light steel girders to tie the sides of the caissons together and prevent the sides from spreading.

CHAPTER VI.

Pneumatic Cylinders and Caissons (*continued*).*

COMPRESSED air was first used for engineering purposes in this country during the construction of Rochester Bridge in the year 1851.† A little before this Dr Potts had used the vacuum process for sinking cylinders and had also used caissons open to the air which did not keep the water out. Lord Dundonald had also taken out several patents for the use of compressed air for other purposes.

The bridge consisted of three large openings spanned by cast-iron segmental girders and one opening span. The central opening was 170 ft. wide, and the other two spans each 140 ft. wide. The river piers were 1,118 sq. ft. in area, and were each supported upon fourteen cast-iron cylinders 7 ft. in diameter.

The vacuum process was first tried, and by this method about 500 tons were sunk, when it was found that the bottom was of Kentish ragstone, and therefore this method was unsuitable. Sir Charles Fox, who was in charge of the construction, then decided to use compressed air, and personally made the drawings of

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* This chapter was originally written for the *Engineer*, and has appeared in its columns. The author is indebted to the Editor for permission to reproduce here.

† *Proc. Inst. C. E.*, vols. x. and xxvii

the apparatus to be used. To Sir Charles Fox, therefore, must be given the credit of originating the use of compressed air for engineering purposes, so far, at any rate, as this country is concerned. There would appear, however, to have been some use of compressed air in France about the same date.

The method adopted was as follows, and by its means the remaining 1,700 tons of cast-iron cylinder were sunk with entire success :—

A wrought-iron cover was bolted to a 9-ft. length of cylinder, and through this cover projected by about a third of their length two D-shaped cast-iron chambers. In the top of each was a circular door, 2 ft. in diameter, opening downwards. On the flat side of each chamber below the cover was a rectangular opening, 2 ft. by 3 ft. 4 in., by which access was obtained to the inside of the cylinder. The buckets were raised by an ordinary windlass fixed inside the cylinder, and a chain passing over the sheave of a light crane allowed the buckets to be swung into the chamber on reaching the level of the opening. The whole arrangement, except for the method of hoisting the buckets, is very similar to that of the Barmouth Lock, shown in Fig. 9. The output was twenty-five buckets per hour, and each bucket held 2 cwt. of excavated material. On the completion of the sinking the cylinders were filled with concrete and brickwork.

This system was adopted shortly after by Mr Brunel for the bridge over the Wye at Chepstow.* This bridge had one span of 300 ft., and two others of 100 ft. The pier supporting one end of the 300-ft. span consisted of six cast-iron cylinders filled with concrete, 8 ft. in

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* *Proc. Inst. C. E.*, vol. vii.

diameter below ground, and founded on rock at a depth of 84 ft. below high water. During the sinking one of the cylinders cracked, and had to be strutted with timber and stiffened with a wrought-iron hoop.

For the centre pier of the Saltash Bridge over the Tamar, Mr Brunel again used compressed air, and designed a caisson on rather more elaborate lines than had previously been used. The pier itself consisted of a masonry column, 35 ft. in diameter, carried up above high water. On it were placed four smaller octagonal cast-iron columns 10 ft. in diameter, reaching to the underside of the girders. For the construction of this pier a cylinder 96 ft. high and 37 ft. in diameter was designed (Fig. 4). The cutting edge was made 6 ft. lower on one side than the other, in order to conform to the slope of the rock below the mud, as ascertained by careful borings. About 14 ft. from the highest point of the cutting edge was a domed roof, the top of which communicated with a 10-ft. diameter shaft open to the air at atmospheric pressure. The portion of caisson below the

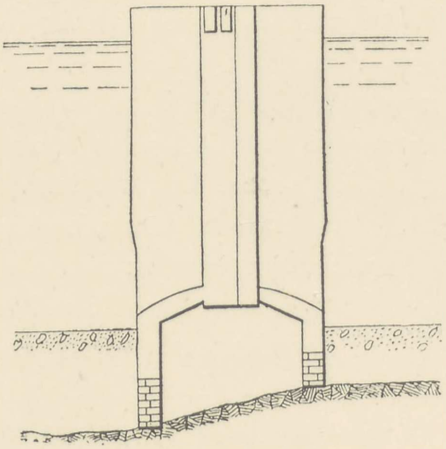

Fig. 4.—Saltash Bridge Circular Caisson, 37 ft. diameter.

dome was surrounded by eleven compartments, or cells, making a wall 4 ft. thick, communicating with each other, and with a third cylinder 6 ft. in diameter, at the top of which was fixed an air-lock, placed inside the 10-ft. shaft but out of centre.

The caisson was sunk partly by being forced through the mud, and finally by excavating, under air pressure, the area between the outer and inner walls of the portion below the dome. On reaching its full bottom the air space was filled with a ring of granite masonry to a height of about 7 ft., and the caisson itself lewised to the rock to do away with any danger of its overturning. An attempt was then made to pump out the water, and to excavate the remainder of the mud through the 10-ft. shaft in the open. The leakage was, however, too great, and as the 10-ft. shaft was too weak to stand air pressure, it was strengthened by a fourth cylinder 9 ft. in diameter, at the top of which was placed a lock, and the excavation completed with the help of compressed air. The interior was then filled with masonry, the inner shell and dome being cut away as the work proceeded.

The chief defect in the design of this caisson seems to be the unequal level of the cutting edge, which would allow the water to enter to the level of the highest point if in fairly open ground, and this appears to have occurred. The design was, however, somewhat complicated, and has not, as a matter of fact, been since imitated. The same difficulty of a sloping rock bottom had to be contended with in the pitching of the two Inchgarvie south caissons at the Forth Bridge, and was met by levelling up by sand bags and piers of concrete.

The cylinders for the Londonderry Bridge, 1859, were sixteen in number, two to a pier, and 11 ft. in diameter, of the ordinary single shell cast-iron type, and the same apparatus as used at Rochester was employed here.*

The Forth Bridge caissons have been so much written about and are so well known as to need no description here, but for the purpose of comparison with other types of caissons, a typical outline section of them is given in Fig. 5.

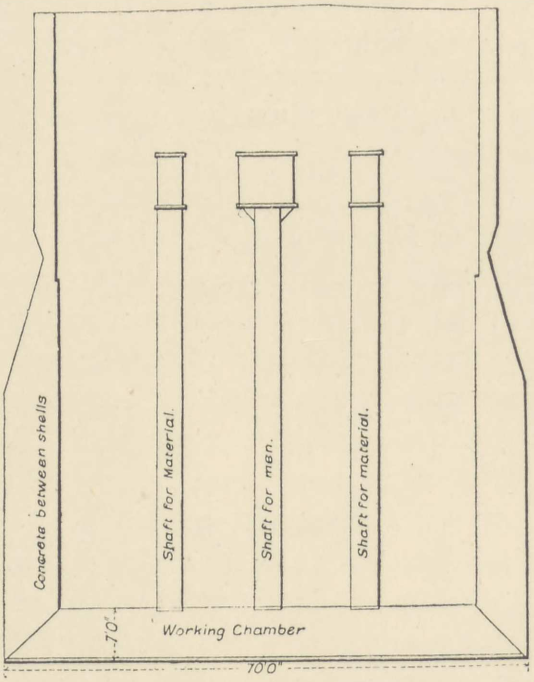

Fig. 5.—Forth Bridge Circular Caissons, 70 ft. diameter.

The Victoria Bridge,† Stockton-on-Tees, 1887, cylinders were of cast iron, 14 ft. in diameter, and $1\frac{1}{2}$ in. metal. During the sinking of one of these a fracture through which the air escaped appeared in the bottom cast-iron length—the bottom length forming

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* *Proc. Inst. C. E.*, vol. xix.

† *Proc. Inst. C. E.*, vol. cix.

the cutting edge was of wrought iron—extending right through it and half way through the length above. This was remedied by lining the fractured segments with wrought-iron plates, and filling the space behind with cement grout. Cast iron is not a suitable material for cylinder work, as not only are cylinders made of it liable to become fractured during sinking, but this often happens after they have been standing for some years, and they are frequently seen bound on the outside with wrought-iron bands.

The Conway cylinders were sunk in order to shorten the span of the Conway tubular bridge, and thereby decrease the stress in the tube, which had become too great on account of the increase in the rolling load since the construction of the bridge. These cylinders were constructed (Fig. 6) of plates of mild steel $1\frac{1}{4}$ in. thick, and were sent out from the yard in 5-ft. lengths. These were bolted together, as added on site, by 1-in. diameter turned bolts, 8-in. pitch, and passing through two 4 by 4 by $\frac{5}{8}$ in. angle bars on the inside. The joint between these was made by flat rubber and red lead. During the sinking these angle bars were used to support a ring of blue brick packed in sand, which considerably reduced the amount of kentledge required to be piled on the top of the lock. The air-lock was fixed on a circular plate bolted on to the top length of the cylinder and stood above it. The two ends were semicircular, and one was divided off from the rest of the lock and formed the entrance chamber for the men. The lower part of the other end was divided into two hoppers with horizontal doors opening upwards. Into these the excavated material, which had been hoisted by an electrically-driven winch placed inside the lock, was emptied. In the side of the locks were hinged doors opening outwards, through which the excavated material was removed. The hoppers were fitted with valves to allow the air pressure to be raised and lowered in the

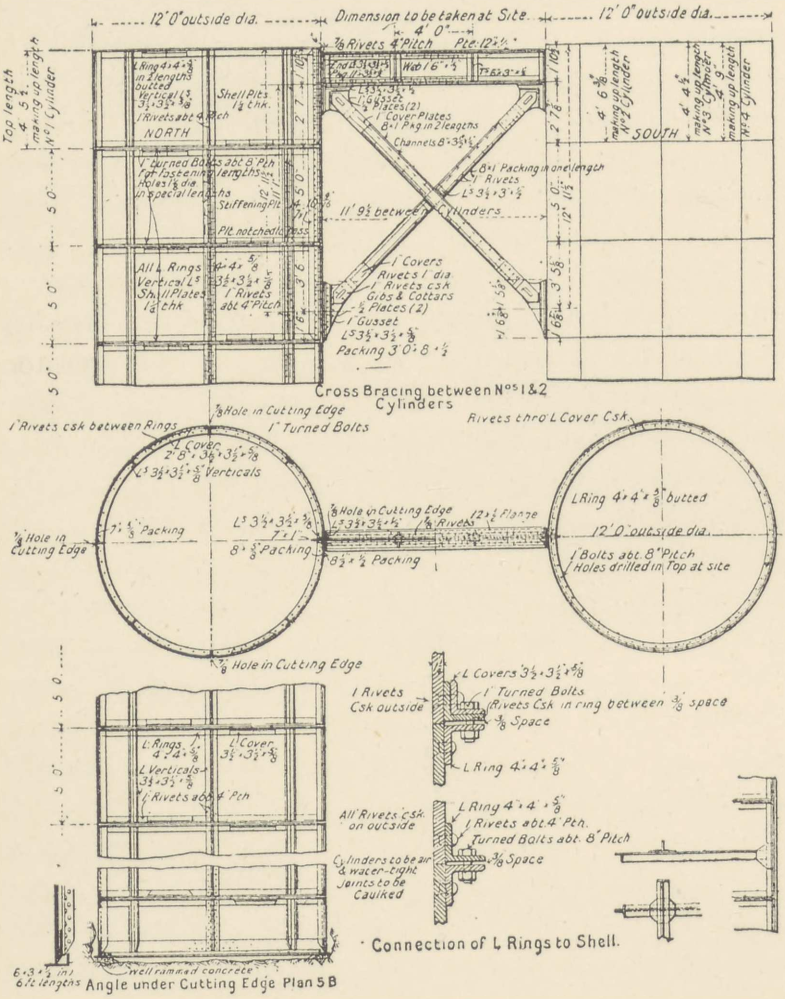

Fig. 6.—Conway Bridge Cylinders.

same way as in the entrance chamber for men. During the sinking these cylinders were guided by four rolled steel joist piles, braced horizontally by channel bars and diagonally by angles. Screws were used for lower-

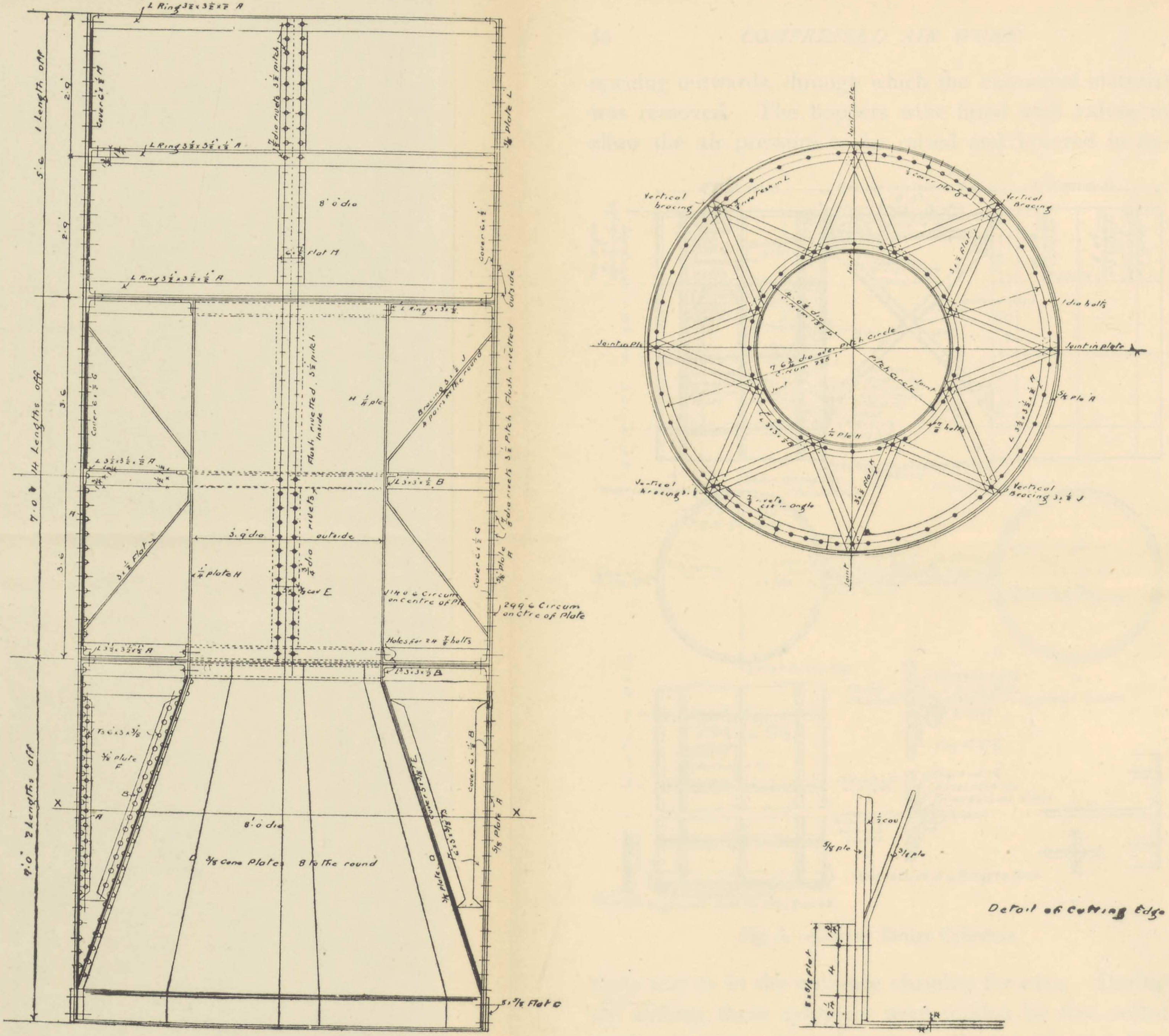

FIG. 7.—BARMOUTH CYLINDERS.

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ing, and, until the rock was cleared away from under the cutting edge, they carried the whole weight suspended by links. When ready, the screws were turned by small capstans, and the cylinders allowed to descend. The bottoming up was on solid granite, and an interesting detail was the 6-in. angle bar, which was placed underneath the cutting edge to prevent its further penetration, and which also to a certain extent increased the bearing area over the granite. (See Plan 5B, Fig. 6.) The filling was of solid brickwork.

The Barmouth cylinders (see Fig. 7) were 8 ft. in diameter, with an inner tube 3 ft. 9 in. in diameter, which latter terminated in a bell mouth to allow room for excavation round the cutting edge. The space between the two shells was filled with concrete to give the necessary kentledge as the work proceeded. Fig. 8 shows the method of sinking. The cylinders were guided in their descent by four piles, to which were bolted angle bar rings encircling the cylinders. Between these and the cylinders 8-in. by 6-in. runners were placed and kept in position by angle cleats riveted to the sides of the rings. The buckets containing the excavated material were hoisted by means of a $\frac{5}{8}$-in. diameter steel bond passing through a stuffing box in the top plate of the lock, and passing round the drum of an ordinary windlass placed on the top of the lock. On reaching the bottom of the lock the bucket was swung into the entrance chamber, and, after the air had been exhausted, was lifted out by means of a second windlass also placed on the top of the lock. The actual staging was slightly different to that shown on account of the presence of the old viaduct during the construction, and of existing fendering, to which the guide piles were braced.

The bridge is a swing one carrying a single line and with two clear opening spans of 52 ft. The roller path is supported on four 8-ft. diameter cylinders, described above, spaced 18 ft. 6½ in. centres, and as it was necessary that there should be no settlement under the

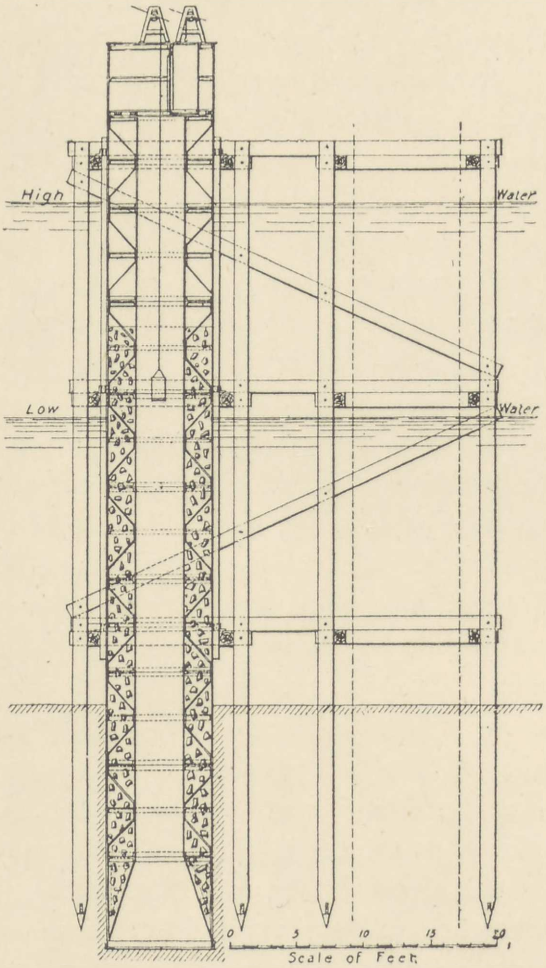

Fig. 8.—Sinking Barmouth Cylinders.

roller path it was decided to carry the cylinders to a solid rock bottom. This was reached at the depth of 95 ft. below water, equivalent to a pressure of 41 lbs. per sq. in. above that of the atmosphere, but owing to a

fresh water spring the air pressure had to be raised to 46 lbs. This is the greatest pressure at which work of this description has been carried out in this country, and in spite of this fact, and that on account of the open nature of the ground the pressure could not be lowered below that of the head of water outside, as is possible on some work, there were no fatal cases of caisson disease, and only one case of paralysis, from which recovery was complete. The men worked at the highest pressure for one and a half hours at a time twice a day. When the sinking was completed the bell mouth working chamber and inner tube were filled with concrete under pressure before the removal of the lock.

The lock itself (Fig. 9) consisted of a circular plate bolted to a special short length of cylinder, and had an inverted D-shaped entrance chamber for men and material. The air valves were so arranged that the pressure in the entrance chamber could be raised or lowered either from the top or, by authorised persons, from inside the chamber. The inside of lock, entrance chamber, and working chamber were lighted electrically. For the remaining piers of the bridge, it was not considered necessary to go down to rock level, as a slight settlement would not, with them, be of serious consequence. Cylinders with a $\frac{5}{8}$-in. thick single shell were therefore adopted, and after these had been sunk by the compressed air method, piles were driven round the cutting edge in the open, and the interiors then filled up with concrete in the usual way.

The type of cylinder built up with steel plates and with an inner shell is perhaps the best that can be adopted. The rate of sinking will be faster, because when moving the lock to add fresh lengths, the time which would otherwise be wasted in taking off and

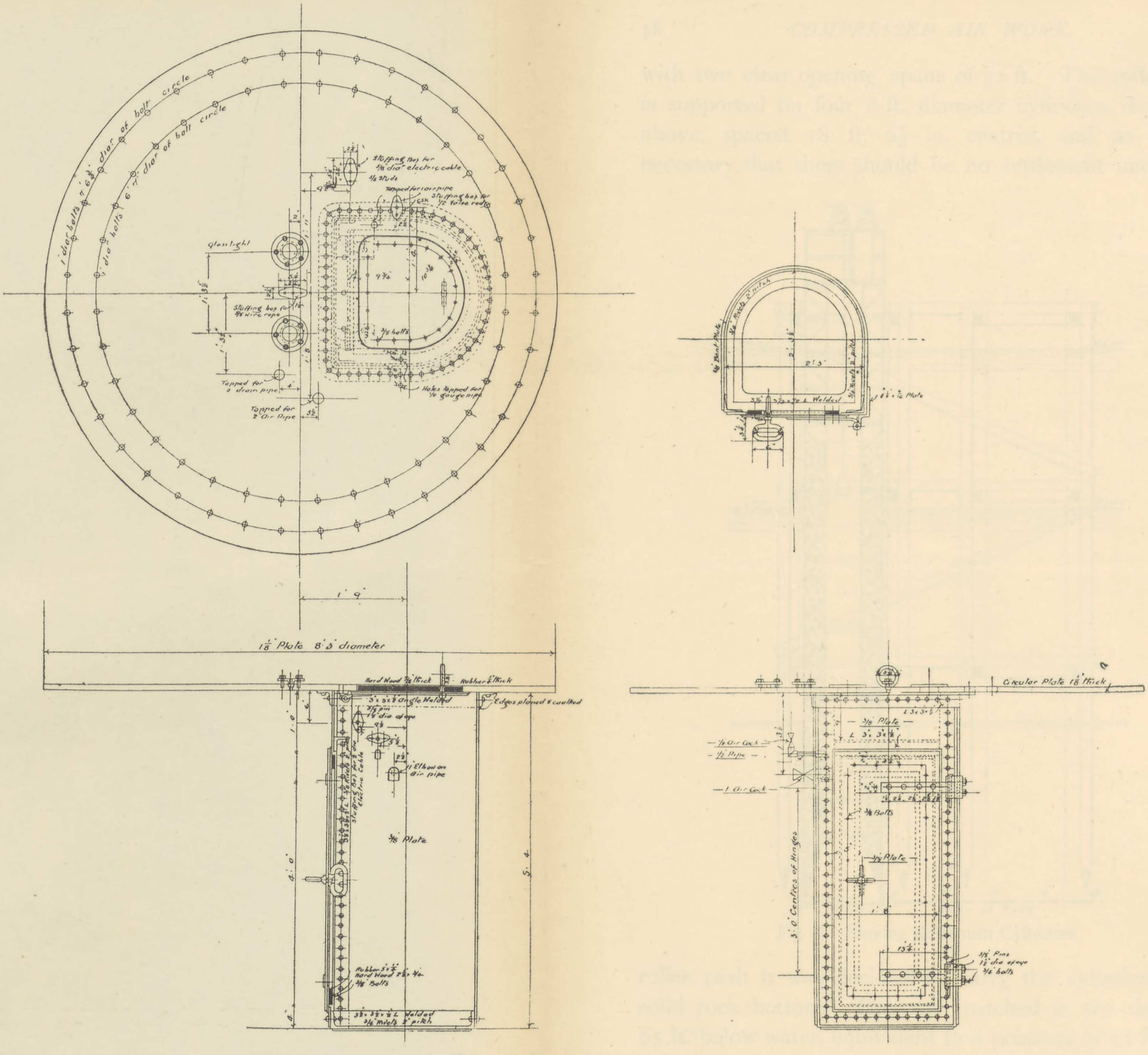

FIG. 9.—BARMOUTH AIR-LOCK.

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The type of cylinder built up with steel plates and with an inner shell is perhaps the best that can be adopted. The rate of sinking will be faster, because when moving the lock to add fresh lengths, the time which would otherwise be wasted in taking off and replacing the kentledge is gained. When also it is necessary to go to any great depths, and there is a considerable area exposed to skin friction, the kentledge required may become so great as to put an unfair stress upon the shell, which, if single, would have to take the whole of the weight as a column.

The new Redheugh Bridge (1901) cylinders were also of this double type, the outside shell being 8 ft. in diameter and $\frac{12}{20}$ in. thick for the top 54 ft., which portion would be above ground and exposed to the action of the air and to salt water. The lower portion, below ground, was only $\frac{8}{20}$ in. thick. The inner tube was 3 ft. in diameter. The sides of the bell mouth were designed by the engineers, Messrs Sandeman & Moncrieff, with the sides approaching more nearly to the perpendicular than was the case at Barmouth. The object was that if the caisson should sink suddenly in soft ground, the men working inside would not be knocked down by the sides, but would be shot up into the inner tube. The sides terminated 7 in. from the bottom, and were riveted to a 7-in. by 7-in. angle bar, which formed a ledge intended to prevent the too rapid descent of the cylinders in soft ground.

The King Edward VII. Bridge caissons differ from the others which have been described, inasmuch as they were not circular, but conformed to the shape of the granite masonry piers with cutwaters, which are founded on them.

The portion of the bridge across the river is in four spans, with a clearance of 81 ft. above high water level. The two centre spans are 300 ft. in length, and the piers supporting them are founded on caissons in the bed of the river. These caissons (see Fig. 10) were built of mild steel, and were 113 ft. long over cutwaters by 35 ft.

wide. The working chamber was 8 ft. high all over at the sides, rising, except at the cutwaters, by a curve in the roof to 9 ft. 6 in. high at the centre. Above the ceiling were girders, 3 ft. 6 in. deep in the middle and 3 ft. centres. The triangular shaped portion above the cutting edge, called the shoe, was stiffened every 3 ft. by diaphragms. This portion terminated about 7 in. from the cutting edge in a similar manner to the Redheugh cylinders, and the ledge so formed acted as a brake in soft ground, and also helped to keep the caisson plumb. The same purpose was effected by two girders with a bottom flange 3 ft. wide, which divided the working chamber into three bays. The first 26 ft. 6 in. of caisson was strongly braced and strutted by steel frames, and was so constructed that it would bear its own weight and that of a certain amount of concrete

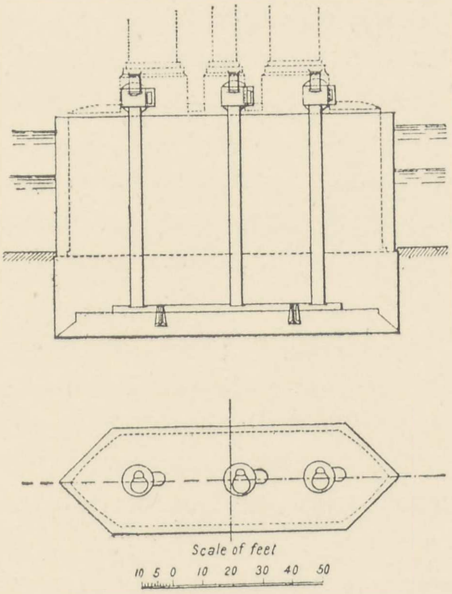

Fig. 10.—King Edward VII. Bridge Caissons.

when resting at both ends on rock or other hard ground and unsupported in the middle. Above 26 ft. 6 in. the caisson was a shell only, and therefore had to be strutted with timbers varying from 15 by 15 in. to 12 by 12 in.

Access to the working chamber was obtained by three shafts. The shafts were of novel design, being, in fact, two shafts run into one (see Figs. 10 and 11) and separated by an iron ladder constructed of 2-in. wide flats riveted to the sides of the shaft by angle bars running the whole length of the shaft on one side, and by short cleats on the other. By this ladder the men descended inside the small shaft, which was 2 ft. in diameter. The other portion, 4 ft. in diameter, was for material. An angle bar ran the length of the ladder riveted to the centre of the flats, and acted as a protection to the fingers and feet of the men, should they happen to be in the shaft at the same time as a bucket.

The lock (see Fig. 11) was circular, 8 ft. 6 in. in diameter by 6 ft. high. The entrance chamber was D-shaped, and bolted on to the outside of the lock, the joint between the two being made with red lead. The air pressure was raised and lowered from the outside by levers, and from the inside with keys by persons authorised to use them. The special feature of the lock was the bucket chamber, which was 3 ft. in diameter and 5 ft. 6 in. high. This chamber had a door which opened downwards, and which was closed after a bucket had entered by a wire bond and hook, which was fastened to a lug on the door by hand each time the door was closed. The bond passed round a drum which was fixed on a shaft driven by a motor placed on the outside of the lock and put into gear by a friction clutch. The bond on which the bucket was hung was 1 in. diameter, and passed through a stuffing box in the lid of chamber. This

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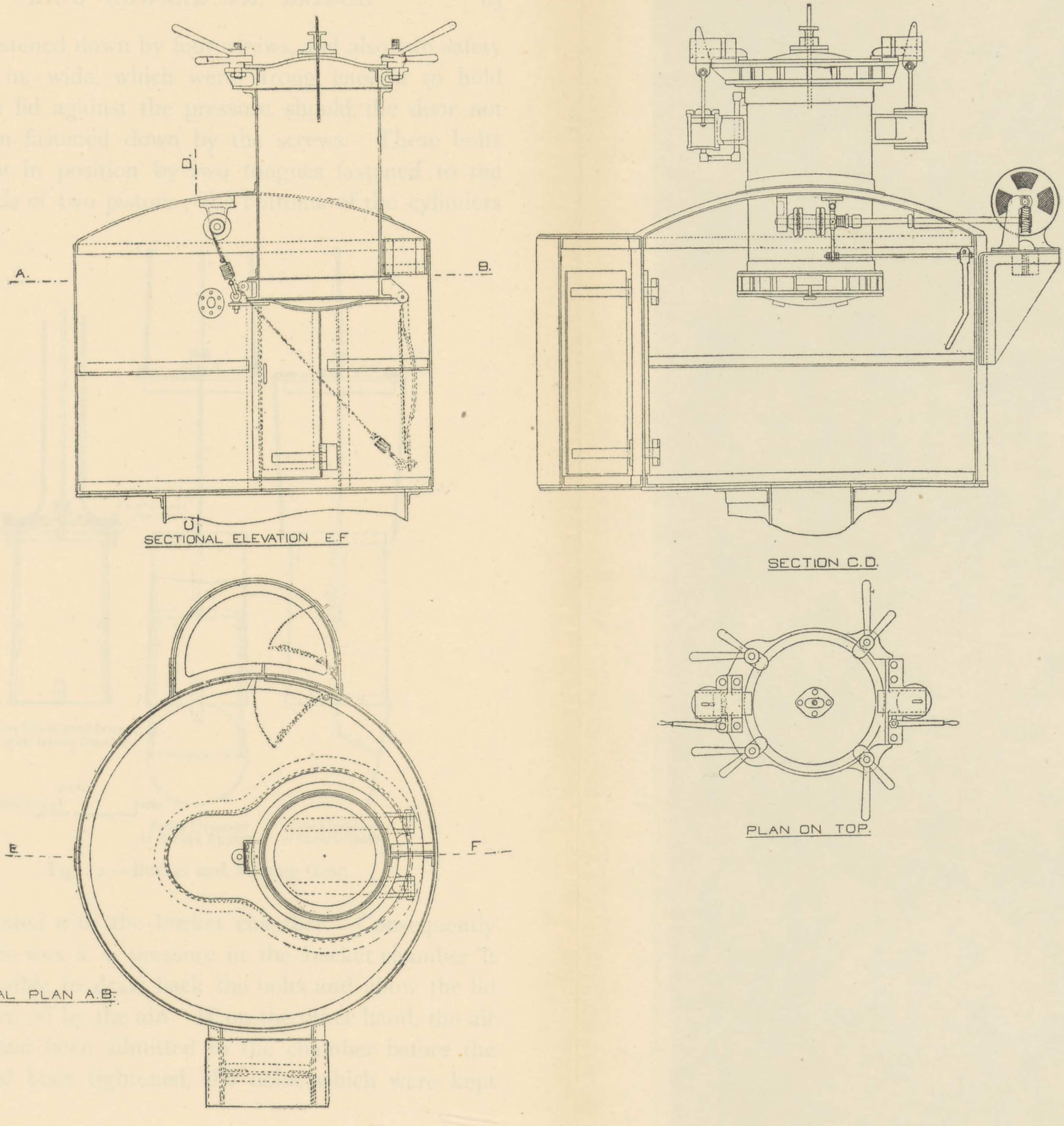

SECTIONAL ELEVATION E.F

SECTION C.D.

PLAN ON TOP.

SECTIONAL PLAN A.B.

FIG. 11.—DAVIS AIR-LOCK.

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lid was fastened down by four screws, and also two safety bolts 11 in. wide, which were strong enough to hold down the lid against the pressure, should the door not have been fastened down by the screws. These bolts were kept in position by two tongues fastened to the piston rods of two pistons; the bottoms of the cylinders communicated with the bucket chamber. Consequently when there was a + pressure in the bucket chamber it was impossible to draw back the bolts and allow the lid to be blown off by the air. If, on the other hand, the air pressure had been admitted to the chamber before the screws had been tightened, the bolts, which were kept

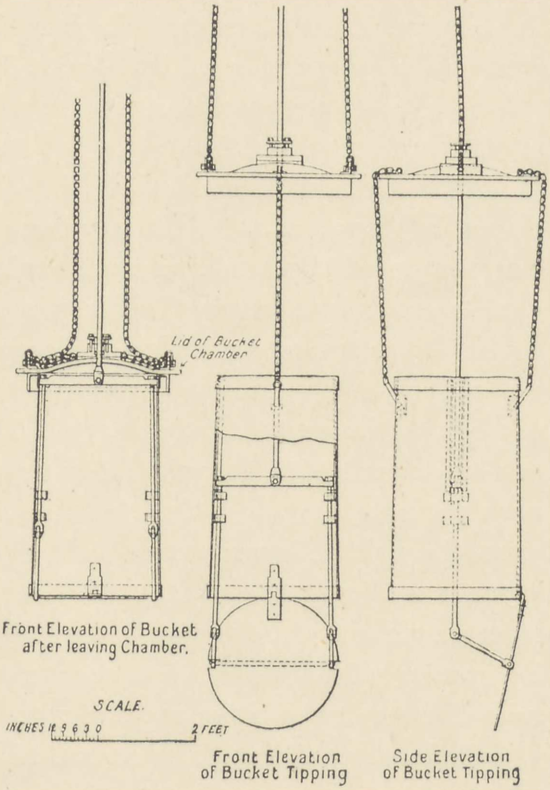

Fig. 12.—Bucket and Tipping Gear.

lubricated, would have been forced home by the tongues. Thus it was quite impossible for an accident to take place through the carelessness of the men working the air valves. The bucket was hoisted by a 5-ton electrically driven crane. The lid of the door was suspended (see Fig. 12) from the jib head of the crane by two chains. As the bucket was hoisted out of the chamber, taking the lid with it, the bucket was attached to the lid by two short chains, which, when the bucket was inside, were bunched up on the lid out of the way. By this means the shell of the bucket was held up when the bucket was lowered and the bottom opened and the excavated material tipped into hoppers to be taken out to sea.

The caissons were built *in situ* on overhanging timber caps or cantilevers marked FF in the diagram, Fig. 13. The method of lowering was as follows. Trestles were erected on each side of the caissons, on which were placed four box girders 3 ft. high and 1 ft. 6 in. wide. At each of the four points of support the top and bottom flanges were cut away to allow the sixteen suspending links to pass through. Between each pair of links was placed a 150-ton hydraulic ram. On the top of each ram were small cross girders and these took the weight of the caisson by means of two 2-in. diameter turned pins which passed through holes in the suspending links which had been drilled every 18 in. The stroke of the rams was 2 ft. They were connected up to two hand pumps and in such a way that the four along one side could be shut off or opened out together, or the four at each end. This was to enable the caisson to be kept straight without too great a load being put on any one pair of links. The rams could also be shut off singly or in pairs. In lowering, the first operation was to insert pins at BB and then raise the rams a few inches until the holes CC in the links

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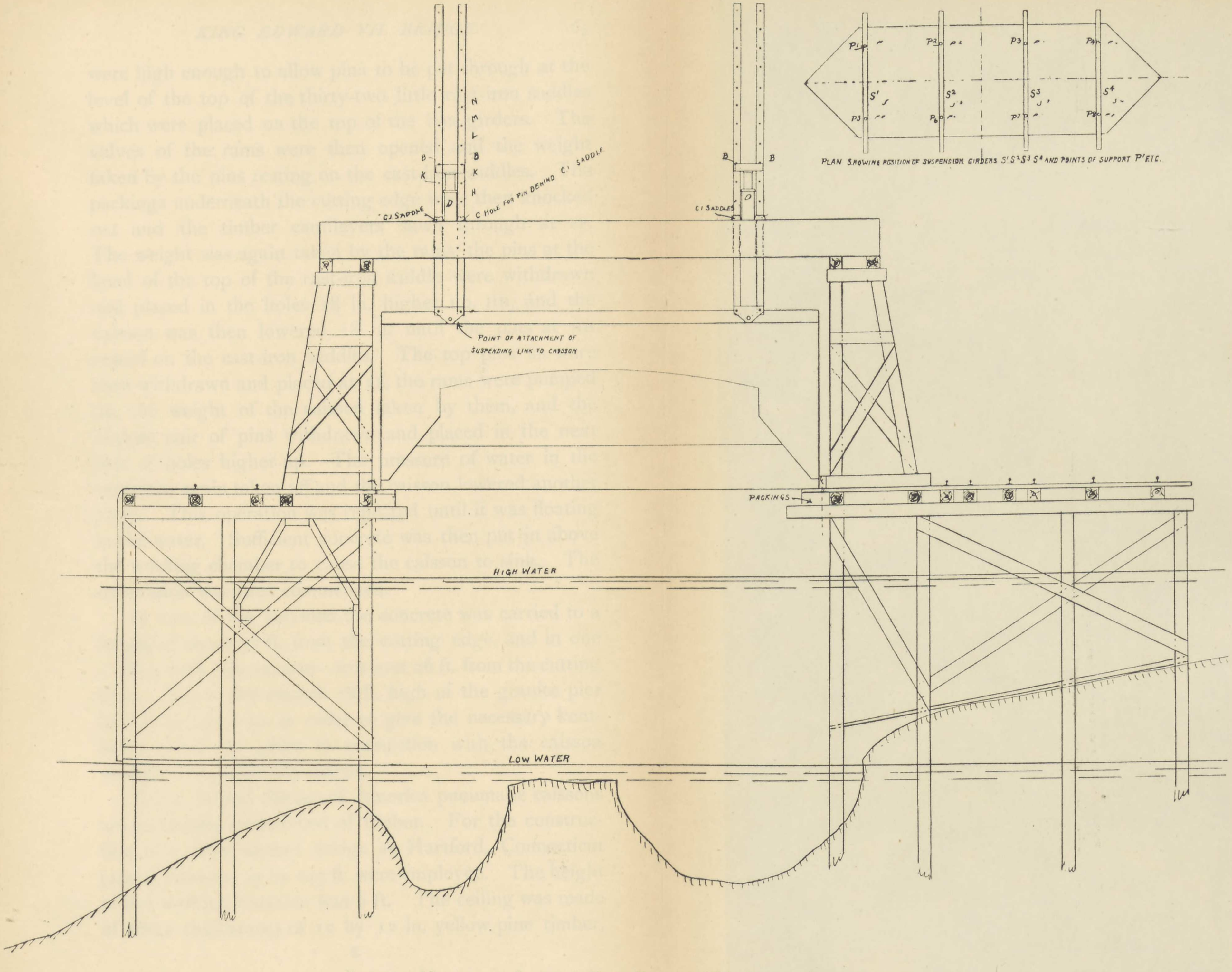

FIG. 13.—METHOD OF PITCHING KING EDWARD VII. BRIDGE CAISSONS.

[*To face page* 64.

were high enough to allow pins to be put through at the level of the top of the thirty-two little cast-iron saddles which were placed on the top of the box girders. The valves of the rams were then opened and the weight taken by the pins resting on the cast-iron saddles. The packings underneath the cutting edge were then knocked out and the timber cantilevers sawn through at FF. The weight was again taken by the rams, the pins at the level of the top of the cast-iron saddle were withdrawn and placed in the holes 18 in. higher up, HH, and the caisson was then lowered 18 in. until the pins at HH rested on the cast-iron saddles. The top pins BB were then withdrawn and placed at LL, the rams were pumped up, the weight of the caisson taken by them, and the bottom pair of pins withdrawn and placed in the next pair of holes higher up. The pressure of water in the rams was again taken off and the caisson lowered another 18 in. This operation was repeated until it was floating in the water. Sufficient concrete was then put in above the working chamber to cause the caisson to sink. The excavation was then commenced.

In two of the caissons the concrete was carried to a height of about 50 ft. from the cutting edge, and in one—the centre pier caisson—to about 26 ft. from the cutting edge. But in this caisson 16 ft. high of the granite pier had to be set also in order to give the necessary kentledge. All the plant in connection with the caisson sinking was electrically driven.

In the United States of America pneumatic caissons are commonly constructed of timber. For the construction of a stone-arched bridge at Hartford, Connecticut (1904), caissons 29 by 143 ft. were employed. The height of the working chamber was 6 ft. The ceiling was made of three thicknesses of 12 by 12 in. yellow pine timber, and the walls of one thickness. The 12-in. thick walls extended to a height of 7 ft. above the ceiling, and above that point were of 2-in. planking spiked to 12 by 12 in. verticals. These caissons were built on two pontoons, and when finished the pontoons were allowed to sink by filling with water until the caissons floated off. They were then floated into position, and sunk by filling with concrete in the usual way. Timber was also the material used for the very large caissons employed in the construction of the St Louis and Brooklyn bridges.

TABLE XII.—*Table of Bridges constructed by the use of Compressed Air for the Foundations.*

Name.	Year.	Type of Caisson.	Material of which Constructed.	Thickness of Metal in Outer Shell.	Diameter.	Area covered in Square Feet.	Depth to which taken below High Water.
				In.	Ft.		Ft.
Rochester - - -	1851	Circular, with single shell	Cast iron - -	$1\frac{3}{8}$	7	39	40
Chepstow - - -	1852	,, ,,	,, - -	...	8	50	84
Saltash - - - -	1854-56	Circular, with double shell	Wrought iron -	...	37	1,075	91
Londonderry - - -	1859	Circular, with single shell	Cast iron - -	$1\frac{1}{2}$	11	95	70
Forth - - - -	1882-90	Circular, with double shell	Wrought iron -	...	70	3,849	89
Victoria (Stockton-on-Tees)	1887	Circular, with single shell	Cast iron - -	$1\frac{1}{2}$	14	154	54
Conway - - - -	1898	,, ,,	Mild steel - -	$1\frac{1}{4}$	12	113	63
Redheugh - - -	1901	Circular, with double shell	,, - -	$\frac{8}{20}$ to $\frac{12}{20}$	8	50	78
Barmouth - - -	1902	Circular, with double shell; circular, with single shell	,, - -	$\frac{5}{8}$	8	50 50	95
King Edward (Newcastle-on-Tyne)	1904	Shape of granite piers, single shell	,, - -	Average $\frac{1}{2}$	...	3,342	70

CHAPTER VII.

Tunnelling.

When compressed air is used with a shield for driving a tunnel in water-bearing strata, and the exposed area is therefore vertical, instead of horizontal as in caisson work, there will be a difference in the head of water, which will have to be met by the compressed air, equal to the height from the invert to the crown of the tunnel. The result is that either the water will tend to come in at the bottom, or else a large volume of air will be escaping round the cutting edge at the top of the shield. When the tunnel is in hard rock free from fissures, this difference of pressure is of very little consequence, but when the ground is soft or sandy, it will be necessary to do away with the open face. The shield is merely a hollow cylinder, or caisson placed on its side, slightly greater in diameter than the iron lining. The front part is divided up into compartments which give standing room to the workers excavating at the face, and also serve to give the shield the required stiffness. This front part is usually divided off from the back by a diaphragm with doors, through which the excavated material is passed. Some shields have a double diaphragm and two sets of doors, so that a different air pressure may be employed at front and back. Hydraulic rams are fixed to the back of the shield all the way round, and at the other end press against the cast-iron lining when pushing the shield forward. The rear part of the shield is called a tail. It is made of two or more plates riveted together with countersunk rivets and overlaps the cast-iron lining. It is long enough to allow of an overlap when the shield has been pushed forward to allow the next ring of iron to be placed in position.

Behind the diaphragm and fixed to the shield is the erector. This is an arm which revolves round the centre line of the tunnel, and is used for picking up and placing in position the iron segments. It contains a ram, so that it can be shortened or lengthened to allow of the segment being swung round conveniently, and then shot out and pressed home when opposite its correct position. It is slewed round, in some shields, by a rack and pinion, and in others by a chain passing over a drum. In either case the power is hydraulic. Shields for tunnels of large diameter are very frequently fitted with two erectors.

Some shields are fitted with a water trap. This was first done at the Vyrnwy Aqueduct Tunnel* at the suggestion of the late Sir Benjamin Baker. The front of this shield, a little way back from the cutting edge, was entirely closed, with the exception of a small hand hole, from the top down to the centre. The remaining portion was fitted with removable shutters. A little way further back was a diaphragm starting from the bottom of the shield, and reaching up to and slightly overlapping the front closed-in half. The result was that any water coming in would rise to the level of the top of the diaphragm at about the centre of the tunnel, and there

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* Simm's "Practical Tunnelling."

overflow. It would thus present a horizontal face to the air pressure, and if this pressure were equal to the head of water at the centre of the tunnel, no water could enter. At this particular tunnel, however, the pressure was kept very much lower than that due to the head of water, and to meet this difficulty the trap was fitted with a lid, which could be closed down if any sign was noticed of the water coming in. It is difficult to keep the pressure sufficiently high to make a water trap quite efficient, but to have the front part of the shield closed half-way down is thoroughly sound, as even if the air pressure is not high enough to balance the water, the latter as it enters will compress the air as it rises, and, provided the tunnel is on the level, there will always be enough for the workers to breathe, and to enable them to escape through the emergency lock. The tunnel will, in fact, from the bottom of the closed-in portion of the shield back to the bulkhead, be converted into a huge diving bell. If the tunnel has a gradient, it may be necessary to introduce hanging screens, with an emergency lock in each, at frequent intervals, more particularly if the gradient is rising towards the face. A water trap will, however, be best in a tunnel of small diameter in which there is not sufficient room for an emergency lock in the upper part of the bulkhead, since the water, when it overflows the lower diaphragm, will stop the escape of air, and the compression of air will start at once instead of only when the lower edge of the screen is touched. But that ample security is given by a hanging screen, or half closed-in shield, in a tunnel of large diameter, will be seen by a glance at Table XIII.

The emergency lock should be always fixed as high up as possible for this reason, and at its level there should be a gangway supported on light brackets fixed to the

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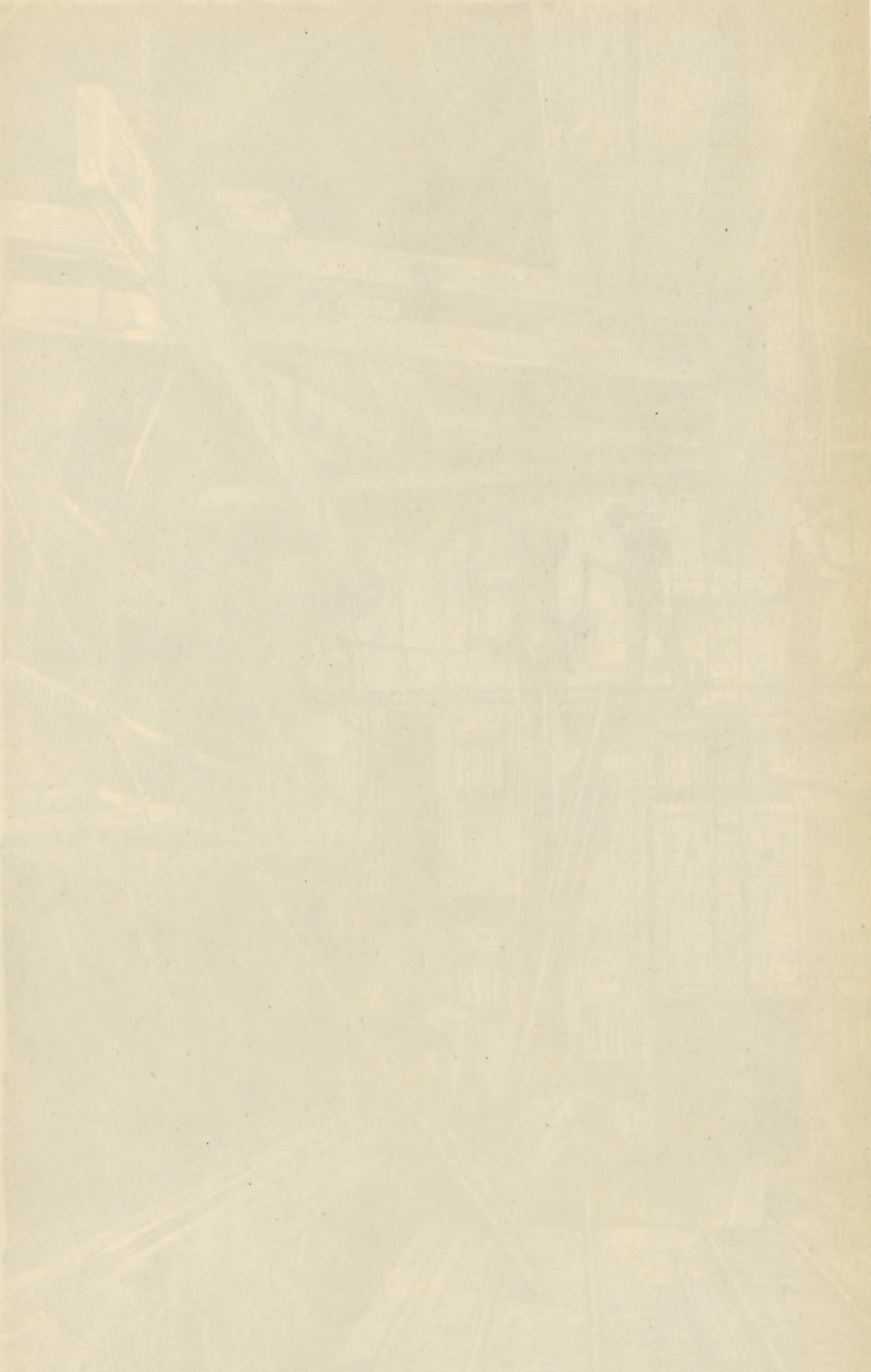
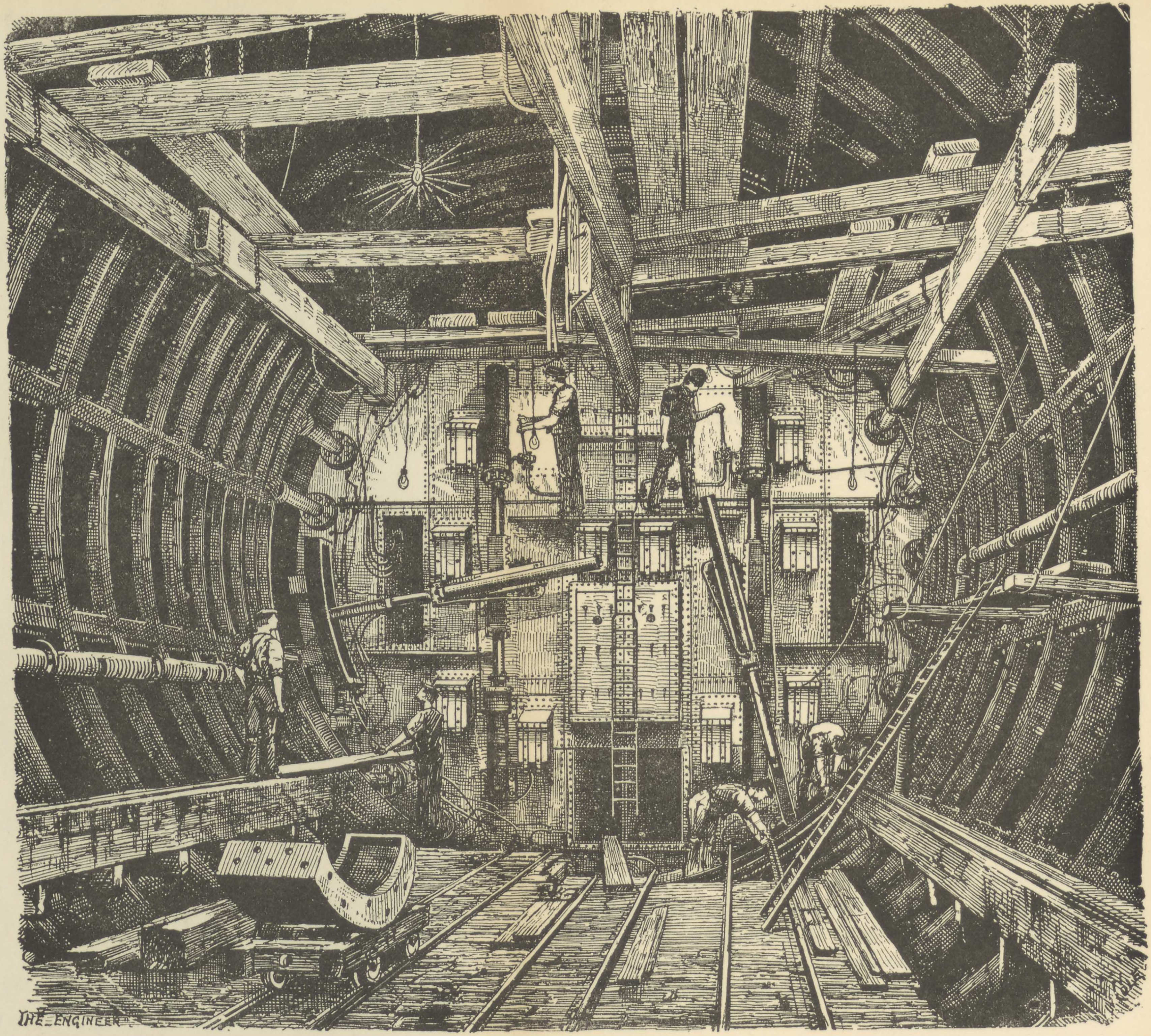


… of Back of Shield, showing Hydraulic Machinery,
[illegible] May 1893.



The Blackwall Tunnel, View in Tunnel at Back of Shield, showing Hydraulic Machinery.
From "The Engineer," 21st May 1897.

[*To face page* 71.

tunnel lining on each side, so that the workers can escape out of reach of the incoming water. Such gangways were used at the Blackwall Tunnel,* and have also been employed at many other tunnels since, both here and abroad.

Additional safety is obtained by a hanging screen which comes half-way down the tunnel and acts in a similar manner to the top half of the safety trap. That used at the Blackwall Tunnel was fitted with a lock which was always kept with the inner door open towards the working face to provide a means of escape should the water rise to the bottom of it before it could be reached. The hanging screens and gangways were introduced at Blackwall by Mr Moir.

Behind the screen again is the bulkhead which divides the front portion of the tunnel off from that portion which is kept at a lower or at atmospheric pressure. This bulkhead is usually made of brick or concrete, and has locks for men and material built into it. These locks are boiler-shaped, and fixed in a horizontal position. The doors open inwards towards the working face, and are lined with rubber gaskets and kept closed by the pressure of the air. They are fitted with large air valves, so that the pressure can be quickly raised and lowered when material is inside, and with smaller ones for men.

For tunnels of 23 ft. diameter and over, two parallel locks are used for material, about 7 ft. or so in diameter, and above them is placed the emergency lock for men in the centre, and as high up as possible. This should always be kept open towards the working face, but should be used occasionally to see that it is in working

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* *Proc. Inst. C. E.*, vol. cxxx.

order. When the air pressure is over 20 lbs., a second bulkhead similarly equipped with locks will be an advantage. The space between them will be kept at about half the absolute pressure for "purgatory" lock working.

In large tunnels two lines of tram rails are used for bringing in the cast-iron lining and other material, and for taking away the excavated material. These start from each material lock and have short lengths of rail which have to be taken up each time a waggon enters the lock. In the early tunnels mules were used to drag the waggons, but the best modern practice is to have an endless wire bond worked by an electric motor. To this the waggons are hitched, and the motor started by signalling with electric lamps.

When a tunnel is being started under a river, a shaft must first be sunk near the bank. This is usually done by means of a steel caisson, and when water is likely to be met with, compressed air must be used. The caisson has a double shell filled between with concrete. Those for the Blackwall Tunnel were 58 ft. external and 48 ft. internal diameter. About 9 ft. from the bottom is a strong roof above which water can be filled in for kentledge when necessary. At the point in the caisson where the shield will start, a circular opening is left, plugged with a single shell well stiffened. When the caisson has reached the level intended for it a strong water-tight concrete floor is laid at the bottom. The air is then taken off and the roof above the working chamber removed, and the caisson lowered into position or built *in situ* in the open. The roof is then put back again higher up, the air pressure put on again, the plug cut out and the shield started on its journey. When the shield can be started in the open, all this is much simplified.

When the strata is of a soft, silty nature, no excavation will be required, but the shield is forced forward by the hydraulic rams. The area of the openings is arranged to be much less than the cross sectional area of the tunnel, and this helps to consolidate the ground in front of the shield. The material is forced through the openings and comes out looking like clay when coming out of a machine for making wire cut bricks. As it comes through it falls behind the shield in big lumps and can then be loaded into waggons for removal. When this method is used the excavated material to be removed will be no greater than the calculated displacement of the tunnel, and is often even less in soft ground. With sand or very soft material the difficulty of work with a shield is much increased, and unless great care is taken, the amount of material to be removed will much exceed the displacement. With such soft material the difficulty of regulating the air comes in. As in caisson work, if too great a volume of air is allowed to escape at the face, blows will be caused, and there will be difficulty in maintaining the pressure. If too little air is used, the water will come in at the lower levels of the face. It is best to do with as little pressure of air as possible. Any surplus required for the health of the workers can be allowed to escape through a valve with an automatic cut-off. The pressure that will be most suitable can be only determined by trial when passing through the strata. With close ground above and open ground below it will probably be found best to regulate the pressure so as to balance the water pressure at the point in the working face where the two meet. As a general rule the two pressures should balance at the level of the crown of the tunnel or a foot or two below it.

When there is only a few feet of ground between the top of the tunnel and bed of the river a clay blanket is sometimes used. This is deposited on the bed of the river by hoppers to form a covering about 8 or 10 ft. thick and 150 ft. wide. The clay will not wash away, as silt or mud would, and the air has to pass through the ground in a slanting direction and therefore has a better chance of keeping the ground dry without churning it up.

There is, however, the danger that a pocket of air may form below the tough clay by reason of the ground sinking during the excavation. Any sudden lowering of the pressure would then cause the clay to collapse inwards and this might cause a flooding of the tunnel. This is not a danger if the blanket be made thick enough.

A combination of soft running material and rock presents the greatest difficulty, as it is necessary to get in front of the cutting edge in order to drill and blast the rock. Under these circumstances it will be necessary to closely board up the soft material, and the boarded-up portion must then be strutted with telescopic jacks or tunnel "guns" so that when the shield is "shoved" forward, the boarded-up portion will not be interfered with. At the Blackwall Tunnel horizontal iron shutters were used. These in their forward position were a few inches back from the cutting edge. They were kept in position by screws passing through lugs with a nut at each side of the lugs. When the shield was "shoved" the front nut was screwed forwards so that the shutters remained stationary while the shield moved up towards them. Before the next "shove" the material behind each shutter was excavated separately, and the shutters screwed forward by means of the nuts to their forward position.

When a tunnel is being driven in rock, a void will be left all round the cast-iron lining. This will have to be filled up with cement or hydraulic lime grout, which also serves to protect cast iron from the disintegration to which it is often so liable. Quick-setting lime grout is also used for tunnels in ballast or in any loose strata. For grouting purposes a plugged hole is left in each segment and when grouting this plug is taken out and a flexible tube screwed in which is connected to the grouting or "baugee" pan.

Equal parts of cement and sand are put into the grouting pan with the right proportion of water and thoroughly mixed by means of a spindle with blades passing through it. The door, which opens inwards, is then pulled upwards and air turned into the pan at a pressure of 100 lbs. to the square inch. This forces the grout through the tube and plug hole into the space outside the iron lining.

If grouting is carried up too close behind the shield, it may cement up the tail of the shield and put too much work on the rams. If this is the case the grouting must be kept well behind the shield, or else lime grout used, which, while setting quickly, does not set so hard.

When, however, the tunnelling is under house property or wharf walls where a subsidence would be serious, the grouting must follow up immediately behind the shield. All round the cutting edge must then be well stopped up with clay and the jacks fitted with segmental plates in order to close up the space between the skin of the tail and the cast-iron lining. This space must be well clayed up. Where there are no grouting plates, segmental boards wrapped round with old cement bags are used.

A tunnel is liable to get flat by reason of the weight above it and also by the weight of its iron lining. Probably this is chiefly due to the weight of the iron lining as it happens with tunnels in mud or silt as well as with those in rock. In mud or silt, which tend to be of a viscous fluid nature, one might expect the pressure to be greater at the sides than at the top. This, however, does not seem to be the case. The result is that the lining will be subjected to bending stress and the flanges will be in tension at their inside edges at the crown and invert of the tunnel and at their outside edges at the sides.

To get over this difficulty turnbuckles are used which pull in the sides of the lining and thus take the flatness out. This should be done before grouting. Once the tunnel has got set in its proper shape it will not get out of shape again.

The flanges of the lining are usually machined except for the last 1 or 1½ in. on the inside. This is cast so as to leave a space of about ⅜ in. between the flanges. When the grouting has been finished, this is caulked with iron borings to form a rust joint, or, better still, with ⅜-in. lead wire. This insures the lining being quite air and water tight.

The shield is directed by means of long rods to fixed points measured off on the tunnel lining. These have to be carefully watched as the shield is being "shoved." If one side shows signs of gaining, some of the jacks on that side will have to be shut off.

It is made to point up or downwards in the same way by shutting off jacks on the top or bottom.

Sometimes a concrete cradle is used. A cradle is a concrete invert which is carried forward well in advance of the shield. It is shaped to the radius of the shield and usually has two rails embedded in it, the tops of which are flush with the concrete. On these the shield slides. With such an arrangement the shield can be kept at the proper level without difficulty, but placing it involves getting out in front of the shield, which is a disadvantage.

TABLE XIII.

Showing Compression, by Rising Water, of Air in top of a Tunnel on the Level when Converted into a "Diving Bell" by a Screen reaching half-way down. This table cannot be used for a tunnel on a gradient.

Initial Pressure in Pounds per Square Inch.	Height of Water up Screen in terms of the Diameter of the Tunnel.						
	$\frac{1}{20}$	$\frac{2}{20}$	$\frac{3}{20}$	$\frac{4}{20}$	$\frac{5}{20}$	$\frac{6}{20}$	$\frac{7}{20}$
	Resultant Pressure in Pounds per Square Inch.						
0	2	5	9	14	23	37	63
5	8	12	17	24	36	55	90
10	14	18	25	34	48	72	...
15	19	25	33	44	61	...	...
20	25	32	41	54	...	...	...
25	31	39	49	64	...	...	...
30	37	45	57	...	...	...	...
35	42	52	65	..	...	...	...
40	48	59	...	...	...	...	...

CHAPTER VIII.

Tunnelling (*continued*).

BLACKWALL AND ROTHERHITHE.

THE Blackwall Tunnel, 27 ft. external diameter, and the Rotherhithe Tunnel, 30 ft. external diameter, are the two largest tunnels which have been constructed by means of compressed air. The Blackwall Tunnel was started in 1891 and finished in 1897, the engineer being Sir Alexander Binnie. The Rotherhithe Tunnel was started in 1904 and finished in 1908 and the engineer has been Mr Maurice Fitzmaurice, C.M.G.

Both these tunnels are for road traffic and have been made by the London County Council. The Blackwall gives a 16 ft. roadway and a footway 3 ft. 1½ in. wide on each side, and the Rotherhithe a roadway, also 16 ft. wide, and two footways, each 4 ft. 8½ in. wide.

The Blackwall Tunnel shield was 19 ft. 6 in. long and 27 ft. 8 in. external diameter.* It was divided into twelve compartments by three vertical and three horizontal divisions. The central division only extended from top to bottom so that there were two compartments at the top, four on the next two levels, and two at the bottom.

In loose ground the front was closed in by shutters

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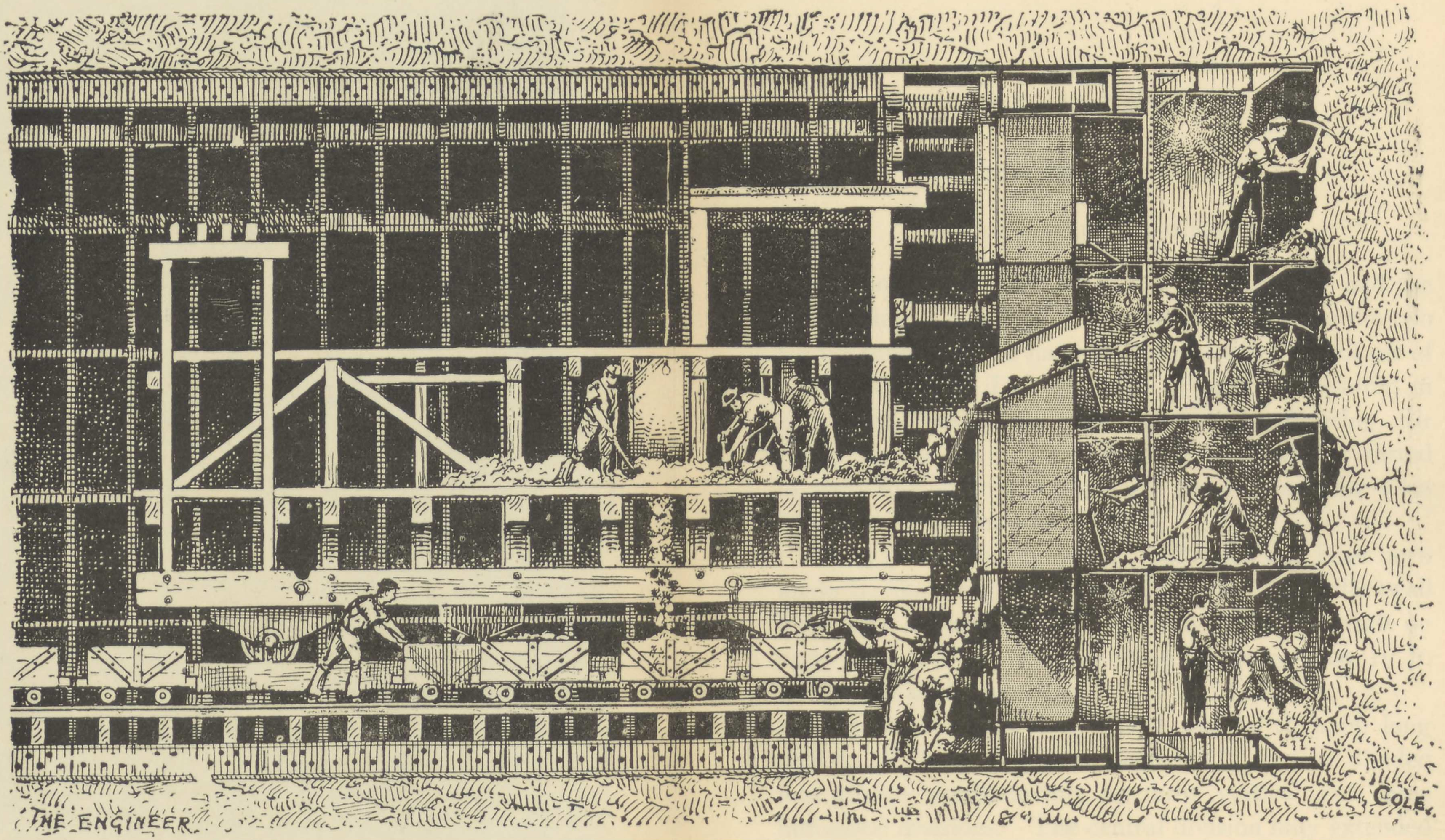
* *The Engineer*, 21st May 1897.

PLATE III.



THE BLACKWALL TUNNEL, LONGITUDINAL SECTION OF TUNNEL, WITH SHIELD WORKING IN CLAY.
From "The Engineer," 21*st May* 1897.

[*To face page* 79.

in the manner described in the last chapter. At a point 9 ft. 3 in. back from the cutting edge the front of the shield was entirely shut off from the back by a bulkhead composed of two steel diaphragms 3 ft. apart, so that a higher pressure could have been used in front of the shield than behind. This method of working was, however, never actually adopted. Material shoots were provided in each compartment worked on the air-lock principle, and there were four air-locks for men.

There were twenty-eight rams 8 in. in diameter, and several round the lower half 10 in. diameter when the shield was entirely in ballast, and these with a water pressure up to 3 tons to the square inch, and neglecting the friction of the rams, gave a pressure on the back of the shield of 2,800 tons. A total pressure of 4,000 tons was, however, required at times.

There were two hydraulic erectors at the back worked by rack and pinion. (Plate II.)

This shield, together with the rest of the plant, was designed for Messrs S. Pearson & Son, Ltd., the contractors, by Mr E. W. Moir, now one of their directors.

There were four shafts on the line of the tunnel, Nos. 1, 2, 3, and 4. Shafts 1 and 2 were on the north side, and 3 and 4 on the south side of the river. Driving was commenced in No. 4 Shaft and was continued through No. 3 Shaft, and from there northwards under the river to Shaft No. 2. The caisson for Shaft No. 4 was carried down 13 ft. below the invert of the tunnel, and this 13 ft. was filled up with concrete with a wrought-iron water-tight floor built in below it. The shield was built on top close to the shaft, and a dock was then dug in the ground underneath and round it. Some of the plates of the caisson were then removed down to the level of the bottom of the dock, and both caisson and dock flooded with water. The shield was then floated into the caisson, and lowered into position by pumping out the water. The plug was cut out in the open, and driving started without the use of compressed air. A good deal of water came in, but this could be dealt with by pumping until a point 67 ft. from Shaft No. 3 was reached, when it was found necessary to use air pressure, and from this point onwards, under the river and through Shafts Nos. 2 and 3 on the other side, and to within about 30 ft. of the cut-and-cover at the extreme north end, the driving was done with the help of compressed air.

After leaving Shaft No. 1 and coming out under the river, very little difficulty was experienced at first, as there was a layer of clay between the top of the tunnel and the bottom of the river. The clay, however, gradually died out, and for a distance of about 350 ft. there was nothing but ballast, the depth of which, between the top of the tunnel and the bed of the river, did not exceed 10 ft., and in some places did not exceed 6 ft. A clay blanket 150 ft. wide and 10 ft. thick was therefore tipped over the tunnel, in order to prevent the air from escaping too freely, and to enable the pressure to be maintained. It also served to fill up any holes which might form at any time by the ground sinking. Such holes would sometimes form and the clay fall and fill them up. Sometimes clay which had filled up holes in this way would come through the openings in the front of the shield and into the tunnel. It was at this point that the 10-in. diameter rams round the lower half of the shield had to be added, as it was impossible to get in front of the shield to excavate, and therefore a very big pressure was required to force the shield forward. During this period a force of 4,000 tons was sometimes required. The 8-in. diameter rams would have been sufficient, but for the fact that at times some of the rams had to be shut off in order to guide the shield.

The maximum air pressure required in the tunnel was 28 lbs. per square inch, and the maximum head of water above the level of the crown of the tunnel was 53 ft. Since 28 lbs. is equal to the pressure caused by a head of 65 ft. of fresh water, it will be seen that the hydrostatic and air pressures balanced at a point 12 ft. below the level of the crown of the tunnel. The range of tide was about 20 ft. and the average pressure was rather below 28 lbs. in the tunnel, but when putting in the floor of one of the caissons a pressure as high as 35 lbs. was required.

The iron lining for the length under the river, and for some of the land part, was built up of 2 ft. 6 in. wide rings, 27 ft. outside diameter and 25 ft. diameter inside flanges, 2-in. metal, and there were fourteen segments and key piece to each ring. These rings each weighed 14 tons 16 cwt. The lining used for the rest of the tunnel had 10-in. deep flanges (*i.e.*, 25 ft. 4 in. diameter inside flanges) and 1½-in. metal and weighed 10 tons 10 cwt per ring.

The resident engineers were Mr Maurice Fitzmaurice* and Mr David Hay.

The Rotherhithe Tunnel extends from Lower Road, Rotherhithe, to Commercial Road, Stepney, and passes under the River Thames. It is situated 2 miles above the Blackwall Tunnel, and 1½ miles below the Tower Bridge.

The general method of construction was very similar to that adopted at Blackwall, *i.e.*, four shafts were sunk on the line of the tunnel, two each side the river.

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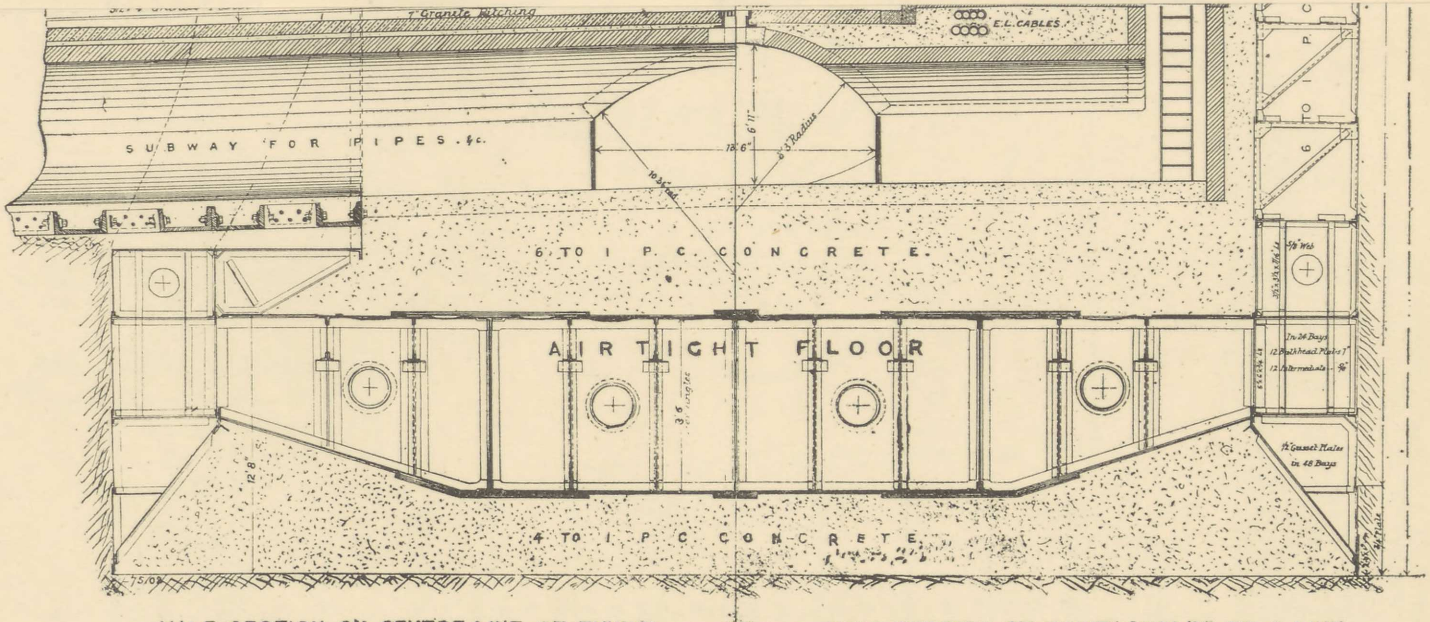
* Now C.M.G. and Chief Engineer to the London County Council.

The distance from the centre of Shaft No. 1 to the centre of Shaft No. 2 was 927 ft. From the centre of Shaft No. 2, and under the river to the centre of Shaft No. 3, the distance was 1,571 ft. 6 in., and from the centre of Shaft No. 3 to the centre of Shaft No. 4 the distance was 1,190 ft. 6 in. There was also a length of cut-and-cover at each end, as well as the open approaches.

The shield used for driving the section under the river was started from Shaft No. 3, which was on the north side of the river, and the caisson for sinking the shaft is shown in Figs. 14A and 14B, and is similar to those used for the other three shafts. It was circular in section, and had two shells. The external diameter was 60 ft., and the internal diameter 50 ft., and the five-foot space between was filled with Portland cement concrete.

The working chamber was formed by an air-tight floor 12 ft. 8 in. above the level of the cutting edge, and this was supported on three girders, 8 ft. 6 in. deep, with three others at right angles to them, or six girders in all, each 8 ft. 6 in. deep. Access to the working chamber was obtained by means of two shafts 8 ft. 9 in. in diameter, placed 12 ft. apart, centre to centre, at one side of the caisson (Fig. 14B). These were connected together at the top by a large dome-shaped air-lock, from which projected horizontally outwards two circular chambers 5 ft. 9 in. in diameter, and with doors opening inwards towards the caisson and therefore kept closed by the pressure of the air only so that they were quite safe and no interlocking device was necessary. They had a length inside, clear from all obstructions, of 16 ft. 6 in. and were made this length in order to take two waggons at once when these



HALF SECTION ON CENTRE LINE OF TUNNEL. —— HALF SECTION AT RIGHT ANGLES TO C LINE.

FIG. 14A.

[*To face page* 82.

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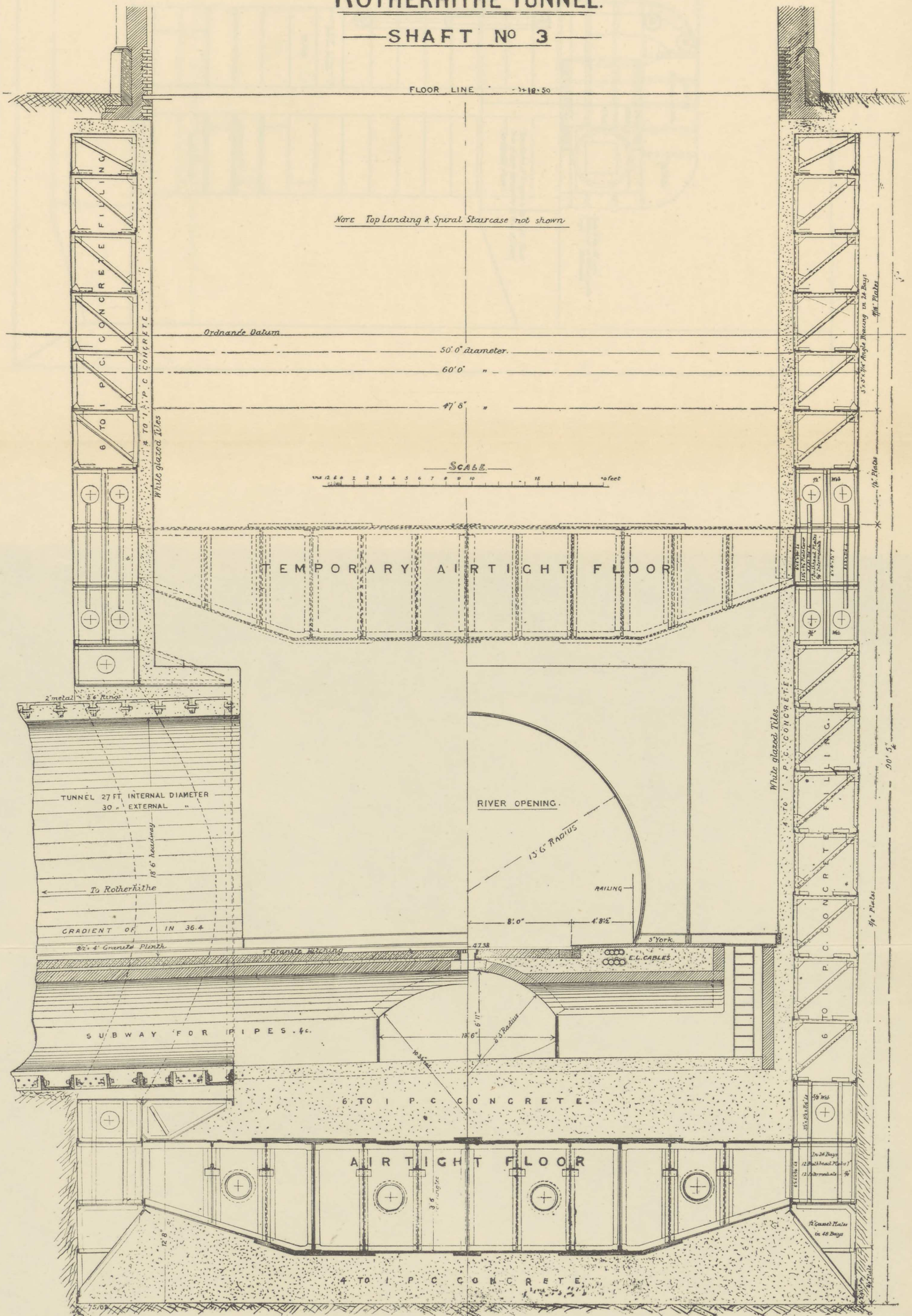
ROTHERHITHE TUNNEL.

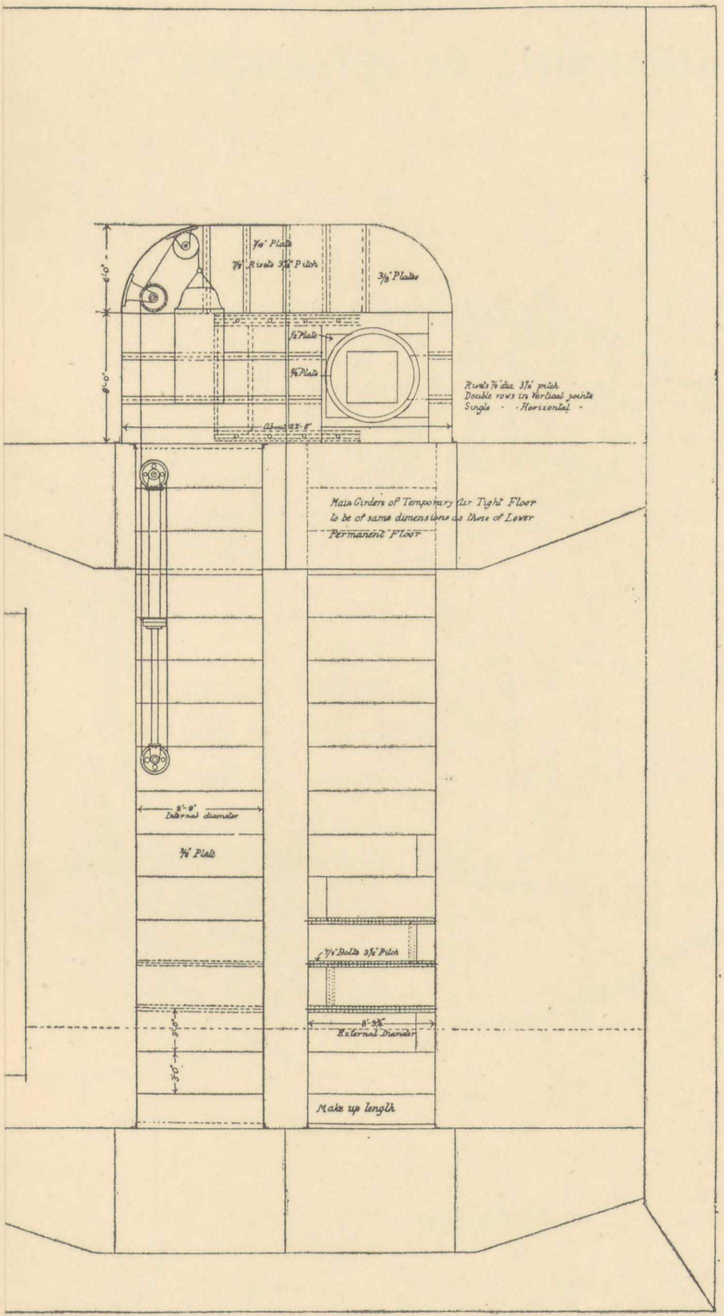
SHAFT No 3



HALF SECTION ON CENTRE LINE OF TUNNEL. HALF SECTION AT RIGHT ANGLES TO C LINE.

FIG. 14A.

[*To face page* 82.



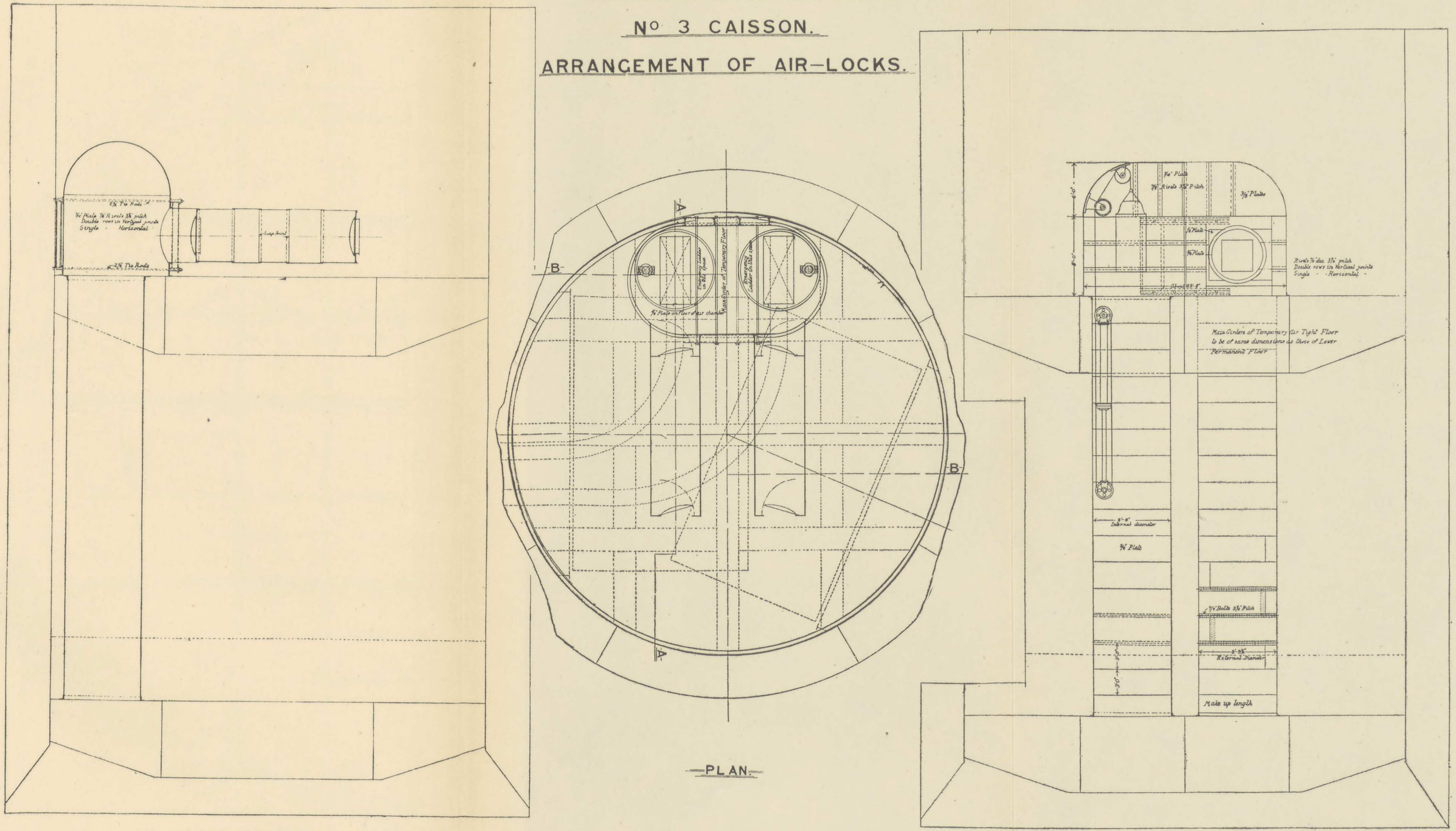
CROSS SECTION. B-B.

[*To face page* 82.

ROTHERHITHE TUNNEL.

No 3 CAISSON.

ARRANGEMENT OF AIR–LOCKS.



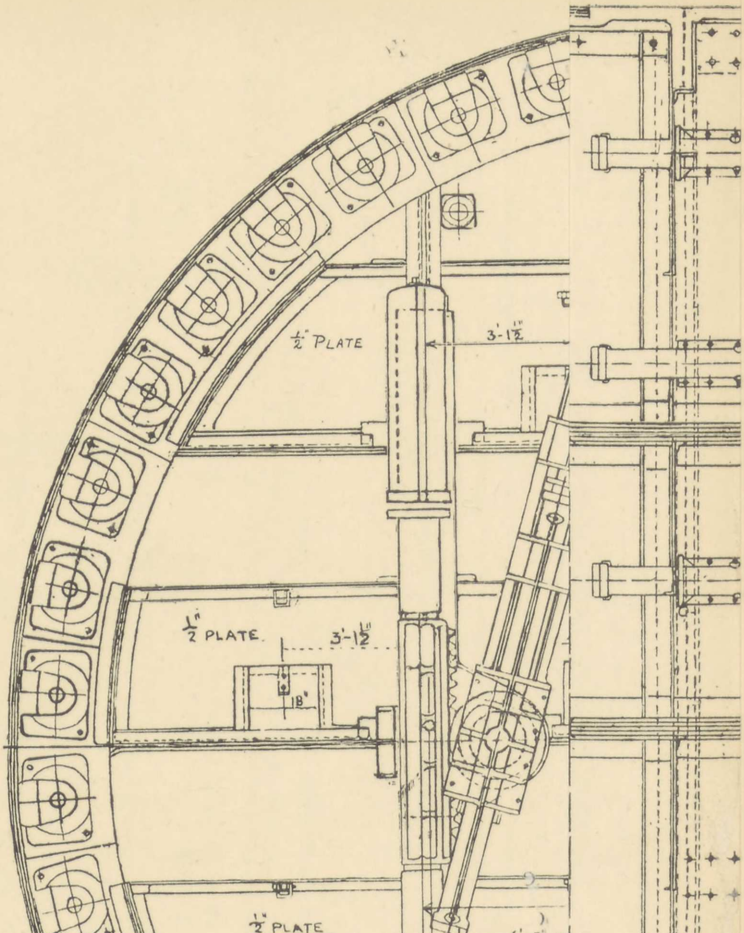
CROSS SECTION. A. A

PLAN.

CROSS SECTION. B–B.

FIG. 14B.

[*To face page* 82.



Half Back Elevation.

nal Section.

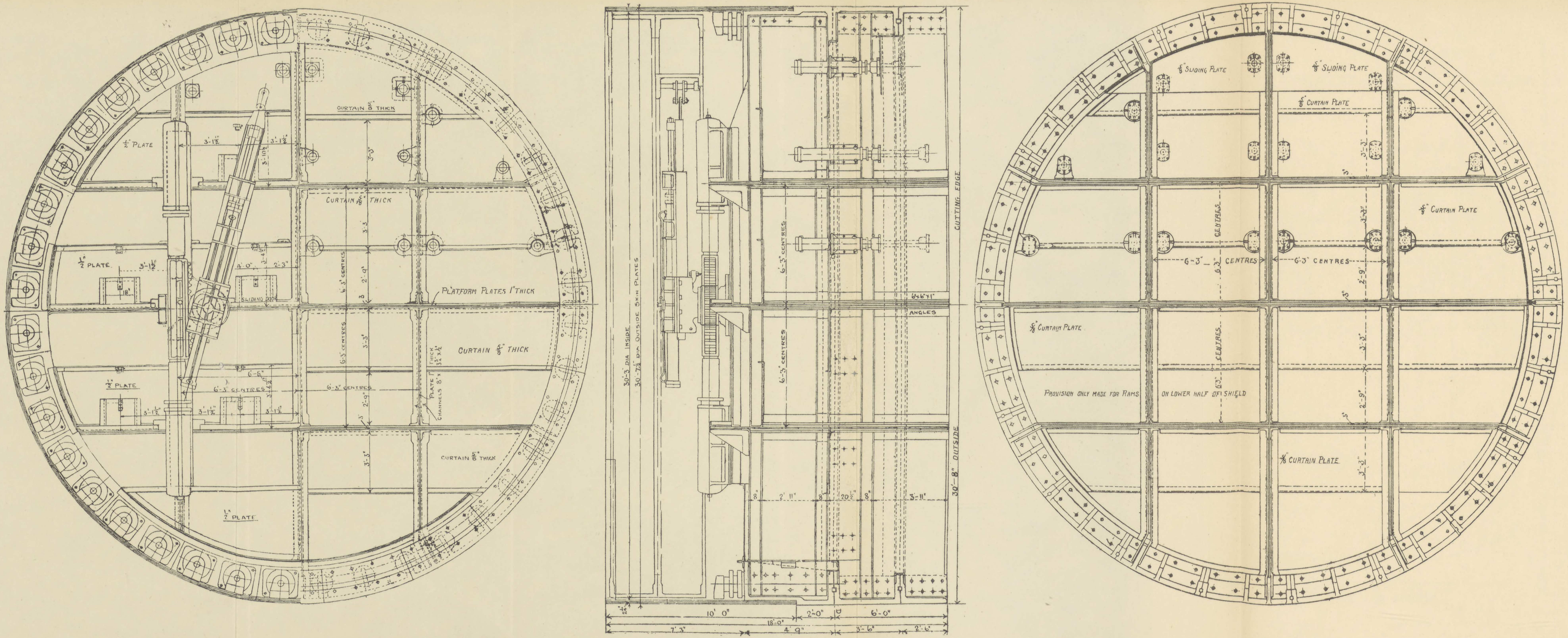
THE TUNNEL S

were sent out of the tunnel full, and they were used in this way until the shield had advanced sufficiently far under the river to allow a bulkhead to be built and the shaft opened to the atmosphere. There was no separate entrance for men, but the same entrance chamber was used for men and material. Buckets were not used, as is generally the case during the sinking of caissons, for removing the excavated material, but this was instead filled into waggons and the waggons hoisted by a lift worked by a hydraulic ram. This arrangement is clearly shown in the drawing, Fig. 14B.

The caisson was sunk until the cutting edge was about 16 ft. 9 in. below the invert of the tunnel, and this 16 ft. 9 in. was then filled up with Portland cement concrete, with the air-tight floor embedded in the concrete in order to make a perfectly water-tight floor. The air-lock and shafts were then removed and the shield built in the open. An air-tight floor was then built at a higher level above the shield, and the air-lock connected directly to the floor without the shafts, as the floor was high enough to make these unnecessary. The plug was then cut out and the shield started under air pressure. Before the large shield was started, however, a small heading tunnel with temporary cast-iron lining was driven under the river. This heading was useful as it showed what was the nature of the strata which would be met with, and it also served to some extent to support the working face.

The front portion of the shield (Fig. 14C) was built up of cast-steel rings in segments breaking joint. These segments were bolted together and were prevented from sliding by steel dowels.

The first ring, 2 ft. 6 in. wide, formed the cutting edge. The other two rings were 3 ft. 6 in. and 4 ft. 9 in.



Half Back Elevation. Half Sectional Elevation at Joint C D. Longitudinal Section. Front Elevation.

Fig. 14c.—Rotherhithe Tunnel Shield.

[*To face page* 83.

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wide respectively. The last ring was recessed to take the tail, which overlapped it for a length of 2 ft. 9 in. The tail was 7 ft. 3 in. long exclusive of the overlap, and was built up of three $\frac{3}{4}$-in. plates riveted together. The external diameter of the tail was 30 ft. 7½ in., and the internal diameter 30 ft. 3 in., so that there was a space all round of 1½ in. between the cast-iron lining of the tunnel and the shield where it overlapped. The cast-steel portion was 30 ft. 8 in. external diameter. This front portion was divided into sixteen compartments by three horizontal and three vertical divisions. Each of the eight top compartments was fitted with face rams, which took the place of tunnel "guns." The two central top compartments were fitted with sliding plates, so that the face of the shield was always kept closed 4 ft. 6 in. down from the crown.

About 5 ft. from the cutting edge a curtain plate was fixed in each compartment, and about 3 ft. 6 in. further back a diaphragm rising from the floor of each compartment, and slightly overlapping the curtain plate. A kind of water trap was thus formed.

The excavated material was passed through openings 18 in. square in the bottom half of the water trap.

The rams for "shoving" the shield, forty in number, were fixed to the flanges forming the joint between the 3 ft. 6 in. and 4 ft. 9 in. wide cast-steel rings. They were constructed for a working pressure of 3 tons to the square inch, and at this pressure the total force shoving the shield forward was about 6,000 tons.

At the back were two hydraulic erectors worked by rack and pinion.

The term water trap, as used above, is perhaps not quite a correct one, because, these traps being at three different levels, a balance could not be obtained between the head of water and the air pressure. What might perhaps happen in a shield of this design, should an inrush of water take place, is that the traps would become filled with silt and mud which would check the outflow of air, and allow the pressure to rise sufficiently to stop the water coming in.

In the centre of the river the tunnel was only 7 ft. below the bed of the river. In the case of the Blackwall Tunnel the Thames Conservancy allowed about 10 ft. of clay to be deposited on the river bed, but in the present case, on account of the works being opposite the Surrey Commercial Docks and the London Docks, they were unable to grant permission for any clay to be deposited. This 7-ft. cover was composed of sand, and the work had therefore to be carried out with great care, and so carefully was the work done that at no time did the water break in.

At the lowest point in the line of the tunnel the level of the crown was 48.67 ft. below high water mark, and the deepest shaft, No. 2, was carried down to a depth 96.56 ft. below high water mark.

The section of tunnel under the river, about 1,500 ft., was completed in nine months. On several occasions 12 ft. 6 in. was completed in the twenty-four hours, and 267 ft. was completed during the month of October 1906. All the work under compressed air was carried on in three shifts of eight hours each. At one time there were 800 men engaged on the works and of these about 450 were working in compressed air at one time, or about 150 men per shift.

The tunnel lining is composed of cast-iron segments bolted together, each ring is 2 ft. 6 in. wide, external diameter 30 ft., diameter between flanges 27 ft. 8 in. The thickness of the metal in the body of the segments is 2 in. and there are fourteen segments and a key piece to each ring.

The cross section of the finished tunnel under the river is shown in Fig. 14D. The paving of the roadway is of compressed asphalt 2 in. thick on this comparatively level portion under the river, but on the approaches, which have a gradient of about 1 in 36, Aberdeen setts are used. The roadway is supported on a 9-in. brick arch and the space between the arch and the cast-iron lining is available for water pipes, electric cables, &c. The cast iron is lined with concrete, and the concrete faced with white glazed tiles, and the internal diameter when so lined is 27 ft.

The contract price for the work was £1,088,484, which did not, however, include anything for purchase of property. This brought the total up to about £2,000,000. The contract time was five and a half years, but the time actually taken was only a little over four years. The total length was 6,833 ft. or about 1.3 miles, and of this, 3,741 ft. is tunnel proper, the remainder being open approach or cut-and-cover.

The tunnel was designed by and carried out under the supervision of Mr Maurice Fitzmaurice, C.M.G., Chief Engineer to the London County Council. The resident engineer was Mr E. H. Tabor. The contractors were Messrs Price & Reeves and they were represented on the works by Mr J. H. Price and Mr James Brown.

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ROTHERHITHE TUNNEL.

CROSS SECTION OF TUNNEL UNDER RIVER.

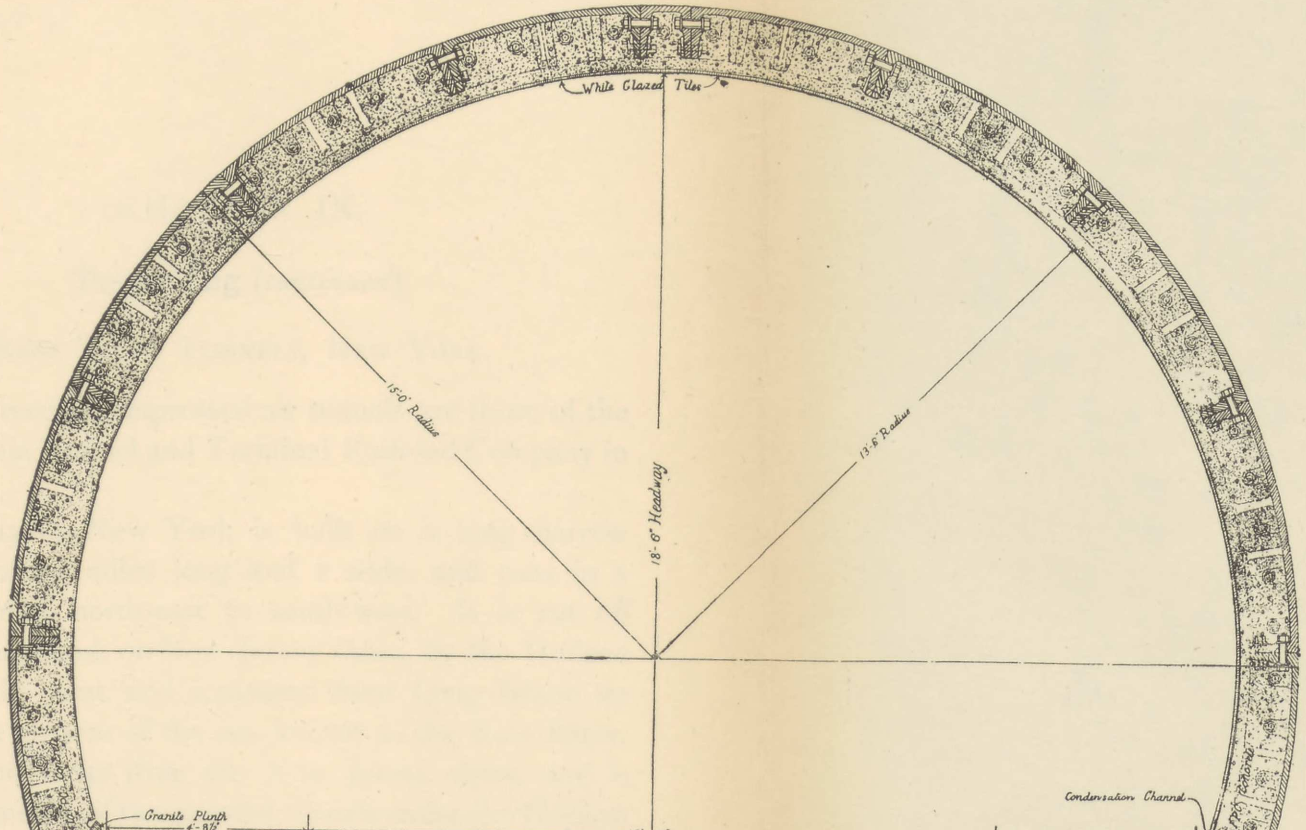


FIG. 14D.

To face page 86.

CHAPTER IX.

Tunnelling (*continued*).

EAST RIVER TUNNELS, NEW YORK.

THE most recent compressed air tunnels are those of the Pennsylvania Tunnel and Terminal Railroad Company in New York.

The city of New York is built on a long narrow island about 14 miles long and 2 wide, and runs in a direction from north-east to south-west. It is cut off from the mainland, or New Jersey shore, by the Hudson River on the west, and separated from Long Island on the east by an arm of the sea known as the East River.

The line starts from the New Jersey shore, and is carried by means of two parallel tunnels under the Hudson River. These two tunnels are then continued under the city to a large new central station in the centre of the island. From this point there are four parallel tunnels, which are also carried under the city to the west shore of the East River, and under the river to Long Island where they connect up with existing systems.

The business portion of New York is in the south of the island of Manhattan, and the part corresponding to our own west end of London is situated in the centre. The route of the railway is located about 4 miles from the most extreme southern point, known as the Battery, and forms a rough dividing line between the two districts, New Jersey and Long Island may be described as the suburbs of New York.

The two parallel tunnels under the Hudson River are about 5,500 ft. in length, and have been driven through silt and mud by means of shields and compressed air. They are 23 ft. outside diameter and have flanges 11 in. deep. The chief engineer is Mr Charles M. Jacobs, and the contractors Messrs The O'Rorke Construction Co. These two tunnels should not be confused with the Hudson Tunnels further south which are 19 ft. 6 in. in outside diameter and 18 ft. inside flanges. One of these two latter tunnels is the original Hudson Tunnel started in 1879. The Hudson is sometimes called the North River.

The four parallel tunnels under the East River are each about 4,000 ft. long, and follow the direction of Hunter's Ferry from Thirty-fourth Street to Hunter's Point. Their outside diameter is 23 ft. with 11-in. flanges, and rings 2 ft. 6 in. wide. This portion of the work is a separate contract, and also the largest in the scheme. It was let to Messrs S. Pearson & Son, Ltd., of Westminster, and has been carried out by them under the personal supervision of one of the directors, Mr E. W. Moir, with Mr H. Japp in charge locally. The chief engineer is Mr Alfred Noble. The work was started in 1904, and at the date of writing (1908) is practically complete. The following description will deal with this portion of the work only.

The rectangular caissons used for sinking the shafts on each side of the river were 74 ft. long by 40 ft. wide, and had double shells 5 ft. apart. The space between was filled in with concrete. There was also a 6-ft. wide division across the centre of the caissons, which formed two wells 29 by 30 ft. One line of tunnel started from each well, and plug holes were left on each side, one on the land side, and one on the river side. These plug holes were slightly larger in diameter than the shields, and until these were built the plug holes were closed by a single skin well braced and strutted. Two tunnels started from each shaft, and there were therefore two shafts on each side the river. These shafts were a little distance apart, so that the tunnels formed two pairs. This arrangement brought the two of each pair rather close together, and so for safety it was found necessary, after the shields had been started together, to shut down two of the tunnels, one in each pair, sufficiently long to allow the other two to get ahead.

The working chamber was 9 ft. in height, and had a single skin stiffened by open brackets. It had a strong water-tight and air-tight roof, and the wells above were filled with water as required, which was pumped in or out as the tide rose or fell, so as to give the necessary weight at high tide when the upward air pressure would be highest, and to take the weight off the packings supporting the caisson at low water when the pressure would be lowest.

There was a combined shaft for men and material in the centre of each well. The shafts had parallel sides with semicircular ends, one of which was divided off by plates to form the man shaft.

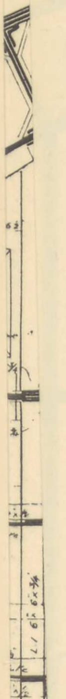
The air-locks were in general appearance very similar to the Davis air-lock (see Fig. 11), but the bottom door of the bucket chamber was closed by a shaft passing through the sides of the lock, and worked from the outside by a balanced lever. The bucket chamber was closed at the top by two sliding doors worked by two compressed air cylinders. These locks were hired by the contractors, as the import duty did not make it economical to import their own. They had seen a good deal of use, and as the sliding doors were not quite air-tight, for a time at low pressures it was found an advantage to connect up high-pressure air, as it was available, in order to equalise the pressure inside the bucket chamber when a bucket was being sent in, instead of using the low-pressure air from the working chamber. Except for this they were quite satisfactory and worked quickly. They were, however, a little dangerous, as there was no interlocking arrangement to prevent both doors being opened at once.

The two caissons on the Long Island side were sunk by compressed air. Those on the Manhattan side were sunk in the open, and were carried down to a depth of 40 ft., where they were made to rest on a ledge of rock 5 ft. wide all round. The shafts were then sunk the remaining 40 ft. without any support to the sides, and the shields were built in them in the open. It was also intended to do this on the Long Island side, but the rock proved too rotten, so the caissons had to be taken down the whole way. On the Long Island side compressed air was used for sinking, and also when the plugs were cut out. After the caissons had been sunk, a water-tight concrete floor was put in, and the air pressure taken off. The shields were then built, and the ceiling of the working chamber put back at a higher level above the shields. The compressed air was then put on again, and the shields started after the plugs had been cut out.

The caissons, after having been put together *in situ*, were pitched in the following manner. Brackets were bolted to the outside skin in pairs. Jacks under each alternate bracket then took the weight, and lowered the other brackets on to packings. The jacks were then lowered by removing some of the packing underneath them, and when they had again taken the weight of the caisson, some of the packing was removed from underneath the remaining brackets, and the caisson was again lowered, until the brackets once more rested on the packings.

As the cutting edge could not be allowed to rest on the rock, which was touched a little way below the surface of the ground, a similar sort of arrangement was adopted inside the working chamber for holding up the caisson and lowering it. Brackets were bolted in pairs to the diaphragms or brackets forming the shoe, and every alternate one was packed up underneath with timber. Beneath the other brackets packings were built up, with a space between the tops and the brackets rather less than the amount the caisson required to be lowered. The other packings on which the weight of the caisson rested were then knocked out by excavating below them, and the pressure lowered a pound or so, and this allowed the caisson to sink gradually down until it rested on the other packings. The packings had to be kept a little high, as there was always some settlement after they had taken the weight of the caisson. The rock was excavated by means of drilling and blasting, and for this purpose air pressure was taken down to the working chamber at an initial pressure of 100 lbs. to the square inch. The rock was loaded into ordinary skips and lifted out by a crane outside the caisson. A hook hanging from the jib of the crane was hooked on to the bottom of the skip as it left the air-lock, and this enabled it to be tipped automatically.

As the work was started from both sides the river, eight shields were required. These were specially designed for the work by Mr Moir. The design is shown in Fig. 15A, and in general principle is very similar to that of the Blackwall Tunnel shields. One or two novel features were however introduced. The tunnels were driven mostly through rock, as to the lower part and sand in the upper, but in one place, for over 1,100 ft. in each tunnel, the rock dipped and quicksand only was met with, so both soft ground and rock had to be provided for when getting out the design. The shields were 18 ft. in length and 23 ft. 6½ in. outside diameter. The tail was built up of three ¾-in. plates, leaving a space of 1 in. between the shield and the cast-iron tunnel lining. There was a double bulkhead which allowed a difference in pressure at the front and back of the shield if necessary, and a means of communication between front and back was given by locks for men and material. There were locks for men on each floor level and material shoots to each compartment. The compartments on each floor level were in communication with each other. There were two horizontal and two vertical divisions which stiffened the shield and divided the front into nine compartments. The front part of the shield was entirely shut off from the back down to the level of the bottom of the safety screen. This screen, a device of Mr Moir's, extended 9 ft. down from the crown of the tunnel, and converted the whole of the working section behind for the top 9 ft. into a huge diving bell on the principle already alluded to. This screen is perhaps one of the most distinctive features of these shields, and is an arrangement in every way admirable, and which no shield should be without when there is any danger of the tunnel becoming flooded. An emergency lock was provided in the top of the bulkheads, with the bottom of the door level about on a level with the bottom of the screen. It might be mentioned again here that should the air



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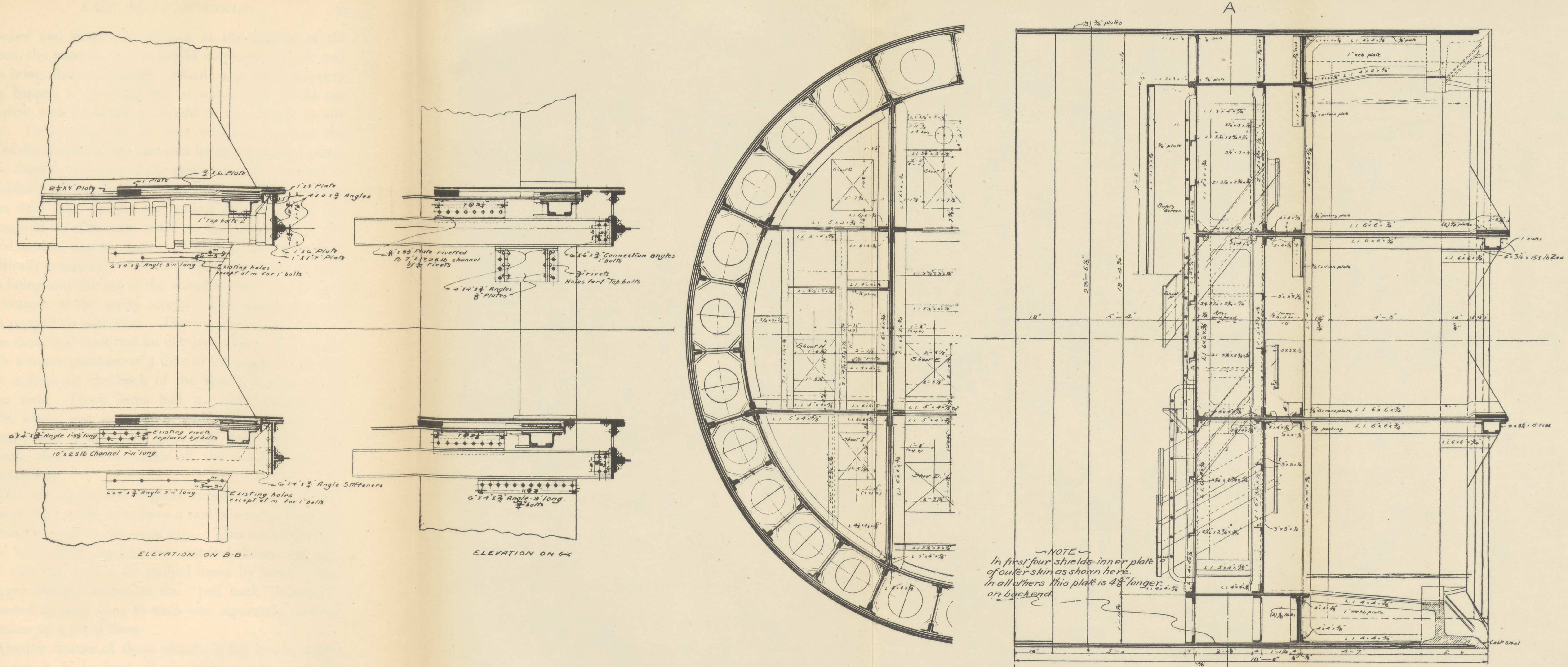


—NOTE—
In first four shields-inner plate of outer skin as shown here.
In all others this plate is 4⅝" longer on backend.

Details of Sliding Floors.

Part Section A B.

Sectional Elevation.

FIG. 15A.—EAST RIVER TUNNELS SHIELD.

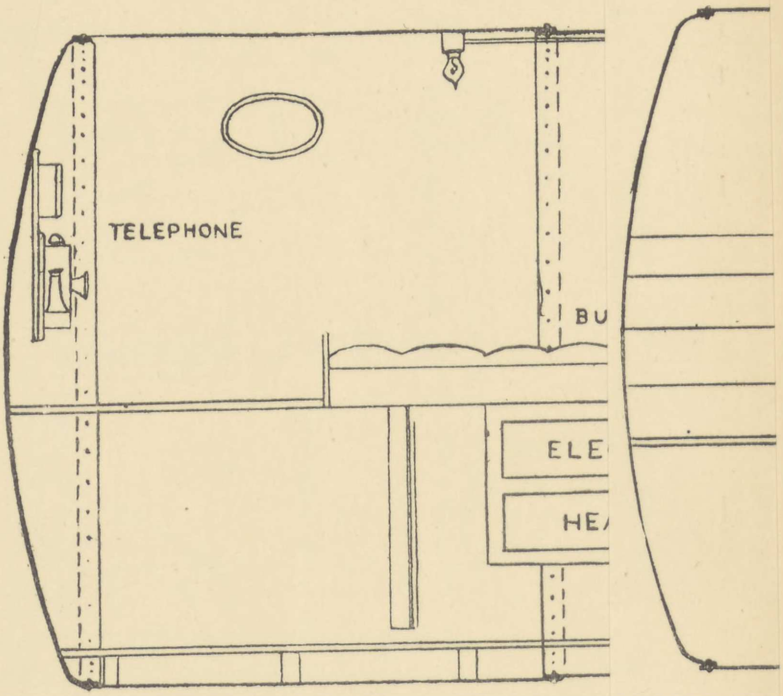
[*To face page* 92.

pressure and water not balance at the bottom of the screen, the water as it rose would compress the air and thus bring about a balance. Should also the emergency lock happen to get half full of water, this would not interfere with its working, or add to the danger in any way. To prevent the air from escaping between the tail of the shield and the cast-iron lining, segmental plates were fixed to the back of the rams round the top half of the shield. Except when an iron ring was being erected, these were kept pushed out against the flanges of the lining, and as they were made to fit quite close to the shield, and to almost touch each other at the ends, they practically completely closed the space between the cast-iron lining and the tail of the shield down to the level of the bottom of the safety screen. This space was also kept pugged up with clay. There were twenty-seven of these rams, and each had an effective area of 54.7 sq. in. With a water pressure of 3 tons to the square inch this gave a force on the back of the shield of very nearly 4,500 tons. These rams had a piston arrangement inside, which was in constant communication with the pressure, and which acted as a pull back. When the pressure, therefore, was taken off, the rams went home automatically.

This arrangement is a great improvement upon the ordinary one, which is, to have a ram of smaller diameter fixed in the head of the large ram. This forces the ram home by pushing against the cast-iron lining, but the small ram has then to be pushed home by hand. Also a copper flexible known as the "pull back" has to be connected up each time to each ram separately, and all this takes up a lot of time.

Another feature of these shields is the hoods, which came out 3 ft. in front of the cutting edge and extended half-way down the shields. Two types of hood were used—some of the shields had one type and some the other. One type was fixed, and the other was made up of segments which could be pushed forward as the excavation proceeded, and which, when the "shove" was made, would slide back again. The object of the hood is to enable the excavation to be taken out with a sloping face instead of a vertical one. They were bolted to the cutting edge, and could be detached at any time if it became desirable to force the shield through soft ground instead of excavating in front of it. They were found very useful, particularly the sliding ones, and saved a good deal of timbering.

The sliding floors were another novel feature. They were made to slide on the top of the permanent floors, and were worked by hydraulic rams underneath the floors, and therefore on the ceiling of the compartment below, from which they were worked. These were of great use in rock, and were kept pushed out against the face and thus prevented any pieces that got loose from falling down. They also intercepted any small piece which did become detached, and thus made it safe for the workers in the invert of the tunnel in front of the cutting edge. As, however, the surface of the rock was naturally rough, spaces would be left through which pieces might fall. To guard against this, ordinary flat-bottomed rails were fixed to slide on the top of the sliding floors. These were pushed forward singly in such a way that they took the shape of the rock, and as they were placed close together, all spaces through which pieces of rock might fall were closed up. When the shove was made, valves in the rams were opened, which allowed the water to escape, and



-Lock. (20 ft.
aisson Disease.

the shield then moved forward, the floors all the time remaining stationary, and supporting the rock face.

These floors were also very useful in giving standing room for the rock drills, and allowing them to be set up in the most favourable position.

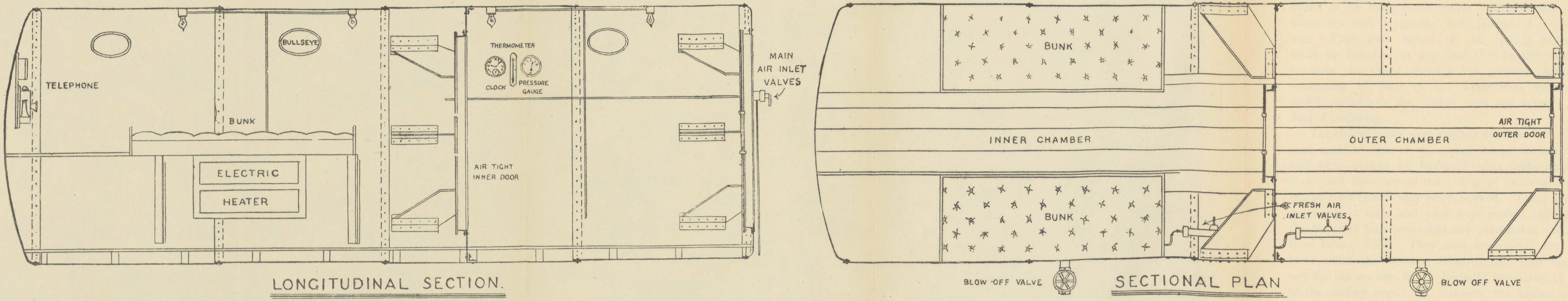
There were two hydraulic erectors of the ordinary type at the back of the shield, worked by a rack and pinion.

The shields were fitted with air pipes so that air could be admitted separately to each compartment, but for most of the time it was not found necessary to do this, and the end of the inlet air main was kept about 30 ft. behind the shield.

There were three boiler-shaped locks in each bulkhead, the emergency lock at the top, and two others below, which could be used for either men or material. These bulkheads were built of concrete.

A travelling platform, similar to the one at the Blackwall Tunnel (see Plate III.), was used for tightening up the bolts from, grouting, and caulking.

Eight medical locks were provided, four each side the river, for treatment of decompression symptoms (Fig. 15B). Each contained two bunks for the patients, and one end was divided off to form an entrance chamber, so that a doctor could enter at any moment to attend a patient without lowering the pressure. A fresh patient could also be introduced at any time during the treatment of another. The locks were warmed with electric heaters, and a telephone was fitted so that the patient could communicate with persons outside. In this connection it is interesting to note that medical locks were first used for the treatment of decompression cases by Mr Moir during the driving of the first tunnel in New York under the Hudson River.



LONGITUDINAL SECTION.

SECTIONAL PLAN

Fig. 15b.—Moir's Medical Air-Lock. (20 ft. by 7 ft.)
For the Treatment of Caisson Disease.

[*To face page* 95.

the shield then moved forward, the floors all the time remaining stationary, and supporting the rock face.

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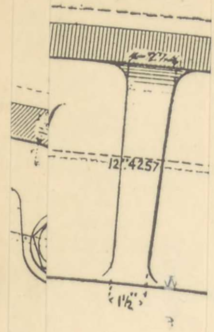
The cast-iron lining was built up in rings, 23 ft. outside diameter, 21 ft. 2 in. inside flanges, and 2 ft. 6 in. wide, with eleven segments and key piece to each ring (Fig. 15c). The key piece was tapered and measured 12.25 in. along the outside circumference, and 12.6014 in. along inside of flanges. This necessitated two special segments, marked B on plan, one on each side the key piece. These special segments measured 6 ft. 5.9948 in. along the outside circumference. All the other segments, A on plan, were interchangeable, and measured 6 ft. 5.6489 in., and their ends were radial to the centre line. The faces of all flanges were machined, and special tapered segments were used on curve and for keeping the tunnel true to line and gradient. In order to enable joint to be broken, segments A and B were made the same length when measured along a line passing through the centre of the bolt holes, and all bolt holes were spaced the same distance apart. The key piece also, when measured along the same line, was equal in length to the distance between two bolt holes. The distance of each end bolt hole from the end of each segment was, of course, half the pitch. If at any time the cast-iron lining was found to be getting out of position, a tapered ring was introduced, with the widest part at any point in the last ring which might be required to correct the error. It will be noticed that the space left for caulking at the ends of the flanges is shaped so as to form a key.



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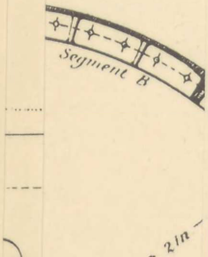

e Tunnel

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Segment A-Cast Iron Ring for Tube Tunnel

Segment B-Cast Iron Ring for Tube Tunnel

Section A A

Section B-B

End View

Key

Section A A

Bolts for Standard Segments

Tunnel on Tangent

Longer Bolts will be required for Taper Segments on Curve

Screw plug for grout hole

Cast Iron Ring for Tube Tunnel

Tube Tunnel in Rock

Fig. 15c.—East River Tunnels, New York.

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CHAPTER X.

Rock Blasting.

The modern commercial explosive consists of two parts, nitro-glycerine, which is the explosive or active part, and an absorbing substance which is usually inert. The force of nitro-glycerine exists in the nitric acid which "nitrates" the glycerine, and which can also impart its explosive character to other inert substances such as cotton, sugar, wood fibre, and most vegetable substances.

Nitric acid is manufactured by distillation from nitrate of soda (saltpetre), which is largely imported into this country from South America.* The distilling is done by sulphuric acid manufactured from cuprous iron pyrites mined in Spain. The sulphuric acid does not itself possess any explosive character. Its function is to absorb the water from the products of reaction when the nitric acid is mixed with the glycerine.

Nitro-glycerine thus manufactured is a liquid, and in this state was formerly used for blasting. Its extreme sensitiveness to shock, however, caused so many disasters that in this country its use in an unabsorbed state has been prohibited. When, however, it is in an absorbed state it becomes quite safe. Thus if a piece of blotting paper be soaked in nitro-glycerine, and then struck, it will explode, but only at the point where hit by

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* "Book of High Explosives," Nobel's Explosives Co.

the hammer, as the shock cannot travel through the paper.

In 1866 Alfred Nobel invented dynamite by absorbing nitro-glycerine in kieselguhr. This is a fine diatomaceous earth consisting of the microscopic shells of diatoms mixed with organic substance. It is first of all burnt to get rid of all the organic substance, and then crushed until it becomes a fine powder. This powder will absorb three times its own weight of nitro-glycerine, and is used in the manufacture of dynamite. Dynamite, therefore, contains 75 per cent. of nitro-glycerine, and is a very powerful explosive. It is safe to handle, and may be even burnt in small quantities without exploding; if, however, it is burnt in large quantities, or in such a way that its temperature is raised beyond a certain point, it will explode. It is not suitable for use under water, because the nitro-glycerine will be caused by the water to exude from the absorbent. Its peculiar characteristic is the instantaneousness with which it explodes; this makes its action local in character and radial in direction. In this respect dynamite may be said to stand at one end of the scale and ordinary sporting powder at the other. Dynamite acts all round, and gunpowder in the direction of least resistance. The difference is, however, one of degree rather than of kind. For this reason dynamite is very suitable for "capping" a boulder. When this is done, the charge is placed on the boulder and covered by a piece of clay. The dynamite, if the charge is big enough, will crack the boulder; gunpowder expanding slowly will merely lift off the lump of clay.

Nobel's blasting gelatine is a still more powerful explosive than dynamite, but it explodes rather more slowly, so that as regards local action it is slightly lower down the scale. The absorbing material is a specially prepared form of gun-cotton which is itself a high explosive, so that blasting gelatine has practically the strength of pure nitro-glycerine. The absorbing preparation is about 7 per cent. and the pure absorbed nitro-glycerine 93 per cent. It is very suitable for use under water, as it can be left there under ordinary conditions for a long time without deterioration in power. It is suitable for hard rock rather than soft, and should not be used where it is desired to detach large slabs without injury. Its property is to shatter rather than to move.

Nobel's gelignite contains about 62 per cent. of nitro-glycerine, the other materials being nitro-cotton, nitrate of potash, and woodmeal. From this it will be seen it is not so powerful as blasting gelatine. It is rather slower in exploding, and therefore less intense in local action. It will not resist water so well as blasting gelatine.

Gelatine dynamite is intermediate in character between blasting gelatine and gelignite as regards strength and water-resisting properties. The comparative strengths of these four explosives, taking dynamite as 100, are:—blasting gelatine, 150; gelatine dynamite, 130; gelignite, 110.*

There are a large number of other explosives on the market which differ only in the nature of the absorbent and percentage of nitro-glycerine.

For rock blasting in tunnel and caisson work it will not be economical to use explosives with too low a percentage of nitro-glycerine. As a general rule the inert material should not exceed 25 per cent., as in

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* "Book of High Explosives," Nobel's Explosives Co.

this class of work it is necessary to shatter the rock in order to get it into the buckets and waggons.

The more powerful explosives will also be found more economical in the end, although higher in first cost, because of the saving in the number and diameter of the holes to be drilled.

Explosives formed of nitro-glycerine cannot be exploded by being set fire to except indirectly by the heat generated. They require to be "detonated." In this respect they are unlike gunpowder, which is converted into a gas by combustion. The process is then a gradual one, because the grains of powder are set fire to in succession. Detonation is almost instantaneous. For this reason, until cordite was invented, nitro-glycerine could not be used for guns or small arms, the tendency being almost as much to burst the breach as to expel the shell or bullet. Cordite is a gelatinised form of gun-cotton and nitro-glycerine made up into sticks of different thickness, and by this means the rate of combustion is delayed. By altering the thickness of the sticks any required rate of combustion can be obtained.

Detonators for use with the safety fuse are small copper tubes containing a compound of 80 per cent. of fulminate of mercury and 20 per cent. of chlorate of potash. The tube is left open at one end, and when getting ready for firing, the safety fuse is inserted and fixed by squeezing the copper tube round it with a pair of copper nippers. A hole is then made in the cartridge at one end, and the detonator inserted in such a way that about one-third of the copper tube shows outside the explosive. This is to prevent the fuse from setting fire to the explosive before the detonator goes off. The paper wrapping of the cartridge should finally be tied round the fuse above the detonator to prevent its pulling out. Before putting the fuse into the detonator, the end should be cut clean in an oblique direction.

In caisson and tunnelling in compressed air, electric detonators are used exclusively.

These are of two kinds, high tension and low tension. Both are very similar in appearance, consisting of small copper tubes filled with fulminate of mercury and chlorate of potash, and closed by a cement plug.

The high-tension detonator is fired by a spark passing between the terminals. The low-tension by a small wire connecting them which gets red hot. The high-tension fuse must be connected up in parallel when there are two or more charges to be fired at the same time. Low-tension fuses are connected up in series.

The low-tension fuse is the one in most general use.

Low-tension fuses, if covered with an iron pot or pipe, can be tested with a galvanometer, but this must not be done with high-tension fuses.

When putting in the detonator, a hole is made in the top with a pointed stick, and the detonator pushed right into the cartridge until it is completely buried. The cartridge should be gently squeezed to just above the detonator, *i.e.*, at the end at which it has been put in, and the paper should then be tied round the wires in the same way as described for the safety fuse. In the States another method of putting in the detonator is used. A hole is made at the side of the cartridge, and the detonator put in until quite buried. The wires are then given a turn round the cartridge at the point of insertion, and then carried to the other end and tied there. The advantages of this method are that it is a good deal quicker than the other, and that a cushion of explosives is formed at each end, which protects the detonator from the tamping rod. Experts in this country do not view this method with favour, on the ground that during tamping the detonator might come out and get into contact with the rock.

The cartridge so charged is commonly known as an "exploder," and "detonates" all the other cartridges in the same hole.

When filling the borehole a wooden tamping rod should be used, and with this the cartridges should be tightly pressed home as put in. The borehole should be made only just large enough to take the cartridges, as if too large a good deal of the force of the explosion will be lost. The exploder is generally put in last, or last but one, and very little force must be used with the tamping rod after it has been inserted. Finally the hole should be filled with clay, dry sand, or paper. Water is also suitable if the hole is in a downward direction. It fills up all voids, and causes the force of the explosion to be immediately felt by the rock without any previous loss of power in expansion.

Below 45 degs. Fahr. nitro-glycerine is liable to become congealed, and when in this condition the explosive must not be used until thawed. The best and safest way to do this is to use a warming pan specially constructed for the purpose, and which will be supplied by the makers. These pans have a double shell, and the space between is filled with hot water. In the States the practice is sometimes adopted of submerging the cartridges in a bucket of hot water. This custom appears a little dangerous, as there would seem some chance of the nitro-glycerine exuding and getting on to the operator's hands or clothes. This method could not be used with dynamite, from which the nitro-glycerine will exude in water. It may be as well to point out here that there are some very strict regulations in this country for the handling and storage of explosives, and it is essential that only methods sanctioned by the authorities should be used. The reason why nitroglycerine requires thawing is that when frozen or congealed it becomes, under certain conditions, less sensitive to shock, and therefore more difficult to detonate, and liable to miss fire. On the other hand it is also known, owing, it is thought, to a certain molecular change which takes place, that in this condition it sometimes becomes more sensitive, and certain accidents which have happened have been attributed to its frozen condition. Usually dynamite becomes less sensitive to shock and blasting gelatine more so when frozen. It will therefore be seen that thawing out is an essential preliminary to use of nitro-glycerine when frozen or congealed, and when the explosive is in this condition care should be taken not to fracture or drop it. The nitro-glycerine may become congealed even though the cartridge still feels soft. Its condition, therefore, must be judged by the temperature and not by the feel of the cartridge.

Although methods of calculating the quantity of explosive required for charging boreholes have been formulated, this is so entirely a matter for practical experience and judgment that no definite rule can be given. The efficiency of the blast depends a great deal upon the skill of the driller in "pointing" the drill. In caisson work the best plan is to start at the centre, making the hole at rather a flat angle, so that the rock will be lifted upwards. As holes are drilled in succession in the direction of the cutting edge, the direction of the drill will be more in a downward direction until, when the cutting edge is reached, they will be pointing down at an angle of about 60 degs. with the horizontal.

It will be necessary, when working round the cutting edge, to carry the holes well behind it, and it must also be remembered, especially when low grade explosives are being used, that a length of 6 in. of the hole drilled and the rock surrounding it will usually remain intact after the charge has been fired.

In tunnel work the blasting must be started with a small heading, and if possible this should be kept in advance of the main tunnel. There are two ways of starting such a heading; one is to drill four or more holes meeting at a point, so that when the blast is made the rock comes away leaving a cone-shaped hole. The other way is to drill two vertical lines of holes inclining towards each other, so that the rock is brought away in a V-shaped wedge. In either case the subsequent holes will be in a direction nearly parallel to the direction of the tunnel. Here again, although it is best to have some system, the skill of the driller in pointing his drill is of great value. The author knew one drill foreman who pointed his drills according to no known law, and nevertheless did great execution, in which unfortunately the shield sometimes had its share. Great care must be taken when working round the cutting edge of the caisson to see that it is not damaged by using too heavy charges. It is also important that the holes should be so placed that the shattered rock is not hurled in a direction where it will do damage. With a shield of rather light design the author has found it necessary to use planks placed in front of the divisions forming the compartments of the shield, in order to prevent them from getting bent or fractured.

Drills for caisson work are usually mounted on tripods, and the sizes vary from 2 in. diameter of cylinder and 5 in. stroke to 5 in. diameter of cylinder and 8 in. stroke.

The drills are fixed to the tripod by a universal joint clamp, or similar arrangement, permitting it to be set in any desired direction without altering the position of the tripod. The actual drill cylinder is fixed in a cradle in which it slides when the drill is being fed forward. On the legs of the tripod are three weights which vary from 145 to 450 lbs. the set of three. The smaller sizes with cylinders 2 in. and $2\frac{1}{4}$ in. diameter are known as "baby" drills, and are worked by one man. All sizes above this require two men, a driller and a helper. The driller stands by the bit and keeps an eye on it to see that it is going straight. He generally holds a spanner in his hand to hit the drill if it sticks in the rock. The helper stands behind the drill with his right foot on one of the weights fastened to the legs in order to help to steady it, and feeds forward the drill as directed by the driller. These larger drills are known in the States by the name of "Giant," but it is a term not used over here.

Another arrangement is a tunnel column which has a screw jack at one end by which it can be fixed either vertically or horizontally or, in fact, in any direction in which a hold can be obtained, in a tunnel heading, or between the floor and ceiling of a compartment in a shield. The drill is fastened to a cross arm which is in its turn clamped to the column. Two drills are frequently fastened to one column. Sometimes small hand drills, similar in appearance and principle to a pneumatic hammer, are used. These are useful for putting in a small hole in a boulder or large piece of rock too big to go into the waggons or skips.

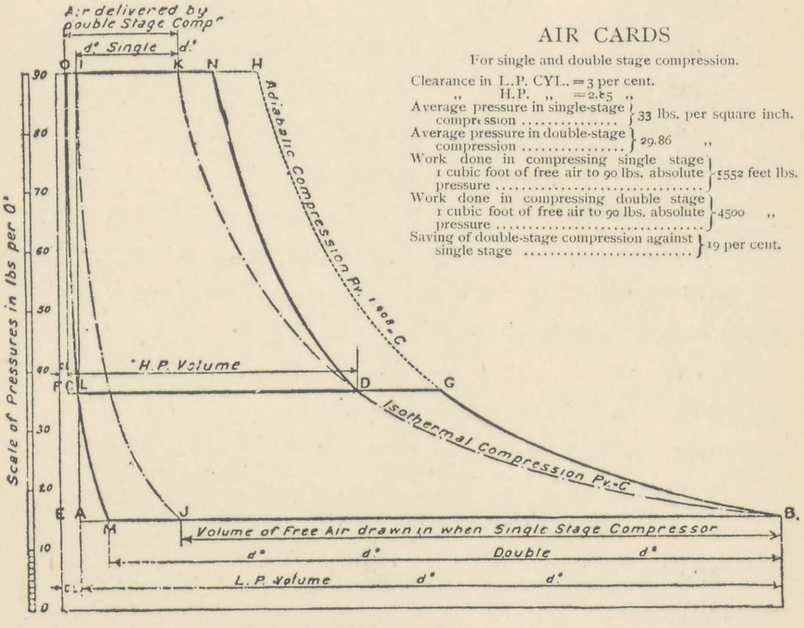
CHAPTER XI.

Air Compressors.

In tunnel and caisson work air will be required at pressures up to 45 lbs. per square inch or so for filling the working section of the tunnel and working chamber of caisson. For working the rock drills and grouting, a pressure of about 100 lbs. per square inch will be wanted.

For the lower pressures one-stage compression is used, but above 75 lbs. two-stage compression will be more economical and is generally used.

The advantages of two-stage decompression can be seen by consideration of the diagram (Fig. 16). The curve B, H shows the pressure and work done during compression up to 75 lbs. pressure. The air taken into the cylinder at atmospheric pressure is compressed, following closely the line of adiabatic compression. Adiabatic compression takes place when air is compressed without parting with any of the heat acquired from the work done upon it during compression. Isothermal compression takes place when air is compressed and remains at the initial temperature. This can only happen when the air has time to part with the heat acquired by coming in contact with some colder body. In the cylinder the air will part with some of the acquired heat by coming in contact with the water jacketed cast-iron walls. But however perfect the water jacketing may be, compression cannot be truly isothermal, and it will therefore be somewhere between adiabatic and isothermal and generally more nearly approaching the adiabatic line. When H is reached the air will be discharged into the receiver at 75 lbs. pressure. The piston then travels to I, the small space I-O representing the clearance. As the piston returns the small amount of highly compressed air left in the clearance expands till J is reached, when atmospheric air begins to be taken in. The work done during single-stage compression up to 75 lbs. pressure is represented by the cycle B, H, I, J, and the free air capacity by J, B. But in the case of a single-action diving pump the work done would be represented by B, H, I, A, since, neglecting friction, the work represented by A, I, J is lost in the return stroke.



AIR CARDS

For single and double stage compression.

Clearance in L.P. CYL. = 3 per cent.	
,, H.P. ,, = 2.85 ,,	
Average pressure in single-stage compression	33 lbs. per square inch.
Average pressure in double-stage compression	29.86 ,,
Work done in compressing single stage 1 cubic foot of free air to 90 lbs. absolute pressure	5552 feet lbs.
Work done in compressing double stage 1 cubic foot of free air to 90 lbs. absolute pressure	4500 ,,
Saving of double-stage compression against single stage	19 per cent.

By permission of Messrs Fraser & Chalmers, Ltd.

Fig. 16.

When two-stage compression is used, the low-pressure cylinder compresses up to 20 lbs., represented by B, G. From G the piston travels to L, whilst the air is discharged into the intercooler at a pressure of 20 lbs.

On the return stroke the clearance air expands to M, and atmospheric air is taken in from J to B. It will be thus seen that there is an increase in free air delivery equal to M, J.

In the meantime the compressed air in the receiver is cooled, and contracts to D, a point on the curve of isothermal compression, and follows the cycle D, N, O, L.

The air will always contract to approximately K on the isothermal line before it can be used, and the useful discharge with two-stage compression is, therefore, K, O, instead of K, I, as given by one-stage compression, or a gain represented by O, I, which is the same when reduced to atmospheric pressure as M, J, which represents the gain in free air delivery.

E-A represents 3 per cent. clearance in the large cylinder, and F-C 3 per cent. clearance in the small cylinder.

It will be seen, therefore, that two-stage compression gives greater economy in power and an increase in free air capacity. This increase in free air capacity is theoretically of no advantage when working rock drills, because the increased volume due to heating and expansion is as useful as an increased volume of free air. Practically it is so because the heated air would become cooled to approximately its original temperature when passing through a long line of pipes, and thus there would be a loss in volume and power. In itself there is no disadvantage for this class of work in having the air at a high terminal pressure, and sometimes the practice is adopted of after-heating in order to get increased power.

There is another reason, however, why the air must not be allowed to attain too high a temperature in the cylinders. That is this. Too high a temperature is destructive of lubricants, and if these are of a common low-grade quality, they are soon burnt into gritty or gum-like substance, and if the temperature is raised above the flash-point of the oil, there is the danger of an explosion or ignition in the compressor or air receiver. Such an occurrence in an air receiver would be highly dangerous, as it might happen without wrecking the receiver, and the smoke generated, if it happened with the low-pressure receiver, would be driven into the working section of tunnel, or working chamber of caisson, and endanger the lives of the workers.

When water is cheap, it is an advantage to have water-cooling before admitting to the air cylinder. This should be followed by intercooling, in the case of two-stage compression, and then by after-cooling. This after-cooling in the low-pressure mains is useful in keeping the temperature at a point comfortable for the workers. By drying the air it also helps to prevent moisture being deposited which would cause them to get frozen up in severe weather. This will not, however, get rid of all the moisture, and drip valves should be fitted at any low point to allow any moisture deposited to be withdrawn. These also are, however, liable to get frozen up if not protected, so that there is a distinct advantage in having dry air.

This also applies to the high-pressure mains. The fall in pressure due to expansion may also cause the exhaust of drills and other engines to get frozen up if the air contains much moisture.

Whether the air taken in is water-cooled or not, it should always be drawn in from outside the enginerooms, as the difference in temperature, especially in winter, will give a great increase in power. This is important also from the point of view of the health of the workers, as the air will then be much freer from dust and other impurities.

In general arrangement the compressors of the leading makers are very similar. For two-stage compression the duplex type is favoured. In this type of machine there are two air cylinders and two steam cylinders, and these form practically two machines side by side. The low-pressure steam compresses the low-pressure air, and the high-pressure steam compresses the high-pressure air. Each pair of cylinders are connected together by one long piston rod giving a tandem drive. This is the method adopted by Messrs Walker Bros. and Messrs Fraser & Chalmers for their most modern machines. The Ingersoll-Rand Co. also favour this type, but manufacture a large number of tandem drive machines, that is to say, machines with three or four cylinders on one long piston rod, three cylinders when air alone or steam alone are to be compounded, and four cylinders when both are to be compounded.

The duplex arrangement is equally suitable for compounding either air or steam only.

For tunnel work where most of the air required will be at a low pressure, the steam only will be required to be compounded.

The compressors used at the Greenwich Footway Tunnel were on this principle, and were made up as follows:—Steam cylinder H.P. 18 in. diameter, L.P. 30 in. diameter, and two air cylinders 24 in. diameter. Length of stroke, 3 ft. 6 in. These engines were manufactured by Messrs Walker Bros., and supplied by them to the contractors, Messrs John Cochrane & Son. They also supplied Messrs S. Pearson & Son with the compressors for the Blackwall Tunnel, and Messrs Price & Reeves with those for the Rotherhithe Tunnel. Those for the Blackwall Tunnel had steam cylinders H.P. 24 in. diameter, and L.P. 40 in. diameter, and air cylinders 24 in. diameter with a stroke of 3 ft. 6 in.

The Rotherhithe Tunnel compressors had steam cylinders H.P. 18 in. diameter, and L.P. 34 in. diameter, and air cylinders 30 in. diameter with a length of stroke of 3 ft. 6 in.

The Blackwall Tunnel compressors were water-cooled by means of a water injection into the cylinders. The makers, however, do not usually recommend this, owing to the detrimental effect upon the valves and seatings, and the author has been informed by Mr Moir that the economy resulting from this method of cooling was exceedingly small.

For the sinking of the King Edward Bridge caissons electric driven one-stage compressors were used, and these had 15-in. diameter air cylinders with a 3-ft. stroke. These were supplied to the contractors, Messrs The Cleveland Bridge and Engineering Co., by the Airdrie Iron Co. They were run at a constant speed and the pressure regulated by the air lifting the valves and causing the engines to run light. The valves were of the Riedler type.

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