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“The Greenwich Footway Tunnel.”

By WILLIAM CHARLES COPPERTHWAIT, M. Inst. C.E.

THE work described in this Paper is the second tunnel undertaken by the London County Council with a view to improve the means of communication between the districts lying north and south of the River Thames and east of the Tower Bridge. It is intended especially to connect the working-class district of the Isle of Dogs, where house-accommodation is scarce, with the areas covered by workmen's dwellings on the south side of the river.

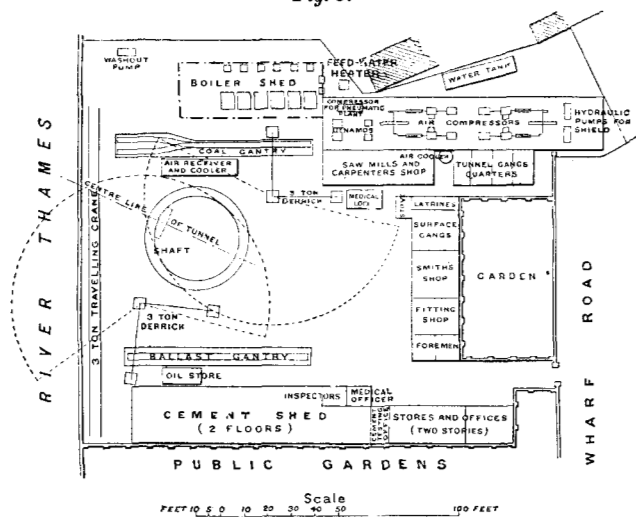
A ferry between Greenwich and the Isle of Dogs has existed for a considerable period. The exclusive privilege of working it, which had been enjoyed since 1676 by a company called the Potter's Ferry Society, was partly abrogated by an Act of Parliament<sup>1</sup> passed in 1812, creating a statutory ferry for horses and vehicles, but leaving to the society its rights in respect to foot-passengers. The horse-ferry was extinguished by the Metropolitan Board of Works in 1883. The foot-passenger ferry-rights still exist, and are owned by the Great Eastern Railway Company and leased by them to the Thames Steamboat Company. Notwithstanding the grave objections and hindrances to a steamboat-ferry in a crowded river like the Thames, the yearly traffic amounts to about 1,300,000 passengers. In 1897 the London County Council obtained an Act of Parliament for the construction of a subway between Greenwich and Millwall, power being taken at the same time to compensate existing interests. The contract for the works was let to Messrs. J. Cochrane & Sons in March, 1899, and actual work was commenced in June of the same year. The shafts were sunk and the tunnel was bored by June, 1901, and the subsidiary works are now approaching completion.

<sup>1</sup> “Poplar and Greenwich Ferry Act.”

## GENERAL DESCRIPTION OF THE WORKS.

The subway consists of a tunnel under the River Thames, connecting two shafts 1,217 feet apart; one situated in the Island Gardens, Poplar, in the Isle of Dogs, and the other on the west side of Church Street, Greenwich, and immediately behind the well-known Ship Inn. These shafts are 43 feet in external diameter, and within them are placed circular staircases and lifts to give access to the tunnel. Their depths from ground-level to the floor at the tunnel-entrance are respectively 44 feet and 50 feet. The external diameter of the tunnel is 12 feet 9 inches; it is of cast iron, and similar in character to other iron tunnels recently

Fig. 3.



PLAN OF CONTRACTORS' YARD, POPLAR.

built in London. From each shaft the tunnel dips towards the centre of the river with a gradient of 1 in 15; the middle portion of the tunnel is on a gradient of 1 in 277, falling towards the Greenwich shore. These gradients were entailed by the advisability, from motives of economy, of limiting the depths of the shafts, and by the necessity of complying with the conditions of the Act authorizing the undertaking, which stipulated that the level of the tunnel should be such as to allow of dredging in the river a channel 500 feet wide and 48 feet deep at high water. The general plan and longitudinal section of the tunnel are shown in Figs. 1 and 2, Plate 1.

It was arranged to drive the tunnel from the Poplar shaft; and a site for the contractors' yard, etc., was provided by enclosing temporarily a portion of the Island Gardens. The whole area available for the buildings and plant, including the site of the Poplar shaft, measured only 200 feet by 170 feet; and considerable ingenuity was shown by the contractors in utilizing the ground so as to provide for their machinery and at the same time for cement-stores and for the accommodation of workmen and others, as required by the contract. *Fig. 3* shows the general arrangement of the Poplar yard.

### SHAFTS.

The two shafts are alike in general construction, and differ only in depth, that on the Poplar shore measuring 60 feet 4 inches from top to cutting edge, and the Greenwich shaft 66 feet 8 inches.

*Caissons.*—The caissons are 35 feet in internal, and 43 feet in external diameter, and are formed with two steel skins, the 4-foot space between which is filled with 6 to 1 Portland-cement concrete. The skins are formed of horizontal rings built up of plates, which are generally about 4 feet 9 inches in depth and vary in thickness from  $\frac{5}{8}$  inch at the bottom of the caisson to  $\frac{5}{16}$  inch at the top; the vertical joints in each ring are arranged, wherever possible, to break joint with the rings above and below. The skins are braced together with vertical angle-bar frames and horizontal angle-bracings. At the points where the main girders of the air-tight floors are attached, the webs of which are carried through to the outer skin, vertical plate gussets are fixed in the rings above and below, to resist deformation under the severe stress produced at the ends of the girders by the air-pressure on the floor. The stress in each flange at the wall of the caisson with a pressure of 20 lbs. per square inch amounts to nearly 300 tons. Around the tunnel-opening, also, the caisson is strengthened by numerous plate gussets.

The cutting edge is 7 feet in depth, and is formed by inclining the inner skin to meet the outer: at the edge thus formed an extra plate,  $\frac{3}{4}$  inch thick, is placed round the outer skin for greater stiffness. The bottom edges of the cutting-edge plates are not flush with one another, but each edge is 1 inch above that of the plate outside it, so as to allow of easy caulking. The cutting edge is further strengthened by forty-eight triangular vertical gussets  $\frac{1}{2}$  inch thick. At the top of the inside skin of the cutting edge is fixed round the entire circumference an angle-bar 6 inches by 6 inches by  $\frac{3}{4}$  inch. It was intended to use this as a bracket under

which timbers could be fixed in order to control the sinking of the shaft. In practice, however, all such work was done by timbers fixed under the main girders of the air-tight floor.

The outer skin of the caisson was without the usual batter, but the plates of each ring were inclined outwards towards the top, so that the top edge of every ring touched a vertical cylinder. The caisson was therefore of uniform diameter from top to bottom, excepting for the extra  $\frac{3}{4}$ -inch plate at the cutting edge; and although the absolute necessity of preventing any spreading during the erection of the successive rings (whereby the caisson would have been made wider at the top than at the bottom) rendered great care necessary in riveting up the work, still the extra trouble and expense so incurred were more than compensated for by the results obtained in the sinking of the shafts: results which the Author believes were largely due to the absence of taper in the shafts and of consequent settling of the ground around them. Iron rivets were used throughout; and all riveting, whether gap-riveters or hand-pistols were used, was done by compressed-air power. Three tiers of pipes were fitted through the sides of the caisson, and connected to the wash-out pump, through which water could be pumped to lubricate the outer skin in case of necessity. These, however, were little used.

*Air-tight Floors.*—Each caisson is provided with two air-tight floors, a permanent one fixed below the tunnel-opening and above the cutting edge, and a provisional one fixed, when in use, a few feet above the tunnel-opening. These floors were alike in construction, being formed of two pairs of main girders crossing each other at right angles; the intermediate areas were crossed by small girders and the whole frame was covered by buckled floor-plates bolted to the girders. The provision of two air-tight floors has the advantage that, while a single floor above the tunnel-opening is a necessity for starting the tunnel-shield in water-bearing strata, the use of the lower floor only during the operation of sinking the caisson, while allowing an ample working-chamber underneath for the miners, enables any kentledge used in sinking to be placed near the bottom of the caisson, and so keeps the centre of gravity of the whole structure, when sinking, much lower than is possible with an upper floor only. This lessens materially the tendency of the shaft to tilt over to one side when sinking. Against this advantage must be set the increased cost of the shafts, due to the extra depth required to make room for a floor with girders 4 feet 6 inches in depth, clear of the tunnel-opening above it and the cutting edge below.

*Tunnel-Openings.*—The opening in each shaft for the tunnel is 15 feet 3 inches in diameter. During the sinking of the caisson it was closed by a “plug” formed of steel plates, fitted between girders in such a way as to be removable singly when the shaft was sunk to its proper depth and the shield was ready to start. The face-plates of the “plug” were held in place by two girders, which divided the opening into three horizontal strips about 5 feet deep. These areas were again divided vertically by three smaller girders, 5 feet apart. The face-plates were fitted and bolted to the girders in the areas so formed, wood packings being used, to facilitate their removal when necessary. Bolts were also used for making up the girders, so that they could be removed in pieces. The girders were bolted to horizontal brackets, fixed on the skin of the circular plug-opening, and themselves removable.

*Method of Erection and Sinking.*—As the methods employed in sinking the two shafts were identical, it will suffice to describe the work on the Poplar shaft, which was the first one sunk. All the steelwork used in the caisson was first put together in the builders yard in sections of not less than four rings at a time, so as to ensure good fitting; and so well was this work supervised that, when it was put together again on the site of the shaft, but little adjustment was found necessary. To ensure the caisson being perfectly cylindrical, which was particularly important for the reason already mentioned, the contractors were required to put in the concrete filling between the skins as the erection of the steelwork advanced, that is to say, the concrete filling for each ring was (save in exceptional circumstances, such as frosty weather) always put in to within 2 feet of the top before the riveting of the next ring was proceeded with. It was therefore necessary to make each ring absolutely correct before going on with the next above, because, the concrete filling once in, no further adjustment was possible. Only in the two top rings, when all danger of the shaft being jammed in sinking had disappeared, was this procedure departed from. This method of working was also advantageous in ensuring that the concrete filling was tipped only a few feet from the skip. As soon as the cutting edge and the lower air-tight floor with the ring surrounding it were riveted up, and the concrete filling was in place, the blocks on which the caisson had stood were removed and the sinking was commenced; but for some time, owing to delays in the delivery of the steelwork, very slow progress was made.

The erection of the caisson was commenced on the 26th September, 1899, and by the 13th March, 1900, one-half was erected and the

cutting edge was sunk to a depth of 24 feet 6 inches below ground-level, when the quantity of water met with prevented further progress, and sinking was stopped until the arrangements for working in compressed air could be completed. So far the sinking of the caisson had been done in the open, the material inside the shaft being removed in the ordinary way, and the lowering of the structure being controlled by foot-blocks under the cutting edge. No kentledge was required at this stage, the shaft going down easily when released, and being never more than a few inches out of level. The material passed through was mainly river-mud and silty clay; but at 22 feet below the surface ballast was found, through which, as already stated, water found its way from the river, the water in the caisson rising and falling with the tide. In order to continue the sinking of the caisson under compressed air the bottom floor-plates were fixed on the girders, and the upper floor-girders were erected in position. On these upper girders were placed the air-locks, from which shafts 3 feet 6 inches in diameter were carried down through the lower floor, thus giving access to the working-chamber below it (Fig. 4, Plate 1). On the 2nd May, 1900, the work of sinking the caisson was resumed under compressed air, the erection of the steelwork of the caisson having in the meantime been completed to within 15 feet of the total height. The remaining rings were erected during the time the shaft was sinking.

The method of sinking the caissons under compressed air was as follows. Starting usually with the ground-level in the pressure- or working-chamber about 1 foot 6 inches above the bottom of the cutting edge, the miners excavated daily to a depth of about 1 foot below it, leaving all round the cutting edge a berm between 1 foot and 2 feet in width. The amount of excavation was limited by the number of skips which could be passed through the vertical air-lock in a given time; and in practice it was found that four men working in the pressure-chamber could keep the skips filled as fast as they could be returned empty. Daily, generally during the breakfast-hour of the morning shift, when the men were out of the caisson, the air-pressure in the working-chamber was lowered until the caisson commenced to move. No further reduction of pressure was then made, and the movement of the caisson was gradually stopped by the tapered cutting edge burying itself anew to a depth of 1 foot to 2 feet below the general level of the excavation. The air-pressure was then again raised sufficiently to dry the bottom of the shaft, and the same process of excavating and sinking was repeated. It was found possible to carry on simultaneously the

different operations of plating and riveting the skins, putting in the concrete filling, and sinking the shaft; and by careful organization it rarely happened that one operation interfered with or delayed another. It will be seen from the Table giving details of the sinking-operations (p. 8) that the daily progress under compressed air was singularly uniform.

The strata met with 3·00 feet below Ordnance datum, or about 20 feet below ground-level, were water-bearing. The top surface of the ballast, which was found on the north side of the caisson about 22 feet below ground-level, sloped rapidly southward, and some difficulty was expected in keeping the cutting edge level on that account. As a matter of fact, for a few days the error of level of the caisson amounted to  $6\frac{1}{2}$  inches, being the largest amount of tilt recorded; but this was put right, and subsequently the caisson, though sinking at an average rate of 1 foot 3 inches per day, was never more than  $1\frac{3}{4}$  inch out of level. Below the ballast, at about 41 feet below ground-level, was found a bed of close grey sand, at times almost as tough as soft sandstone. It was noticed that the skin-friction of the caisson, which, when the lower portion was in the ballast, had been generally 4·5 cwt. to 4·7 cwt. per square foot, became less as the cutting edges sank deeper into the sand; and the last observations, taken when the caisson was nearly down to the required level, gave a skin-friction of just under 3·8 cwt. per square foot. The probable explanation is that, owing to the consistency of the sand, most of the air escaping from the pressure-chamber passed up close to the outside of the caisson and so made an air lubricant for it. The lubricating-pipes which were provided in the caisson were used on a few occasions, but without appreciable results, perhaps owing to the choking of the pipes by the dirty water used, but more probably owing to the air that escaped from below driving away the water from the caisson as soon as it left the pipes.

The total weight of kentledge put into the caisson was only 921 tons, which, with the weight of the steel and concrete in the structure, made finally a total weight of 2,560 tons. By the provision of an air-tight floor at the bottom of the shaft, the contractors were enabled to provide the necessary kentledge by tipping the ballast as it came up through the air-locks into the shaft below, and by running in water from a pipe above. As stated above, the sinking of the Poplar shaft under compressed air was commenced on the 2nd May, 1900. It was sunk to the required depth by the 31st of the same month. The Table shows the daily progress from the 10th May onward, with the loads

# 8 COPPERTHWAIT ON GREENWICH FOOTWAY TUNNEL. [Minutes of

on the caisson, pressure, etc., from the commencement of work under compressed air until the shaft was sunk to the required level.

Date.	Depth of Cutting Edge below Surface.	Cutting Edge out of Level.	Depth sunk each time of lowering.	Load on Shaft including Kentledge.	Air-Pressure.	Remarks.
1900. May.	Fect.	Inch.	Feet.	Tons.	Lbs. per Sq. Inch.	
2	24.80	$\frac{1}{2}$	..	1,346	6	{ Pressure put on. Cutting edge in ballast at north side. Skin-friction 4 cwt. per foot.
7	27.50	$6\frac{1}{2}$	2.70	1,362	6	
10	28.60	$1\frac{1}{2}$	1.10	1,412	6	
11	29.60	$1\frac{1}{2}$	1.00	1,457	8	
12	31.83	$\frac{7}{8}$	2.23	1,618	8	Skin-friction 4.7 cwt. per foot.
13	33.70	$1\frac{1}{2}$	1.87	1,826	8	
14	35.80	$1\frac{1}{2}$	2.10	1,943	8-10	
15	37.26	$\frac{7}{8}$	1.46	2,114	10	{ Skin-friction 4.75 cwt. per foot.
16	39.16	$\frac{3}{4}$	1.90	2,257	10-11	
17	39.96	$\frac{3}{4}$	0.80	2,371	11-12	
18	41.50	$\frac{7}{8}$	1.54	2,371	11-12	{ Cutting edge in close grey sand. Skin-friction 4.6 cwt. per foot.
19	42.50	1	1.00	2,371	10-11	
20	43.60	1	1.10	2,371	10	Lubricating-pipes in use.
21	44.75	$\frac{1}{2}$	1.15	2,421	10	
22	46.42	$1\frac{1}{2}$	1.67	2,421	10 $\frac{1}{2}$ -13	
23	48.31	$\frac{7}{8}$	1.89	2,421	11-13	
24	49.46	$\frac{7}{8}$	1.15	2,421	13	
25	49.82	$\frac{3}{4}$	0.36	2,421	14	
26	51.80	$\frac{3}{4}$	1.98	2,449	15	
27	53.35	$\frac{3}{4}$	1.55	2,477	15 $\frac{1}{2}$	
28	55.20	$\frac{3}{4}$	1.85	2,505	16	
29	57.13	$\frac{3}{4}$	1.93	2,533	16 $\frac{1}{2}$	
30	58.55	$\frac{3}{4}$	1.42	2,561	16	Skin-friction 3.8 cwt. per foot.
31	60.30	..	1.75	2,561	20	

It will be seen from this Table that from the 10th to the 31st May, a period of 22 days, the depth sunk daily varied but little, only twice falling below 1 foot and twice exceeding 2 feet. When sunk to the proper depth the caisson was exactly plumb. As the Greenwich caisson was sunk in a similar manner, and with the same uniform speed and accuracy, the use of vertical sides to the caisson, and of an air-tight floor near to the cutting edge during sinking, would appear to be justified. The vertical sides of the caisson prevented, as far as could be seen, any disturbance of the surrounding ground during the operation of sinking; at least no cracks were visible on the surface more than two or three feet away, and those which appeared within that distance were slight. When the plug of the tunnel-opening was removed and the shield was pushed forward into the solid ground, no previous



movement of the strata was perceptible. The steadiness of the caisson when in motion was no doubt due in part to the slight disturbance of the surrounding ground; but the lowness of the centre of gravity of the structure, due to placing the kentledge near the bottom of the shaft, probably also accounted largely for the ease with which it was controlled.

On the question of the batter of caissons some interesting remarks were made in the course of the discussion on the Black-wall Tunnel.<sup>1</sup>

*Removal of Tunnel-Plug.*—As soon as the Poplar shaft had been sunk to the required depth, the working-chamber under the air-tight floor was filled with 6 to 1 Portland-cement concrete to the level of the underside of the floor-girders; and when that had set, pressure was taken off, and the floor-plates were removed. Concrete was then filled in between the girders to just below the floor-level, and the plates were replaced, grout being afterwards forced beneath them under pressure, through holes provided for the purpose. The material for the shield was then lowered through the upper floor-girders, the air-locks and tubes being moved for the purpose, and the shield was erected on a timber cradle laid on the lower floor. The position of the shield during erection is shown by dotted lines in Fig. 5, Plate 1. A ring of concrete was then built inside the tunnel-hood, leaving an opening large enough to admit of the passage of the shield. Behind the shield some temporary tunnel-rings were built, extending to the skin of the caisson, for the shield to push against. This done, the upper floor-plates were fixed on the girders already in position, the air-locks were replaced, and air-pressure was again applied. The actual removal of the "plug" was carried out as follows (Fig. 5). Across the plug-opening, at a distance of 4 feet from the steel plug, and about 5 feet from the invert of the plug-opening, a 12-inch by 12-inch timber was fixed, bearing on the concrete ring previously referred to, which was itself secured by rails bolted to the circular hood. Below it was placed a 12-inch by 6-inch timber, similarly bearing against the concrete; and close poling was then built in front of the joists, forming a diaphragm from the invert of the plug-opening to above the level of the lower girder of the plug. The lower plates of the plug were then removed one by one, and the space between the solid ground so exposed and the timber diaphragm was filled with well-pugged clay. The lower girder was then removed, the

<sup>1</sup> Minutes of Proceedings Inst. C.E., vol. cxxx. pp. 80-89, *passim*.

bottom edges of the plates above it being held by stretchers to the 12-inch by 12-inch timber. Two similar timbers were then fixed above the first, and close poling was placed in front of them, thus raising the timber diaphragm to the level of the second girder of the plug; the plates below were in turn removed, and the exposed face was supported by clay filling as before. In this way all the steel plug was removed, and in its place the tunnel-opening was closed by a timber diaphragm and some 4 feet of clay in front of it. The shield was pushed forward until it touched the timber diaphragm, which was subsequently cut out to allow of its passage.

#### TUNNEL-LINING. (Figs. 6, 7 and 8, Plate 1.)

The cast-iron lining of the tunnel is similar in character to that used in previous works of the same kind. It is 12 feet 9 inches in external diameter and 11 feet 9 inches in internal diameter, the rings being 1 foot 8 inches long, and each consisting of eight segments and one key-piece. The weight of the lining is 4 tons  $2\frac{1}{2}$  cwt. per lineal yard: that of similar lining for tunnels in London clay is about 2 tons 17 cwt. per lineal yard. The bolt-holes in the circumferential flanges of the segments are arranged so that adjoining rings can be made to break joint, as was done throughout the tunnel. All bolt-holes were made with their outer edges bevelled off, as shown in Figs. 7 and 8, Plate 1. When the bolts were put in, lead washers (short lengths cut from lead piping) were put on them; and, on the bolts being screwed up, the lead completely filled the space around them at each end made by the bevelled edges of the bolt-holes. This arrangement proved very successful, and comparatively few bolts were found to be leaking when the air-pressure was removed. The risk of damage by electrolysis did not appear sufficiently probable to forbid the use of lead. All joints of castings were planed, except on the space left on each face for caulking. These spaces were filled with the usual mixture of iron filings and sal ammoniac; but before filling the mixture in, soft lead wire was everywhere hammered in. The regular use of this lead wire, which kept out the water while the rust-joint was hardening, resulted in considerable saving later; for when the air-pressure was removed there were less than a dozen places in the 12,000 lineal yards of caulked joint which required cutting out and recaulking. The grouting-appliances for filling in spaces behind the tunnel-lining were of the usual character.

### THE SHIELD.

The shield employed in making the tunnel was of the kind known as the "trap" or "box" shield. The trap consists essentially of two diaphragms, the front one filling the upper half, and the back one the lower half, of the circle enclosed by the cylindrical skin of the shield. The bottom of the front diaphragm is a few inches lower than the top of the back one. In the event of an inrush of water from a "blow" occurring at the face, the water must flow over the top of the back diaphragm to get into the tunnel, and before it rises high enough to do this the bottom of the front diaphragm is under water, and all escape of air through the shield is stopped. The water in fact becomes a seal to hold the air.

*Historical Notes on the Trap-Shield.*—The first shield of this type actually used was employed in a tunnel under the Mersey, made in connection with the Liverpool Waterworks, and was briefly described in the discussion on the late Mr. J. H. Greathead's Paper on "The City and South London Railway."<sup>1</sup> In that Paper is figured<sup>2</sup> a shield with a combination of trap and air-lock, designed by Mr. Greathead, and actually constructed in 1876, for use in a projected tunnel under the Thames at Woolwich. The Author believes that, with these two exceptions, no communication dealing with this kind of shield is to be found in the publications of the Institution. The diagrams, *Figs. 9*, which show side by side successive shields built on the trap principle, may therefore be of interest.

It will be seen in Mr. Greathead's Woolwich shield that, combined with the trap formed by two diaphragms, there is an arrangement for placing the front of the shield under compressed air, the tunnel behind being apparently under normal pressure.

The Mersey shield was originally a shield with a concave diaphragm consisting of removable plates with a door at the bottom. This proved unsatisfactory, however, and the shield was modified under the advice of Sir Benjamin Baker, K.C.M.G., Past-President Inst. C.E., in 1891, as shown in *Figs. 9*, and gave good results. The lower half of the original diaphragm was replaced by shutters or curtain-plates. Farther back in the shield was built a box forming the back diaphragm of the trap. By means of a sliding lid to this box the whole face could be completely closed. The work of excavation was carried on by removing one or more of the

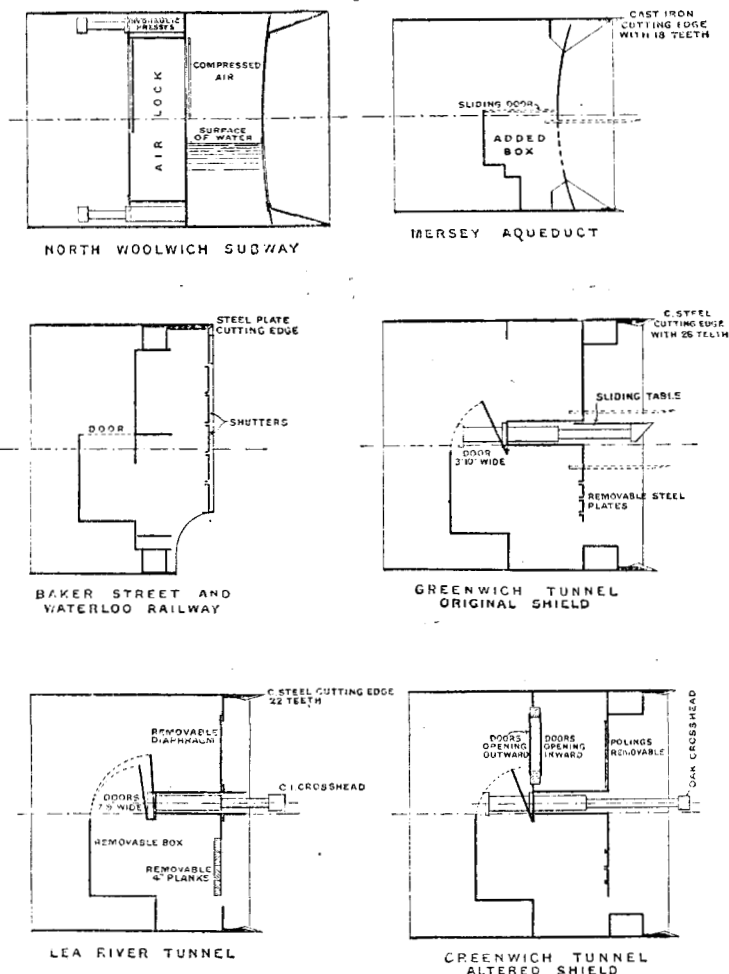
<sup>1</sup> Minutes of Proceedings Inst. C.E., vol. cxxiii. pp. 100 and 104.

<sup>2</sup> *Ibid*, p. 66.

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curtain-plates below the front diaphragm, and removing the face at the bottom, needles being driven forward into the solid about

*Figs. 9.*



Scale 1 Inch = 10 Feet  
 INCHES 12 6 0 1 2 3 4 5 10 15 FEET  
 EVOLUTION OF THE "TRAP" SHIELD.

half-way up the face to prevent too much spoil from coming down in front of and above the cutting edge. The teeth or knives on the

cutting edge were a useful feature of the shield, and greatly lessened the amount of power required for pushing it through ballast. The experience gained with this shield, and the method of working adopted, suggested several features in the Greenwich shield as at first constructed.

A trap or box shield (*Figs. 9*) was used in the Baker Street and Waterloo Railway tunnels under the Thames at Charing Cross.<sup>1</sup>

In *Figs. 9* is also shown the arrangement of the shield used in the Greenwich Tunnel, before and after alteration. Essentially it is similar in design to the shield previously described for the Mersey aqueduct tunnel; but face-rams with sliding tables have been added, which with other details will be described later.

The remaining diagram in *Figs. 9* shows a shield now in use in a tunnel under three arms of the River Lea required in connection with some main-drainage extensions. The Author is assisting Sir Alexander Binnie in this work, and the shield was designed about the same time as the shield for the Greenwich Footway Tunnel, but before the latter work was commenced. In the Lea shield, which has the diaphragms common to the others, face-rams with square cross-heads are provided. The object is to work with a timbered face held up by these rams—which, when extended, project well beyond the cutting edge—and then, as the shield is pushed forward, to keep the face-rams stationary, still holding the poled face, by allowing them to come back relatively to the shield in a manner similar to that shown in *Figs. 13*, which represent the Greenwich shield doing such work. The cutting edge is provided with twenty-two teeth, and, in place of steel curtain-plates below the front diaphragms, 4-inch planks are used. The above method of working is not novel; it is similar to the plan adopted in the lower part of the Blackwall Tunnel shield, and described in the Paper<sup>2</sup> by Messrs. Hay and Fitzmaurice on that work. In that instance there were no face-rams in the shield, and a telescopic stretcher was employed. A special feature of the Lea shield is that the diaphragm and box are removable; and further, the front diaphragm is made in sections hinged together, so that in good material work can be carried on with an open face. This construction was adopted because it was known that, although most of the tunnel was in gravel, a considerable length was in water-tight clay, where special precautions would not be required.

The two shields of the trap kind with which the Author has

<sup>1</sup> *Post*, p. 29.

<sup>2</sup> *Minutes of Proceedings Inst. C.E.*, vol. cxxx. p. 71.

had to work have given satisfactory results. No serious flooding of either tunnel under his charge has occurred; but on several occasions at Greenwich small inrushes of water, caused by a "blow" at the face, have happened; and the ease with which the water was held, immediately it rose high enough in the shield to seal the opening between the diaphragms, was noticeable.

*The Greenwich Tunnel Shield.*—The shield used in driving the Greenwich Tunnel is shown as originally built in Figs. 10, 11 and 12, Plate 1. Certain alterations, the nature of which will be indicated later, were made in it during the progress of the work.

The shield measures 14 feet 1 inch over all in length, and has an external diameter of 13 feet. The skin is formed of 1-inch steel plate, in seven segments, the longitudinal joints having 1-inch cover-strips. To prevent the cover-plates from stripping when the shield is in motion, the cast-steel cutting edge is thickened in front of them. The cutting edge is made in thirteen segments, each of which has two 6-inch teeth cast on it; and immediately behind the cutting edge is a circular built box-girder, 1 foot 8 inches by 1 foot 2 inches, to which it is bolted. The provision of this box-girder was specially insisted on by the Chief Engineer, and its insertion certainly ensures the shield keeping its shape. Further rigidity is given to the front of the shield by a vertical stiffener, 2 feet 8 inches in width and  $\frac{3}{4}$  inch thick, bolted at top and bottom to both cutting edge and circular box-girder. Behind this is placed the front diaphragm, which closes the upper half of the shield, and extends downward (below the boxes containing the face-rams) to 1 foot 3 inches below the horizontal axis of the shield. Below this line are removable steel-plate curtains or shutters, which, however, were never used. The boxes containing the face-rams, 4 feet long, form part of the front diaphragm; for, though they are open towards the front of the shield to allow of the movement of the rams, they are closed at the back. The top and bottom plates of these boxes are bolted at each end to cast-iron segments of the kind usually employed in small shields for stiffening the skin; and the boxes are thus made to form a horizontal box-girder across the shield. In these boxes are placed the two face-rams, 5 inches in diameter, which were originally made to reach, when fully extended, only to the cutting edge of the shield. They were provided with sliding tables, the edges of which were supported on angle-bars fixed to the frame of the shield. The rams in this form were not accepted by the Chief Engineer without misgiving, and were consequently made so that they could

be easily removed if found unsatisfactory. The idea in putting them in was that they would perform the same function which the loose needles did in the Mersey shield (*Figs. 9*, p. 12), in holding up the material in the upper part of the shield while the miners excavated at the bottom of the face. But in practice, when working in ballast, the ballast came in at the face below them as fast as the miners removed it, and the upper part of the shield in front of the diaphragm became blocked. Ultimately these tables were removed, and oak cross-heads were placed on the rams, which were lengthened; they were in fact made similar to those on the Lea tunnel shield (*Figs. 9* and *Figs. 14*, Plate 1).

Behind the rams is fixed the box which forms the back diaphragm of the trap. It is built in horizontal sections, which are removable, so that its height can be diminished if desired. The top of the box, which is fitted with lids having self-acting catches, is 8 inches above the bottom of the front diaphragm. This is sufficient overlap to form a water-seal, so long as the shield continues level; but as all circular shields rotate more or less in their advance, the effective overlap of the two diaphragms tends to become less as the shield progresses, and perhaps a greater overlap in the first instance is desirable. When the Greenwich shield had finished work it had a considerable tilt to the right, and the water-seal in the box was nearly non-existent. The thirteen rams for pushing the shield forward are of the usual kind. With a pressure of  $1\frac{1}{2}$  ton per square inch, they exert a total thrust of 750 tons.

#### TUNNELLING.

The whole of the tunnelling was done under compressed air. The vertical air-locks in the Poplar shaft continued in use until 142 feet of the tunnel had been constructed, and then a bulkhead, with a horizontal lock and an emergency-lock above it, was built in the tunnel close to the shaft, and the upper air-tight floor and locks were removed and transferred to the Greenwich shaft.

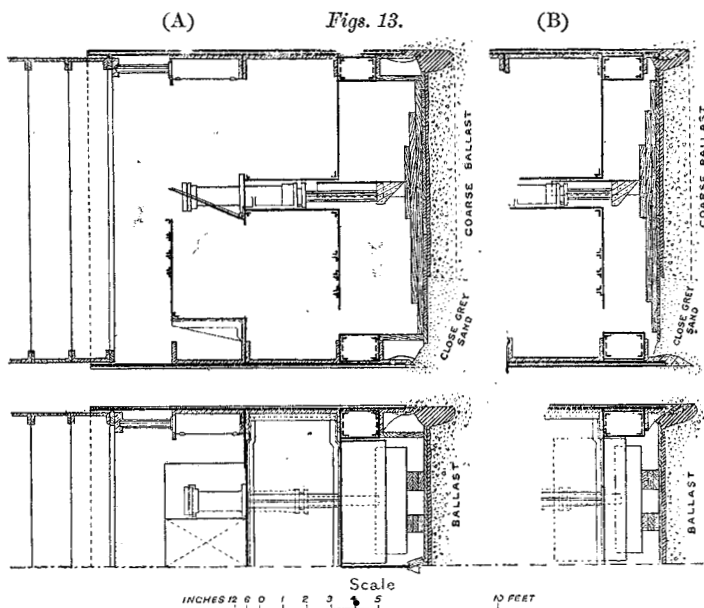
When the plug in the tunnel-opening of the Poplar shaft had been removed, in the manner already described, the shield was pushed forward through the temporary clay face into the ballast. The handling of the shield when partly in the solid and partly under the opening in the shaft required great care; and at the outset considerable trouble was caused by carelessness on the part of a foreman, which, just as the shield was leaving the shaft, caused a fall of the face, and the formation of a large

cavity above the front of the shield. The hole was filled with sawdust through the handholes in the front diaphragm; but in this operation another mishap occurred. By some means the sawdust became ignited, and for 48 hours a fire raged in front of the shield. It was soon found that the face-rams were too short, and further, that the sliding tables did not serve the purpose for which they were designed. For the time being their use was abandoned, and steel bars, about 6 feet in length, were used instead, passing through holes cut for them in the bottom of the front diaphragm. The method was exactly the same as that adopted with the Mersey shield, and some success attended it. At this time the face consisted almost entirely of ballast; and on the Author's recommendation, the contractors decided to abandon the use of sliding tables and needles for holding up the face, to lengthen the face-rams, and to utilize them for holding up the working-face by ordinary close poling. This answered well; and subsequently the method of working was further improved by excavating in front of the cutting edge, and filling the annular channel so made with clay—a method used by Brunel in the Thames Tunnel, and more recently by the engineers of the Waterloo and City, and Baker Street and Waterloo Railways.

*Figs. 13* show the method of working, which is briefly as follows: the only difference from similar work previously done is in the use of the face-rams. Beginning at the top of the shield, the ballast was removed around the cutting edge down to the level of the top poling-board, which, when fixed, was in the first instance held in position by short timbers stretched from the frame of the shield; and similarly all the face of the ballast was poled, each poling being supported in the same way. The poling-boards did not extend the full width of the shield, but were in two lengths, thus allowing only half the face to be worked at a time, in places where the ballast was very open. Clay was put in front of the cutting edge, and doubtless it lessened considerably the work of the shield-rams; but the provision of teeth on the cutting edge has been found, as in the Mersey shield, also useful in this respect. When all the face was poled (*Figs. 13, A*), the face-rams of the shield were pushed forward, and, by means of soldiers, took the pressure of the face, the short timbers which had previously held the polings being knocked out. The shield was pushed forward, and as the cutting edge passed beyond the polings, the face-rams were allowed to draw back relatively to the shield, so that while the shield was advancing, the poled face remained unaltered. The position at the end of the operation is shown in



*Figs. 13, B.* The foregoing method of working was adopted in building the first 220 feet of the tunnel, which was mainly in open ballast with hardly any sand. This work occupied 3 months, namely, October, 1900, to January, 1901. On the 3rd January, the face being entirely composed of close grey sand, the use of clay at the face was discontinued; and when 430 feet of tunnel had been built, the face-rams were no longer used. A little farther on, several feet of close sand and clay were always found on probing above the shield, and the face itself consisted largely of shelly clay; consequently all timbering of the face was given up.



METHOD OF WORKING THE SHIELD.

From the character of the strata shown in Fig. 2, Plate 1, and from the rate of progress there indicated, it will be seen that during the months of January, February, March and April, 1901, the tunnel-work was of an ordinary character; in fact, the shield was worked as an open one until the gradient on the Greenwich side was reached. The front diaphragm had two doors cut in it, which were closed when necessary by short polings fitting into vertical guides at the sides of the doors.

When the shield reached the foot of the 1-in-15 gradient on the Greenwich side of the river, it was resolved, although the character

of the ground continued favourable, to close the shield again; and the alterations indicated in *Figs. 9*, which had previously been fitted, came into use. The front diaphragm was not again closed, but the poling-boards already mentioned were kept in readiness on the shield; and a second diaphragm was placed 4 feet behind the original one, at the back end of the face-ram boxes, and in it was provided an opening with two double doors, the front pair opening towards the face and the other pair towards the tunnel. The inner pair were kept fastened by a short stretcher, which could be easily knocked away; and the door would then fly open with the rush of air through the shield (*Figs. 14*, Plate 1). The outer doors were ordinarily fixed open. In the event of any "blow" occurring, and a fall of the face blocking the ordinary egress through the trap to any men working in the top of the face, escape was rendered possible through these doors; and in practice it was found, when some small blows occurred, that the existence of this means of escape did embolden the men to endeavour to make things safe before leaving the face, instead of rushing out in a panic. The precaution was taken of placing two safety-diaphragms or curtains in the tunnel, at each end of the nearly level portion of the tunnel, that is, at the foot of the gradient ascending to each shaft. These diaphragms were of timber, and were about 3 feet deep from the soffit of the tunnel. If a serious blow had occurred while the shield was climbing the gradient towards the Greenwich shaft, the lower part of the tunnel might have been filled with water, and all escape for the men in the shield might have been cut off without this arrangement, by which a certain air-space was secured between the two diaphragms. A further precaution taken was to provide an extra blow-out pipe, controlled from outside the lock, which extended only to the bottom of the Poplar gradient, and thus afforded means of getting rid of any water which might come into the tunnel as the result of a "blow" when nearing the Greenwich shaft, and which would naturally collect in the lowest part of the tunnel, much below the level of the main blow-out pipe carried forward with the shield.

These precautions happily proved unnecessary, because the material met with for two-thirds of the whole distance proved to be highly favourable for tunnel-work; and when, on approaching the Greenwich shaft, a face almost entirely of open ballast was met with, the same procedure as had been adopted in the bed of ballast on the north side of the river again proved equally satisfactory. How favourable in general was the material met with

may be judged from the fact that from the 22nd February to the 1st May, 1901, an advance of 10 feet was made every working-day without exception. In the open ballast on the Greenwich side of the river a uniform advance of 5 feet per working-day was made.

No difficulty was experienced in making the junction with the Greenwich shaft: the only precaution taken was to drive needles from inside the shaft, round the top of the steel plug, so as to form a hood over the shield when it reached the shaft, and thereby to prevent any fall of the ground above while the plug was being removed.

#### CONDITIONS OF WORK UNDER COMPRESSED AIR.

As at the Blackwall Tunnel, the London County Council made provision at Greenwich for the proper care and protection of the men working in compressed air; and the precautions taken during the progress of the work have been so far successful that the power taken by the Council, in the Act of Parliament authorizing the construction of the tunnel, to compensate men injured in health by working in compressed air, has been exercised in only three cases, and to a total amount of only £20. The County Council appointed Messrs. Leslie and Macmorran as medical officers at the tunnel, and the men working in compressed air were examined by them at least once a week: all men had at the outset to obtain a certificate of health from them before commencing work. It was found that, of the men presenting themselves for employment in the tunnel, 13·9 per cent. had to be summarily rejected; and of those who, having passed the first examination, worked for a longer or shorter time, 5·7 per cent. were subsequently found to be affected by the pressure, and were forbidden to continue working. Dr. Macmorran notes as a curious fact that some men who had previously worked in compressed air, and who, at their preliminary examination by him, were found to have deviations from the normal in their heart-action, but not sufficiently marked to justify their summary rejection, were found, after resuming work for some time, to have no trace of the irregularities at first observed.

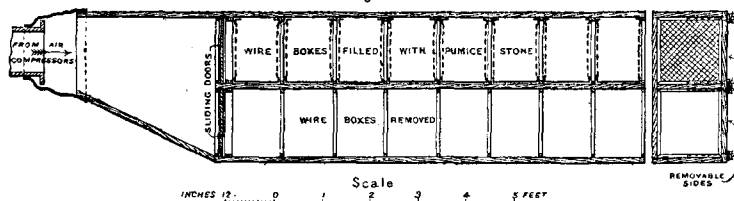
The men worked in 8-hour shifts, with a rest of 45 minutes in the middle, during which interval they were not allowed to remain in the tunnel. Rooms with washing-requisites, etc., were provided for each gang, and hot coffee was served out to the men on leaving the tunnel. A medical lock was provided for treating cases of caisson-sickness but was used only twice. The

amount of free air pumped into the tunnel averaged over 5,000 cubic feet, and never fell below 4,000 cubic feet, per man per hour. The air-inlet pipe delivered immediately inside the lock, and the blow-out pipe was carried forward with the shield. A simple arrangement introduced by the Author had a good effect in purifying the air in the shield. From the construction of the shield it will be seen that, particularly when the doors in the upper diaphragm were open, there would be little or no current of air at the bottom of the box of the shield, and consequently towards the end of a shift there was an accumulation there of carbonic acid. In fact there was frequently 0·2 per cent. by volume of  $\text{CO}_2$  in the air within the shield, when there was less than 0·1 per cent. in the tunnel a few feet behind it. To remedy this, a pipe was passed through the back diaphragm or box of the shield near the top, and carried down inside nearly to the invert. Outside the box it projected a few inches, and on this projecting piece the nozzle of the blow-out pipe was placed whenever it was not in use for blowing water from the bottom of the tunnel. By this arrangement nearly all the air blown out through the pipe was taken from the place where most carbonic acid collected. Samples of air, taken on two occasions before and after using the blow-out pipe in the shield as described, showed a decrease in a few minutes in the amount of  $\text{CO}_2$  present in the air; and had the pipe been fixed to the shield and controlled from outside the tunnel, the air in the shield could have been maintained of equal purity with the air in the tunnel. As the pipe was removable, its use depended on the miners themselves; and every one who has had to do with tunnelling knows that one of the main obstacles in the way of ameliorating the conditions of work in compressed air is the difficulty of making the miners carry out orders, the object of which they imperfectly understand. For this reason it is to be feared that the ventilation described above was not kept working as continuously as it should have been. The condition of the air in the tunnel was generally satisfactory, and only nine cases of caisson-sickness occurred in all, mostly trivial in character and caused by indiscretion on the part of the sufferers.

The Author was instructed by the Chief Engineer to inquire into the possibility of purifying the air in the tunnel by eliminating some of the carbonic acid (which in ordinary air amounts to about 0·05 per cent. by volume) from the air pumped into the tunnel; and the London County Council made a grant of money for carrying out experiments with that object. At the time the experiments were authorized, the tunnel was more than half

completed, and no serious alteration of the air-compressing plant was contemplated or possible. The engines were built by Messrs. Walker Brothers, and were entirely satisfactory in working; but from their construction and the arrangement of the engine-house, it was not possible in any way to box them in so as to arrange that all the air entering the compressing-cylinders should first pass through a purifying-chamber, or an installation similar to the purifiers or scrubbers used in gas-making. It was equally impossible to interpose a purifying-chamber between the engines and the tunnel, even if it had been permissible to incur the risk of a temporary break in the supply of air. Consequently the experiment was limited to trying what could be done in the tunnel itself under working-pressure. The simplest way of taking up the free carbonic acid in the air is by passing the air through or over a substance like lime or caustic soda, for which carbonic acid has a strong affinity. Probably at normal

*Fig. 15.*



PURIFIER FOR REMOVING CARBONIC ACID FROM AIR

pressure the former, used in solution in a scrubber, would be effectual; but a large quantity of lime-water is required even under favourable conditions, and to use such a quantity in the tunnel would have required more space than could be provided. A saturated solution of caustic soda is, bulk for bulk, more effective; and though the limited space available rendered it somewhat doubtful whether any marked results could be obtained by its use, a purifier of somewhat primitive design was constructed, and the results obtained with it were observed by officials of the Chemist's Department of the London County Council, who had also previously from time to time made analyses of the air in the tunnel.

The purifier is shown in *Fig. 15*, and consists of two rectangular trunks of wood, one above the other, open at one end, and having sliding doors at the other end. The ends fitted with doors are connected with the air-inlet of the tunnel by a conical box, the connection with the air-pipe being made air-tight by a

flexible joint. By opening one or other of the sliding doors, the air is made to pass through either the upper or the lower trunk, as required. Each trunk has one side removable, and each contains eight removable wire boxes containing pumice-stone broken small, which, before being put into the trunks, are dipped in a saturated solution of caustic soda. When the upper trunk is filled with freshly dipped boxes, the door of the lower trunk is closed, and its boxes are taken out, dipped and replaced. The bottom door is then opened, and the top one closed, thus diverting the course of the air from the upper to the lower trunk; the boxes in the upper trunk can then be removed and dipped afresh in the caustic-soda solution. A constant relay of fresh boxes was kept up day and night; and the deposit of carbonate of soda on the pumice-stone soon showed that some effect was produced upon the air.

The purifier was in operation for a month, and analyses of the air in the shield were made on fourteen different dates. The results are given in the Table (p. 23), which shows, in addition to the amount of carbonic acid in the air, the air-pressure, the temperature of the tunnel as compared with that of the engine-room, and the amount of air supplied per man per hour, on the days when the tests were made. It will be seen that after the purifier had been taken into use, the average proportion of carbonic acid present in the tunnel showed a decrease on that observed before. If there were no other factors to be considered, such a result would be conclusive, but there are so many circumstances which modify the result that the Author would confine himself to saying that the apparatus employed was responsible for some of the improvement; and that, as some effect was produced by its use, a similar purifying-apparatus properly elaborated may reasonably be expected to eliminate the larger portion of the carbonic acid in the air.

The last two lines of the Table give the averages for all the observations before and after fitting up the purifier. The average diminution of  $\text{CO}_2$  by volume, apparently consequent upon the use of caustic soda, is 0.01 per cent. The average amount of free air supplied per man per hour was a little less, and the pressure per square inch  $3\frac{1}{2}$  lbs. less, after the purifier was put in, than previously: so that these two important factors in determining the amount of  $\text{CO}_2$  in the air do not vary much. The variations in the quantity of  $\text{CO}_2$  in the free air of the engine-room are probably caused by momentary contamination of the air, due to the proximity of the boiler-furnaces. The samples

of air in the tunnel were taken at floor-level; and the percentages

Date.	Air-Pressure per Square Inch.	Temperature in Shield above or below that of Engine-room. Fahr.	Free Air Supplied per Man per Hour.	Percentage of CO <sub>2</sub> by Volume.			Remarks.
				In Engine-room.	In Tunnel.	In Shield.	
1901.	Lbs.	Degrees.	Cub. Ft.				
March 5	24	+10	6,000	0.047	0.073	0.196	Men working.
" 11	21	+19	5,280	0.055	0.097	0.218	End of shift.
" 18	24	+15	5,600	0.045	0.064	0.189	" "
" "	"	"	"	"	"	0.124	{ After " blow-out pipe had been used.
" 25	23	+15	5,280	0.047	0.058	0.125	{ End of shift; blow-out pipe used four times.
" "	"	"	"	"	"	0.098	{ After blow-out pipe had been used.
April 1	25	+13	5,280	0.051	0.087	0.186	{ Men working; blow-out pipe used at intervals.
" 15	26	+ 6	5,280	0.049	0.084	0.173	" "
" 22	24	- 7	5,280	.. <sup>1</sup>	0.098	0.223	" "
" 29	22½	-10	5,280	0.043	0.080	0.170	{ Blow-out pipe in use.
May 6	17	+ 5	7,000	0.049	0.076	..	Shield closed.
" 13	18	- 2	7,460	0.042	0.069	0.100	" "
" 15	"	"	"	"	"	"	{ Purifier in working order.
" 20	19	- 2	5,900	.. <sup>1</sup>	0.056	0.097	..
" 22	17	- 3	6,000	0.067	0.074	0.111	..
" 24	16	- 3	6,870	.. <sup>1</sup>	0.072	0.126	..
" 27	18½	- 7	7,195	.. <sup>2</sup>	0.066	..	..
" 29	17	- 9	6,580	0.047	0.077	..	..
" 31	23	+ 1	5,280	0.052	0.073	..	..
June 3	21	+ 5	5,280	0.049	0.075	..	..
" 6	20	+ 1	5,430	0.068	0.077	..	..
" 7	18	+ 1	5,430	0.059	0.057	..	..
" 10	20	- 5	4,260	0.042	0.066	..	..
" 11	21	..	4,240	0.039	0.072	..	Doubtful.
" 12	20	+ 5	4,100	0.045	0.068	..	..
" 13	19½	+ 6	4,500	0.039	0.062	..	..
" 14	18½	+ 2	4,260	0.049	0.068	..	..
..	22½	+ 6½	5,774	0.0475	0.0786	..	{ Average before using purifier.
..	19	..	5,330	0.0505	0.0688	..	{ Average when using purifier.

given in the Table are the averages of two and sometimes of three

<sup>1</sup> Sample spoilt.

<sup>2</sup> Sample spoilt. Shield in south shaft.

separate samples, one of which was always taken a few yards behind the shield. On the whole, the results of the analyses are encouraging; they appear to show that the purifier produced some beneficial effect.

It is generally agreed that the disease known as caisson-sickness is due to four causes, which react on one another; namely, excess of carbonic acid in the air, excessive air-pressure and limited supply of air, and prolonged continuous exposure of the miners to these conditions. Of these causes of illness, two—namely, the amount of air supplied per man per hour, and the duration of the working-shifts—are strictly regulated by clauses in the contracts, in all works carried out for the London County Council. It would be no small advantage if a third cause of ill-health, and that the most dangerous of all, could be, if not eliminated, at least lessened in effect, by the use of mechanical scrubbers containing some absorbent of carbonic acid. At small extra cost in the first installation of an air-compressing plant, arrangements could be made for passing all the air to the compressors through a purifier; or perhaps a combination might be made of a spray purifier, which at the same time should cool the air on its way to the tunnel. Such a combined cooler and purifier would of course be placed on the pressure side of the engines.

The work was carried out under the supervision of Sir Alexander R. Binnie, M. Inst. C.E., Chief Engineer to the London County Council, for whom the Author acted as Resident Engineer. Mr. James Brown, Assoc. M. Inst. C.E., was Agent and Engineer for the contractors, Messrs. J. Cochrane and Sons.

Mr. C. E. Gaunt and Mr. E. G. Carey acted as Inspectors of steel and cast-iron work for the London County Council; and, as already mentioned, Messrs. Leslie and Macmorran were the Medical Officers in charge of the compressed-air gangs.

The Paper is accompanied by eleven drawings, from which Plate 1 and the Figures in the text have been prepared.



