Discussion.

The PRESIDENT, in moving a vote of thanks to the Author for his interesting Paper, stated that, unfortunately, the Author's business engagements in America did not permit of his crossing the Atlantic to be present that evening. He thought it would be of interest to mention that the Author had formerly held for a long time the office of Vice-President of the New York Central Railroad, which was, of course, a very important position. The Paper described a novel and highly ingenious method of building what he would not call a tunnel, but a subaqueous connection between Canada and the United States, and contained information in regard to its construction and cost which would be of great value. The President.

Mr. E. W. MOIR observed that in many respects the Paper was a difficult one to criticize. The details were so new and so bold that it seemed presumptuous for any engineer to say anything about them but praise. About 5 years ago he was one of the unfortunate beings who struggled with an estimate for the scheme dealt with in the Paper. His firm, Messrs. S. Pearson and Son, did not get the contract; but he noticed, from the statement of cost given in the Paper, that they would have made a very handsome profit at their price if they had been as clever as the firm who obtained the work. The various firms who tendered for the contract had issued to them in New York what he thought could best be described as a "brain poultice" in connection with both the tunnel and the electric equipment. Nine schemes were put in for the consideration of the consulting engineers, but those who tendered never heard how their schemes had succeeded. In the plan put in by Messrs. Pearson it was proposed to use sunken tubes, but not to put the concrete round the outside as was shown in the diagrams. Messrs. Pearson proposed to launch the tubes with the concrete complete inside, except for a few feet at the ends, to make the junction with air-locked ends to the tubes, and then to complete the internal lining. The only credit that his firm deserved was that they were bold enough to say they could complete the work at a price, as the successful firm had done. It appeared to him from the diagrams given that a great deal of concrete had been put around the tubes that might have been saved. The quantity necessary to overcome the buoyancy or to retain the tubes in their place was nothing like the volume there was outside the $\frac{3}{8}$-inch steel casing. Mr. Moir.

Mr. Moir. Messrs. Pearson's scheme involved filling the surrounding space with sand instead of with concrete, which he thought would have met the case; it would not have been so strong, but he thought it would have made an equally efficient job. Possibly, however, it would have prevented any serious settlement of the structure in the trench, to which the Author referred, which in a structure of that kind was somewhat dangerous. In the scheme put forward by Messrs. Pearson there was to be a continuous support, levelled by a diving-bell, to place the tubes on, and it was hoped by that means to avoid any settlement. It seemed to him rather risky, in a current flowing at 3 knots per hour, to dredge a trench at right angles to the stream and fill it with concrete, without being sure that all the silt had been removed from the bottom. The test-results given in the Paper seemed to show that the concrete was of excellent quality; it had been passed through water and had set in water; and therefore it seemed to him the samples proved that concrete nowadays was made unnecessarily rich in cement. Engineers had been worrying contractors about cement-specifications for many years, making them more stringent all the time. During the last 30 years the quality had been improving very much, but engineers still specified a 2-to-1 mixture for mortar, or 6-to-1 concrete, as if cement were lime. The specification in this case called for 4-to-1 concrete inside the tubes, while only 6-to-1 material was required for that lowered through the water. Two of sand and 4 of broken stone amounted practically to 4 to 1, and he submitted that that was an exceedingly rich mixture. The costs given in the Paper were very interesting, and were seldom obtained in the Proceedings of The Institution—he was afraid, for trade reasons. In America the staffs of the engineers of the railway-companies invariably took the time on the whole of the works. Their inspectors were young engineers who had graduated at universities; they acted, among their other duties, as timekeepers, and the cost of every piece of work, whether contract work or day work, was recorded. For that reason he thought that American Papers, giving, as they did, actual data, were often more interesting than English Papers. Referring to the question of costs, it was stated on p. 27 that the Detroit tunnel had cost \$332 (£69 6*s.*) per lineal foot of single track. The St. Clair tunnel, one of the earliest subaqueous tunnels, crossing at Sarnia, a little farther up the same river, had cost \$333 per lineal foot of single track, whereas the North River tunnel in New York City, where prices were notoriously higher than at Detroit, and which had been built under compressed air, had cost only \$300 (£62 12*s.*) per lineal foot. Turning to p. 40, it would be seen that the cost per cubic yard of excavation of the subaqueous portion of the Detroit tunnel was only 50 cents, whereas he expected the cost of excavation in New York would be more like 10 to 15 dollars per cubic yard when dug out. There was evidently room for cross-river connections on this system—and probably at much lower cost; and there was no doubt that in many situations the method would be exceedingly useful. He fully anticipated that some day the English Channel would be subaqueously "bridged" by a system on the lines of the work carried out at Detroit. Many years ago the same plan was suggested for connecting Denmark and Sweden—he thought by a Swedish engineer, shortly after leaving the employ of Messrs. Fowler and Baker on the Forth Bridge; and he understood that Mr. Barlow suggested many years ago a similar method for crossing Rio de Janiero harbour. If engineers were ultimately able to fix the maximum draught of ships, it would appear that some such scheme, suspended, like Mohammed's coffin, between heaven and earth, might be used to bridge many channels, if masses of foundation could be dropped into water which was too deep to permit of their being laid properly by divers. He noticed from the Paper that the contractors had been unable to carry out the shore approaches by the method of timbering suggested in the preliminary specification. Messrs. Pearson's tender did not endorse that part of the suggested scheme at the time, and they suggested making the shore approaches by means of circular shields in two distinct tracks. The contractors began to build their shore approaches with a series of headings, but ultimately they had to give up that plan and adopt what would appear, from the progress made, to be a somewhat inefficient makeshift, considering that an advance of only 9 feet was made per day with a shield, which was a very slow rate at the present day. The scheme as a whole, however, was full of new suggestions, and inasmuch as the Author gave such great credit to the contracting staff, Mr. Moir was sorry to see that the names of individual members of it did not appear in the Paper. When Messrs. Pearson made their tender, the joints, for instance, were not designed, and a great many details that appeared in the Paper did not appear in the original specifications. The Author frankly admitted that the contractors designed many of the details of the scheme, and Mr. Moir therefore wished that their names had been given, so that they might appear on the record as having done such good work. Mr. Moir.

Mr. C. O. Burge remarked that the question of crossing Sydney Harbour had been considered in Australia, and much discussion had taken place as to whether a bridge or a tunnel would Mr. Burge.

Mr. Burge. be the proper means to adopt. The Royal Commission which investigated the subject about 2 years ago came finally—guided largely by the success of the Detroit tunnel—to the decision to adopt the system set out in the Paper. As in the present scheme, they were limited in depth. The railways on each side of the river could not be approached with a gradient steeper than about 1 in 50; consequently it was necessary to adopt a shallow tunnel. The scheme had been before Parliament, and he believed the work would probably have been commenced by the present time, but for the dissolution of the State Parliament, which had thrown parliamentary proceedings somewhat out of gear. When the Australian engineers came to design the work, no doubt they would be greatly guided by the present Paper and the discussion upon it. The question he desired to ask was, what necessity was there for having longitudinal reinforcement in the lining? The tubes appeared to have stood for 7 months without any lining or reinforcement after they were unwatered. It seemed to him that the whole massive concrete structure, strengthened longitudinally by the tube itself, would be fully sufficient to meet all the stresses that were likely to come upon the structure in a longitudinal direction. On the 29th April, 1910, an article appeared in the *Railroad Age Gazette*, in which the statement was made that one of the tubes on the Detroit tunnel had gone out of position when being sunk, but that, by a very extraordinary circumstance, a large steamer passing over caused such a movement in the water as to get it exactly into its right position! If that report had appeared in an ordinary journal it would have been less surprising, but it had appeared in a technical paper, and therefore he thought it would be interesting if the Author were able to say something about it. Details of the five tunnels which it was proposed should be made across Sydney Harbour for railway, tramway, and road, had appeared in *Engineering*[1].

Mr. Thomson. Mr. T. FRAME THOMSON remarked that he had had the pleasure of going through the Detroit tunnel in the first passenger-train which traversed it. The Author made somewhat of an apology for not dealing at greater length with all the details of the subject which were of interest; but Mr. Thomson thought very few Papers had been read at the Institution in which every aspect of the subject had been so fully and clearly dealt with as in the present instance. There was one feature of the tunnel which was of special

[1] Vol. lxxxviii (1909), p. 673.

interest to British engineers at the present time, when reciprocity was so much to the fore. The Michigan Central Railroad was the best line in the whole of the North American continent for high speed. It was laid with rails rolled in Canadian mills, and it was laid in Canadian territory; and the new 16-hour trains between New York and Chicago were to be run over that road. He thought it was reciprocity indeed that the best express trains of the United States should run over Canadian territory. Mr. Moir had made a comparison of the cost of building the Detroit tunnel with the North River tunnel in New York, so far as the excavation was concerned. He presumed the tunnel to which Mr. Moir had referred was excavated, but the Hudson River tunnels were not excavated, because the material was so soft that the shields could be driven through with an admission of only 5 to 10 per cent. of the mud through the face of the shield, and that might vitiate any comparisons. The comparisons made by the Author of the relative merits of the direct-current, three-phase, and single-phase systems were extremely interesting. Referring to the subject of signalling, he did not know whether the latest methods of signalling on the New York Rapid-Transit Railway had been brought to the notice of The Institution. He had seen on that railway an apparatus which had struck him as being peculiarly ingenious. A series of short blocks approaching the stations were arranged to operate at certain time-intervals, so that if a train passing between any two of the blocks took less than a certain time, the brakes were applied and the train was pulled up before it reached the platform. Mr. Thomson.

Mr. F. HUDLESTON remarked that he had read the Paper with a great deal of interest, because it dealt with an entirely different class of subaqueous tunnels from those constructed in England, and therefore it naturally appealed to an English engineer. Mr. Moir had already pointed out that, so far as the costs were concerned, these did not come out any better than for shield-driven tunnels. In the present case he thought the costs would have been distinctly higher if it had been necessary to construct the tunnel under similar conditions to those that had to be faced occasionally in England. For instance, if the tunnel had had to be made in an open trench, in a river which had very strong currents, and a good deal of sand moving about in it, it would probably have been found almost impossible to keep the trench open long enough to sink the various sections of the tunnel. On the other hand, in a river like the Detroit River, where apparently there was no movement of sand, and where it was desirable to keep the tunnel as high as possible, engineers Mr. Hudleston.

Mr. Hudleston. would be driven to devise some arrangement of the kind adopted, because it would be almost impossible to drive a shield through bad soil of the description mentioned, within 3 or 4 feet of the river-bed. The shallowest tunnels constructed in England had been at least 7 or 8 feet below the bed, and even then more solid stuff was met with than the half-clay and half-silt present in the Detroit River. As the Author pointed out, there were many advantages in the method adopted. For instance, it was possible to get nearer the surface; the approach-tunnels were therefore shorter, and generally the mere fact that they were shorter made the work a good deal easier. Nevertheless, he did not think such a tunnel could have been constructed across the Thames, as the interruption of traffic caused by the presence of the dredgers would have been prohibitive. In sundry other estuaries in England the flow of sand was so large, and the movement of the sandbanks was so considerable, that in practice it would be impossible to keep the trench open long enough to sink the tunnel. He differed from Mr. Burge's view that the concrete lining of the tunnel need not have been reinforced. Had the engineers not reinforced the lining, but tried to keep it tight by caulking, sooner or later there would have been very severe hydrostatic pressure at the back, and if there were any movement through the concrete, the skin of the tube would have no power to resist such pressure. He would not say anything as to the exact amount of the reinforcement, but he considered that in principle the reinforcement was perfectly correct in such a case. During the time the tunnel was under construction it did not much matter if water did get in, because that could be relieved by drilling holes through, but to have left the tunnel unlined on the inside would, in his opinion, have been an impossible proceeding. With regard to Mr. Moir's remarks about settlement, he did not quite understand why there should be much settlement in the tunnel, because the pressure per square foot on the ground below the tunnel would not be very different from what it was before, unless the ground was extraordinarily soft. If settlement did occur, it would be rather awkward, because the leaks would be appalling; but he did not think there would be much settlement, because he noticed from the drawings that the tunnel was set down first on fairly strong grillages, and then, as the whole thing was concreted up, a very even pressure was obtained over the whole of the foundation. The pressure could not be much, because there was only 20 feet of solid concrete, which did not amount to much per square foot. The Paper was so full of detail that it was difficult to criticize it exhaustively. The only other point to which he wished to refer was the eminently simple method by which two adjacent sections of the tunnel had been connected (Figs. 16A and 17). There was a long pilot pin to guide the tube into place, and a spigot joint, which was a fairly easy piece of work. That was very elastic and would allow for a considerable degree of movement and settlement during construction and before the tunnel was finished. After it was finished and concreted up, it was difficult to conceive that there would be much settlement. Mr. Hudleston.

Mr. R. J. G. READ thought the Paper was exceedingly interesting, and the work to a large extent very original. A similar work had been carried out in Paris for the crossing of the River Seine, at two places, by the Metropolitan Railway. The tunnel was sunk into the bed of the river from the surface, but not exactly in the same way as that carried out by the Author. The French enclosed their tunnel—a single tube with two tracks—in a caisson, which was built round it in skeleton ironwork and concreted before sinking; when concreted it was sunk on to the bed of the river, and further depth was attained by excavating in an air-chamber under the bottom of the caisson. That work had been accomplished very successfully. As had been pointed out, a very large quantity of concrete had been used in the Detroit tunnel, but nothing like that quantity had been used in the French tunnels. After the River Seine had been crossed, the excavation was continued with a shield, in a manner somewhat similar to that adopted in constructing the tunnels under the River Thames. He noticed that in making the contract for the carrying out of the Detroit tunnel it was stipulated that the date of completion was to be the 1st June, 1909, and that a penalty was imposed on the contractor if he did not complete it by that time, while he was to receive a bonus of £200 per day if he completed it sooner. It was stated in the Paper that the tunnels were not completed till February, 1910, the first train running through on the 26th July of that year. He would like to know whether the penalties had been imposed, and, if not, what had been the reasons given for non-completion to time. Mr. Read.

Mr. DAVID HAY expressed his appreciation of the work and of the boldness, ingenuity, and skill displayed in carrying it out. Mr. Hudleston had spoken of the difficulty of carrying out such work in Great Britain, on account of the high velocity of the tides, and the consequent silting up. To a certain extent Mr. Hay agreed, but he thought this would only entail a little more dredging in the first instance or clearing out of the silt immediately before the tubes were placed in position, and the method would be well worth considering under certain conditions. About 40 years ago he Mr. Hay.

Mr. Hay. remembered seeing drawings of a scheme for tunnelling the Channel by submerged tubes. The idea, he believed, originated with Mr. J. Somes Story, M. Inst. C.E. The success of any such scheme, however, must be entirely dependent upon the feasibility of depositing the concrete under and around the tubes, and the system described by the Author, which was new to Mr. Hay, seemed to be admirable for its purpose. In a work where the main difficulty had been so successfully met, it seemed rather ungracious to criticize adversely any of the minor works, but he wished to say a word on the subject of the approach-tunnels. The work had evidently been carried out in three stages: first a tunnel for the centre wall, and then the two side tunnels. That must have been a very expensive proceeding, and opening the ground three times must have caused serious subsidence and consequent damage to the property above. It would have been more economical, he thought, to have constructed two entirely separate tunnels on each side of the river. The 18-foot headway above the rails appeared large, but no doubt there was reason for it. Although not familiar with American prices, he thought two tunnels 20 feet in internal diameter, with cast-iron lining, might have been constructed, apart from contractors' profits, for £200 per lineal yard for the double tunnel. In that way the 1,800 yards of tunnel would have cost about £360,000, as against the actual cost of £572,000, a difference of over £200,000, apart altogether from the damage to property, which must have been very considerable.

Mr. Copperthwaite. Mr. W. C. Copperthwaite thought the Paper described a remarkable instance of the value of imagination in engineering. Given certain conditions, the work had been so arranged that it had been carried out exactly in a manner suited to those conditions. He was not, however, prepared to say, as the Author did, that the system was in any sense a substitute for the English method of driving subaqueous tunnels by means of a shield and cast-iron lining—a method connected with the name of Mr. Greathead. It seemed that the conditions under which the work had been done were entirely special. In order to carry out such a work satisfactorily it would have to be done under a waterway where there was no very rapid current, or, at any rate, where there was a regular current; secondly, it must be in a waterway where the material of the river-bed would not silt up; and thirdly, and perhaps as important a point as any, the waterway must be under the control of authorities who were tolerably complaisant. He could not imagine obtaining such special privileges on the River Thames, nor could be imagine that any trench dug in the Thames in the manner shown by the Author could possibly be kept clean enough to enable concrete to be laid down which would

Mr. Copperthwaite.

be in any degree watertight. Neither could he imagine mooring on a river like the Thames, say between Vauxhall Bridge and London Bridge, where the current ran at times at the rate of 4 knots per hour, barges depositing concrete in a comparatively limited space underneath. But, of course, this criticism did not affect in any way the extraordinary merit of the method described in the Paper, in the particular place where it had been carried out. It had been proposed twice in England to carry out a large subaqueous tunnel-work by lowering a tunnel, so to speak, in blocks. The first case was on the Humber, and the scheme was prepared by the late Sir Benjamin Baker, Past-President Inst. C.E., who proposed to lower a double brick tunnel, in lengths of about 50 or 60 feet, into places dredged for them, and, having joined them as closely as possible, to cover the joints with lead sheeting placed on by divers. Then the water was to be pumped out and the tunnel gradually closed. He accepted the information given to him by Sir Benjamin, but had a feeling that he would rather be directing the work from the surface than from underneath. The other case was in connection with the Blackwall Tunnel. One of the numerous schemes considered by the Engineer of the London County Council was a project for lowering the tunnel in one length. It was suggested that a trench should be dredged and a steel tube built and lowered into it. That scheme was put on one side on account of the natural difficulties of the river, and the tunnel was carried out by the now ordinary English method. There was one matter upon which he would like to have some information, namely, the shields. Mr. Hay had already criticized the method of carrying out the approach-tunnels, and it did look extraordinary. Two separate tunnels would probably have been much better, and certainly they would have been easier to make. As he understood the Paper, the approach-tunnels were commenced with the idea of building them by timbering. He could not understand why, when the engineers found they had to use a shield, they built a shield which was certain to give trouble in guiding. It seemed to him, from his experience of shield work, that if, instead of being made semicircular, the shield had been made with a flattened base, it would have travelled much more easily and have kept in line. No doubt the engineer had had a good reason for making it in the way he did, but it could not be in order to save material, because the saving in that respect would be very slight in comparison with the trouble and labour involved in keeping the shield in line. With regard to the question of cost, the Author stated that the tunnel under the Detroit River worked out at 4*s*. 6*d*. per cubic foot of content. It might be of interest to

Mr. Copperthwaite. give the cost of some similar work in London. In ordinary London clay, where for certain reasons it was necessary to work under compressed air, an ordinary "tube" railway-tunnel cost about 3*s.* per cubic foot of content. That included nothing for rails or roadway, the 3*s.* being the actual cost of making a reasonably watertight tunnel. In the case of a tunnel like those at Blackwall and Rotherhithe the prices ranged between 4*s.* 2*d.* and 5*s.* $1\frac{1}{2}$*d.* per cubic foot of content. Then there was the curious case—particularly interesting in connection with the subject under discussion, and especially in connection with Mr. Hay's suggestion that it would have been much cheaper to build two separate tunnels—of the Glasgow tunnels, which consisted of three tunnels side by side. Instead of building one large tunnel for the roadway and footway tunnels they built two road-tunnels, one for the traffic in one direction and one for the traffic in the other, and a footway tunnel. The cost of those tunnels was only 2*s.* 6*d.* per cubic foot of content. Adding 50 per cent. for American prices, in a case such as that described by the Author, where the labour cost nearly as much as the material, the cost of the Glasgow tunnel was something under 4*s.*; and the Author only claimed that the cost of his tunnel was 4*s.* 6*d.* Under similar conditions, therefore, there was very little difference between a 16-foot tunnel constructed in Glasgow and a tunnel with an 18-foot headway constructed in Detroit by the particular method described.

Mr. Monkhouse. Mr. E. W. Monkhouse endorsed what had been said as to the importance of the Paper and the care that had been taken to overcome the difficulties. Some of the arrangements appealed to him, as a mechanical engineer, very strongly. He had tried to put himself in the position of the man who had to lower the tubes into the water and connect them up, and had tried to see the difficulties to be overcome to get them into position. Although a great many details of those difficulties were set out in the Paper, there were others which it would be of advantage to have noticed. To lower a tube 250 feet long on to a grillage, as the tubes had been lowered at Detroit, so that the holes of the adjacent ends of two tubes came opposite one another, must have been very difficult; and the whole of the slinging arrangements must have been extraordinarily accurate in order that the pilot-pins might be of use in getting the tubes into their exact places. The diaphragms around the tubes must also have been made very accurately, because if the tubes had been the least bit off the square neither the pins and their sockets nor the bolt-holes of adjacent sections would have come opposite to each other. Again, if the tubes had been a very

Mr. Monkhouse.

small amount out of level across the river, they would have had to be raised, and a 250-foot tube could not be hove up by bolts without probably tearing the flange off, because the tube was only of $\frac{3}{8}$-inch metal and the flanges were not large. Therefore, the tubes must have been set very accurately in level and line. The difficulties of fixing barges so as to lower tubes of that kind on to the bed of a river in a tideway were very great. He had had some experience of mooring ships and other things in dry docks, and he knew something of the difficulty of getting any ship or structure affected by the wind to settle down in a particular position. The scows were standing on four legs which did not seem to be raked at all. The moorings must have been very rigid, otherwise there would seem to be a danger of the spuds "capsizing." The barges in the Thames which worked with hand-dredgers for dredging up ballast were fixed by spuds, but those spuds were inclined at an angle. The barges were moored by anchors fore and aft, and were fixed sideways by the spuds; otherwise the dredges would slue them out of their proper position. The Detroit spuds were said to be extensible, and he would like to know what the mechanical arrangement was for extending them, and whether, in order to get the derrick properly fixed on the spuds, the weight of the scows was taken on the spuds, and what means were adopted for doing this, so as to get a firm seating on the ground. The profile of the tunnel was more or less curved, and he would like to know whether the lengths of tube had been made to fit that profile, or whether the radius was so long that the tubes could be hove up together so that the joints met. The rubber joints would no doubt give a little, but it did not seem to him they would give enough if there were any considerable curvature in the profile. The method of getting the concrete to the bottom of the river was very ingenious, but how had the concrete been got underneath the tubes? It seemed easy to get it in between them or at the sides, but not so easy to get it underneath them, or to ensure that the concrete underneath the tubes was really solid. Had the divers pushed it under, or had it been left to chance to flow under? The Author spoke of prodding holes in the bottom of the river so as to get in concrete piers on which to put the concrete raft, and Mr. Monkhouse would like to know what those prodding tremies were like; he thought they must be some kind of boring-machine. If a tube of any kind were prodded into the clay, the core would have to be removed from the tube before the concrete was put down, but nothing was said about that in the Paper. He would like to know what means of communication were adopted between the divers and the men on the

Mr. Monkhouse. scows, and between the divers themselves, as it would seem that some communication would be necessary, especially in the process of setting the tubes. As to the electrical arrangements, he agreed with the Author in his adoption of continuous rather than alternating current; not because he thought alternating current was in any way less reliable than continuous, but because, for the work under consideration, continuous current seemed to be quite as good as alternating and somewhat less complicated. One of the reasons given for making a contract with the Detroit Edison Company for the supply of current was that the Tunnel Company would be able to call on the supply-company at any time for any power they wanted. The contract might have been wise, because it had saved the Tunnel Company from spending capital on a generating-station, but it did not seem that with the arrangements made they could call on the Edison Company for any quantity of power at a moment's notice. The Edison Company supplied three-phase current, and had installed at the tunnel two 1,000-kilowatt motor-generators. Motor-generators of that size transforming from three-phase current at a certain pressure down to continuous current at some other pressure were not to be bought over the counter, so that the Edison Company could not really be called on for any excess power at a moment's notice. From the point of view of reliability, therefore, there did not seem to be much in it, as the power that would be necessary to take an 800-ton goods-train up the incline of 1 in 50 at 10 miles per hour was just under 890 kilowatts, which was fairly near the full load for one machine, so that there was only one machine to spare. It would be interesting to know what price was paid per kilowatt-year to the Edison Company, and also what price was paid per unit; but perhaps that was a question that should not really be asked.

Mr. Moir. Mr. E. W. Moir thought that Mr. Copperthwaite might have taken his figures from the gross prices including contractor's profit, whereas the Author quoted net prices. Further, the Author had added only about 15 per cent. for certain charges which were undefined. It would be interesting to know what that 15 per cent. covered. If it was supposed to cover contractor's profit, depreciation of plant, and so on, it appeared to be less than any figure that he would consider sufficient for that purpose.

Mr. Tripp. Mr. W. B. Tripp mentioned that in 1873 there was a severe contest in the Houses of Parliament over a scheme for the Humber. It was a very ingenious design, on the principle of ordinary bridge-piers, sunk by means of the pneumatic process. It was considered that it would be just as easy to make a section of tunnel

Mr. Tripp.

through the air-chamber of the caisson as it would be to fill it with concrete; and that by sinking a sufficient number of piers in line with one another, it might be possible to get a succession of sections of a tube, so that when they were completed all that would have to be done would be to join them up and withdraw the caissons. That was worked out for the Humber, the scheme involving the use of three working-vessels, each 160 feet long. The middle vessel was to be a pontoon 160 feet long, 42 feet wide, and 12 feet deep. Underneath the pontoon there was the ordinary air-chamber, and elevated above it on columns was a working-deck clear of the water. That was to be floated out at slack water of flood-tide and sunk. There was various apparatus connected with the vessels, and screw-piles to support and give an even bed in the river. When sunk down about 24 feet below the river-bed the top of the pontoon would be level with the bed of the river, and a number of air-tight ballast-barges were to be sunk on to the top of the pontoon, serving to weigh it down and also to prevent the sand from accumulating on the top and preventing the caissons from being floated. The lower half of a pair of single-line railway-tunnels was then to be constructed in the caisson; they were to have a head wall at each end, the inner half of the wall to be of brickwork and the outer half of weak mortar. When the lower half had been built, the caisson was to be lifted and the upper half built in the same way. Puddle was to be put into the cavities left by the columns of the air-chamber. One section was to be completed and the ballast-barges floated off, and then the vessel was to be floated up and sunk again as near as possible to the end of the completed section. The end of the caisson was to shear through the weak mortar that had been left to keep out the sand, and then the new section was to be proceeded with in the same way. The novelty was in the joining up, which was to be done by raising the caisson 9 inches at a time, and the bricklayers were supposed to reach out underneath the end of the caisson and fit the bricks into the toothing of the last section. It was said there would be no difficulty in doing that because it had been practically carried out. Then another section would be done, and the whole thing thus carried right across the Humber. The scheme passed the House of Commons after a fight, but was thrown out by the House of Lords on the ground that it was impracticable. It was an ingenious scheme, and some of the details might not be unworthy of being placed on record.

Mr. Mordey.

Mr. W. M. Mordey remarked that, like most modern engineering problems, the one under discussion was partly electrical, and electrical engineers would have been very glad if the Author had

Mr. Mordey. added to his interesting Paper more details of the methods employed and of the reasons that had led him to the choice of his system of driving. It was satisfactory to find that it was a recognition of the possibilities of electric driving that had led to the construction of the work. In the Paper a little Table was given showing a great difference in capital cost and in working-cost between the direct-current system, the three-phase system and the single-phase system. According to that Table the capital cost of the single-phase system was about 32 per cent. higher than that of the direct-current, and the annual working-costs were about 20 per cent. higher. He was not speaking as an advocate of alternating-current work or of single-phase working, but he thought the Table taken by itself, in view of the conditions of the work, might lead to some misapprehension. He would like to direct attention to the problem the Author had to solve. It was quite a simple problem, namely, to work a railway $1\frac{1}{2}$ mile long with less than forty trains per day. That was a very different problem from railway electrification in the broad sense. It might be remembered that 9 years ago Mr. Bernard Jenkin and he had the honour of reading a Paper at the Institution on the Electrical Working of Railways. They examined all the known systems with a view to find out which was the system having the fewest disadvantages for railway electrification generally, and they arrived at the conclusion that although the single-phase system had serious disadvantages in some directions—disadvantages that had been partly removed in the last 9 years—that system offered fewer disadvantages than any other electric system for railway working on a broad and comprehensive scale. They directed their attention to finding out what was the best method, not merely of working a short town section with a very heavy traffic, but of making that town section part of a large railway system, and they came to the conclusion that in dealing with problems of railway working—dealing with them of course as electrical engineers only, and considering main-line working, long-distance traffic, express trains at high speeds, frequent trains with many stops and with rapid acceleration and rapid retardation, and so on—on the whole the direct-current system, necessarily more or less low-tension, was not as good as a high-tension alternating-current system capable of simple transformation; and that of the various alternating-current methods the single-phase system offered the fewest disadvantages. He did not put it higher than that. The Author had not helped towards the elucidation of that problem, and indeed had not set out to do so. Mr. Mordey wished to ask members not to take the little Table on p. 32—which he had no doubt was perfectly accurate and fair—showing a very unfavourable comparison between direct- and alternating-current working, as necessarily condemning the latter system. It merely showed, he thought, that the Author had been perfectly right in choosing the former system for the limited and quite simple requirements that he had before him. Mr. Mordey.

Mr. J. SAYERS concurred in the remarks of the last speaker. Mr. Sayers. Unless it was remembered that the Detroit work was a very special and limited problem—the working of a short section of line in the middle of a steam line—the Table in question would be very misleading. He also held no brief for any particular system of working railways, but he happened to have had experience of single-phase work, and he certainly could not imagine how, even for that length, those figures had been obtained. He referred particularly to the cost, and without questioning the accuracy of the Table he would be very pleased to have some details, if possible, of the respective rival tenders. Those remarks applied to maintenance as well as to capital cost. It was stated in the Paper that in estimating for the single-phase or three-phase equipments the contractors had to allow for any extra cost in increasing the headway, and that he could not understand. The tunnel as made allowed plenty of headway for a high-tension conductor, because there was 18 feet from the top to the rail-level. On the Heysham branch of the Midland Railway there was only 13 feet 10 inches in places, and it had been rather a difficult problem there because on a steam railway allowance had to be made for the steam-engines; but with 18 feet there would be plenty of room for insulation. Really and truly, the problem was not between continuous current and alternating current, but between high pressure and low pressure. At present the continuous current for the third rail had necessarily to be at a low pressure on account of difficulties of insulation, but if a continuous-current system could be worked directly from the contact-wire at high pressure, he thought it would be the simplest problem of all. He was not quite clear what the ducts shown in the diagram were for. As there was only one contact-rail, he concluded that the current came back by the running-rails. It was generally understood to be the better practice to have the return-current brought back by a conductor-rail.

Mr. F. HUDLESTON thought Mr. Sayers was under a slight misapprehension. Mr. Hudleston. The American loading-gauge was much larger than the English, and there was nothing like the clearance there would be in a tunnel of that size with the English loading-gauge.

Mr. E. W. MOIR believed the East River tunnels were about 16 feet 3 inches from the rail to the underside of the crown. Mr. Moir.

Mr. Dawson. Mr. WILLIAM DAWSON remarked that 18 feet was about the standard headway of American tunnels measuring to the crown of the arch. The maximum height of a locomotive in England was 13 feet 6 inches, but in America they were built up to 16 feet high. The Paper specially interested him because about 5 years ago, in travelling from Niagara Falls to Chicago by the Michigan Central Railroad he had to cross the river at Detroit. The train of twelve coaches was run on to ferry-steamers in three rows of four coaches each, and the operation took about 35 minutes. Mr. Kinnear, the Chief Engineer of the Detroit Tunnel, happened to be travelling in the same train and told him they were about to construct a tunnel underneath the river; and he thought the manner in which the work had been done reflected great credit, not only on the designers, but also on the contractors who carried out the works. It did not seem to him that the method of holding the sleeper-blocks down was altogether satisfactory, as they rested in a channel of concrete, secured only by a small dowel. He would have thought that the upward movement on the conductor-rail and the downward movement on the running-rail would have produced a tendency for the sleeper-blocks to become loose. The flat-bottomed rail was adopted, he presumed, because sleepers of hard wood, such as oak, cedar, or chestnut, were used, whereas in England chairs had to be used in order to distribute the weight over the softer sleeper, which consisted mostly of northern pine (*Pinus sylvestris*). He thought the Americans were gradually coming to the English type of permanent way, because on many of their roads they placed a flat plate underneath the rail for the purpose of distributing the weight over the sleeper, and they also fixed brackets alongside the rail around curves, which practically corresponded with the English chairs. He noticed that the percentage of carbon in the rails was much higher than was adopted in England, the upper limit being as high as 0·75 per cent. He would like to know whether the determination had been made by total combustion, or by what was known as the Eggertz colour-test: 0·75 per cent. seemed a very high percentage in rails for passenger-lines; it was 50 per cent. more than was recommended by the British Engineering Standards Committee.

The Author. The AUTHOR, in reply, expressed his gratification at the courteous reception of his Paper by The Institution and by those who had been good enough to participate in the discussion. No difficulty had been experienced in keeping the subaqueous trench free from silt or drifting material. Just before sinking the tubes, any loose

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material was removed by dredging; and later, in advance of the depositing of concrete by the tremie, all sediment was sucked out by pumping from the scow above. He had observed that even in such loose materials as river-silt in the vicinity of New York, comparatively little trouble was experienced from sloughing in of the sides of the dredged channels after the slopes had reached their proper angle. As to the settlement referred to by Mr. Moir, this had been experienced more or less in all subaqueous tunnels through soft materials during the period of adjustment to surrounding conditions, as, for instance, in the several tunnels at New York City and elsewhere. Since the establishment more than a year ago, of the final levels, and the commencement of regular traffic, there had been no settlement whatever, and in fact, as remarked by Mr. Hudleston, it was not to be expected, seeing that the load per square foot on the underlying material (1,680 lbs.) was no greater—indeed even less—than it had been under the original conditions (2,175 lbs.). The adoption of the reinforcement referred to by Mr. Burge had arisen from the desire to secure a structure that would distribute loads without danger of cracks from unequal settlement or changes of temperature, especially in anticipation of possible corrosion of the steel tubes in after years. The insistence upon an inner lining continuous from shore to shore and of sufficient strength to distribute stresses as well as to resist hydrostatic pressure, had been one of the reasons that had led to the rejection of other trench methods involving the use of jointed lining. In connection with the remarks of Mr. Moir and Mr. Read, the employment of a permeable material, such as sand, around the exterior of the tubes had been discussed but not considered permissible, as a surrounding envelope of sufficient strength and watertightness was needed to prevent the collapse of the steel tubes after they were unwatered and pending the placing of the interior continuous lining or tunnel proper. Referring to the comments of Mr. Monkhouse, the care used in the shipyard in regard to the bolt-holes, pilot-pins, and sockets, and the temporary stiffening by radial rods and bulkheads, had prevented difficulty in joining the sections in situ. Cables anchored to heavy concrete "dead men" sunk to the river-bottom had held both scows and tubes in place against the force of the current. Little trouble had been experienced in operating the spuds by means of suitable devices on the scow. The radii of the vertical curves in the profile were so long that it was not necessary to build the tubes other than straight. No trouble had been experienced in working the concrete beneath the tubes, as the concrete had been mixed "wet" so as to flow easily under and around the tubes, rising gradually in each pocket to the full

The Author. height in such manner as to guarantee a solid mass. Prodding had been performed by the ordinary tremies, which were first permitted, while empty, to sink by gravity in the soft underlying clay, and then were slowly withdrawn as the concrete was fed in from the top, the weight of the column of concrete driving out the core of clay and at the same time pressing sideways so as to enlarge the hole and build up a column shaped somewhat like an inverted Christmas-tree. Communication between the divers had been effected by signals with which the men became very proficient, the telephone having been tried and abandoned. As to the episode mentioned by Mr. Burge, it had happened in one instance that the swell of a passing steamer, together with the efforts of a tug, had moved a misplaced section sufficiently to approximate to its correct position without lightening the load through the agency of the auxiliary cylinders. While all the contractor's details for achieving the specified result, including the method of building and sinking the tubes and connecting them by means of pilot-pins and circumferential bolts, had proved highly successful and well adapted to their purpose at Detroit, they were not necessary to the application of the general scheme in other places where the surrounding conditions or the ingenuity of the contractor might render desirable the employment of other details; as, for instance, the separation of the sections so as to permit the exterior concrete to flow not only around but also between them, and to form bulkheads that might be excavated later as the sections were unwatered. With regard to the approach-tunnel design referred to by Mr. Hay, Mr. Copperthwaite, and Mr. Moir, the use of the centre wall had been imposed by the necessity for keeping the two tracks as close together as possible, so as to not unduly spread apart the twin tubes of the subaqueous section; to facilitate the construction of the cross passages; and also to minimize the width of the open cuttings and thereby avoid interference with adjoining surface tracks. But for these considerations the use of separate tunnels would undoubtedly have been preferable. In answer to Mr. Moir's comparison of costs, the Author would explain that the section of the North River "McAdoo" tunnel, for which a cost of \$300 per lineal foot of single bore had been given, was about 60 per cent. of that of the Detroit tunnel-section, and that instances at New York more nearly comparable with Detroit would be those of the Pennsylvania Railroad tunnels, some of which, with a somewhat smaller cross section, were reported to have cost considerably over \$500 per lineal foot of single bore, exclusive of contractor's profits. The most rational comparison would be to take the Sarnia tunnel, having practically the same cross section and passing through similar material. The cost of this tunnel built by day labour, about 1890, with no contractor's profits, was said to have been $333 per lineal foot of single bore, this applying not to the under-river portion alone as taken by Mr. Moir, but to the entire distance between the portals, including both approaches. Compared with this amount the cost at Detroit was $273 per lineal foot of single bore, which sum, by the way, had included 15 per cent. for overhead charges but no contractor's profits, thus corresponding with the basis adopted for the "McAdoo" and Sarnia tunnels. Taking into account increases of 10 to 25 per cent. in the cost of labour and materials during the past 15 or 20 years, it might be conservatively stated that the cost of the Sarnia tunnel, on the basis of prices and costs during the period of the construction of the Detroit tunnel, would not be less than $350 to $375. Applying the lower of these prices to the situation at Detroit, in conjunction with the greater length of tunnel imposed by the necessity of placing the approach-tunnels about 10 feet lower, the comparative cost of construction, excluding contractor's profits, would be somewhat as follows:— The Author.

Compressed-Air-and-Shield Method Based on Up-to-date Sarnia Costs.

	Feet.
Length of Detroit tunnel between portals as built .	8,310
Extra length	1,167
	9,477

Total length of single bore, 18,954 feet at $350 . . =	$6,633,900

Adopted Method.

Total length of single bore as built, 16,620 feet at $273 =	4,544,900
Excess cost of compressed-air-and-shield method . . .	$2,089,000

Not only had there been this saving of more than $2,000,000 from the use of the method adopted, but also avoidance of danger to workmen from labouring in high air-pressures and poisonous gases which existed in the clay overlying bed-rock at this place, the saving due to not having to lift the traffic an additional 18 feet, and non-interference with existing tracks and stations in the neighbourhood of the tunnel-summits. While under suitable conditions the adopted method offered marked advantages as to cost, gradients, and efficiency of working, as remarked by Mr. Copperthwaite, it should not be considered applicable to situations where the compressed-air-and-shield method was peculiarly adapted. Every problem, of course, required the treatment best suited to its particular needs.

The Author. In reply to Mr. Read's inquiry, the penalty had not been collected, in view of the satisfactory work of the contractors and of certain delays that were beyond their control. With regard to the electrification, the net height of 18 feet in the tunnel was required by the railroad for equipment clearances, and therefore the cost of securing any greater height for overhead conductors had been considered to be a proper charge against the system requiring it. The contract for power gave to the railroad-company a range of demand ample to cover its greatest possible needs, the battery in the substation "floating on the line" so as to regulate sharp fluctuations as well as to store energy for the needs of service in excess of the capacity of the motor-generators, which, by the way, were built for 100 per cent. overload. As remarked by Mr. Mordey, it could not be claimed that the adoption of the direct-current system on a 4½-mile link in a trunk-line railroad could be considered as necessarily having any bearing on problems elsewhere with entirely different conditions; but it seemed proper to say that the result at Detroit pointed to the danger to the best interests of shareholders in a blind acceptance of the teachings of those who advocated the adoption of any one electrical system as a standard to be used in all cases, to the exclusion of other systems. As stated in the Paper, the adoption of that policy might have meant a loss to the company of about $40,000 per annum. The ducts referred to by Mr. Sayers were for high- and low-tension cables for propulsion, lighting, and pumping purposes, as well as for telephone- and telegraph-wires. The running-rails were utilized for the return of the propulsion-current, as that was the practice in America. The Author regretted that he was not at liberty to furnish the details of the rival tenders for electrification. In response to Mr. Dawson's question, the carbon determinations for the steel rails had been made by the colour-test, occasionally checked by total combustion. High percentages of carbon were found to be proper with open-hearth steel having low percentages of phosphorus and sulphur. In conclusion, the prices mentioned in the Paper did not purport to cover the total cost to the Tunnel Company, as they did not include the contractor's profit They did, however, embrace labour, materials, plant, and payments to sub-contractors, plus 15 per cent. for overhead charges. Those using the figures should, of course, vary them to suit local conditions, and a suitable amount should, of course, be added for profit if the work was to be done by contract, or for contingencies if it was to be done by day labour.