Paper No. 5056.[1]

"The Construction of the Mersey Tunnel."

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Correspondence.

Mr. J. I. GRAHAM observed that it was not generally realized that the proportion of carbon monoxide present in the exhaust gases of petrol-driven cars was as much as, or sometimes more than, 6 per cent. When that was understood, the danger of running the engine in a confined space such as a closed garage would be obvious. The inhalation of an atmosphere containing 1 per cent. of carbon monoxide, but having plenty of oxygen and being otherwise respirable, would be followed by insensibility after about 1 minute if hard work were being carried out, or in about 3 minutes if resting, whilst 0·3 per cent. would produce unconsciousness in about 5 minutes during work or 15 minutes if the subject were at rest. In an atmosphere containing 0·12 per cent., 45 minutes would produce disablement where hard work was being carried out, whereas at rest disablement would take place after about 2 hours. Even with 0·04 per cent., headache and discomfort would be evident after 45 minutes of hard work, and 0·02 per cent. would be responsible for headache in some cases after a couple of hours. In a recent Paper [2] the late Professor J. S. Haldane had discussed the physiological effects of small quantities of carbon monoxide, and showed why a limit of 0·025 per cent. was fixed for the carbon monoxide concentration. In that Paper he drew attention to the recent work of Dr. Esther Killick on acclimatization to a small concentration of carbon monoxide, a matter obviously of great importance to patrols and other people who had to be in the tunnel for a prolonged period. Dr. Killick had shown that acclimatization to, say, 0·02 per cent. might be such that the blood of the acclimatized person might only be saturated to less than two-thirds of the saturation of someone unacclimatized. Mr. Graham.

Valuable data had been published in a report [3] by the U.S. Bureau of Mines, which included many analyses of exhaust gases and figures for the production of carbon monoxide in cubic feet per hour. Owing

[1] p. 473 (April).

[2] "The Ventilation of Tunnels," Journal Inst. Heat. and Vent. E., vol. 4 (No. 37, 1936), p. 18.

[3] *Report of the New York State Bridge and Tunnel Commission to the Governor and Legislature of the State of New York*, 1921. Appendix No. 3, p. 91.

Mr. Graham. to the, in general, somewhat larger petrol-consumption of American cars compared with cars in Great Britain, it seemed probable that the figures for carbon-monoxide production given in that report were higher than the average production in Great Britain, apart from the question of vehicles fitted with diesel engines. As the Author had pointed out, the assumption that 1·5 cubic foot of carbon monoxide was emitted per minute per car was no doubt distinctly high. The authorities responsible for the control of the ventilation of the Holland tunnel had first fixed a limit of 0·04 per cent. of carbon monoxide, but when, at the request of the engineers of the Mersey tunnel, he had visited the Holland tunnel, he had been told that a lower limit had had to be arranged largely owing to the nuisance from mist and impaired visibility. Even with 0·025 per cent. the visibility had been reduced as a result of the suspended matter and condensing moisture expelled from the exhausts. The carbon-monoxide recorders installed in the Mersey tunnel ventilation-buildings were, in general, much the same as those fitted in the Holland tunnel, for the design of which Dr. S. H. Katz was responsible. The measurement of the carbon monoxide depended, as the Author had stated, on the oxidation of the carbon monoxide to carbon dioxide in the presence of a catalyst, which was a mixture of specially-prepared copper oxide and manganese dioxide. By means of a series of thermocouples arranged differentially, the heat of oxidation was indicated or recorded on instruments calibrated directly in parts of carbon monoxide per 10,000. For the plant to function satisfactorily it was essential for the air under test which was passing to the catalyst chambers to be very efficiently dried. In the original plant that had been done by passage through concentrated sulphuric acid, but as a result of a long series of tests in the Mining Research Laboratory at Birmingham, and in conjunction with the Kestner Evaporator Company and the Cambridge Instrument Company (who had been responsible for the production of the analysers and recording apparatus), a double-unit silica-gel drying plant had been supplied for each analyser. That method of drying the air had, he believed, resulted in a longer life for the catalyst, and was undoubtedly very much simpler from the point of view of operating the plant. The air under test was dried to a moisture content of under 0·01 grain per cubic foot.

The Author had pointed out that at the present time the carbon-monoxide content did not normally exceed one part in 10,000. Owing to the larger diameter of the Mersey tunnel the effect of a slight fog was, he thought, more apparent than a mist of similar concentration in the smaller Holland tunnel. At 0·01 per cent. of carbon monoxide the mist or fog, although appreciable, did not interfere with driving in the slightest. It was however, interesting to consider the effect of an increase in the number of diesel-engined vehicles. In his opinion, unless means were taken to remove the suspended matter from the exhaust of such vehicles the fog formed would be almost more objectionable than the vitiation of the atmosphere by carbon monoxide. He had tested the exhaust gases from a number of diesel engines, more particularly those designed for use as mine locomotives, and as a rule he had found that, as compared with petrol engines, only about one-tenth the quantity of carbon monoxide was formed, and even less when the engine was running efficiently under full load. Mr. Graham.

Another matter connected with the construction of the tunnel, and one which was, he thought, of interest, was the possibility of the production of a harmful atmosphere during cement-proofing through the production of finely-divided silica. He had investigated that possibility at the request of the late Professor J. S. Haldane, and had found that the very fine dust, which was of particle size less than 10 microns, suspended in the air during that operation had consisted practically all of cement-dust, the free silica forming under 1 per cent. There was thus no danger of workmen developing silicosis in such operations.

Professor DOUGLAS HAY pointed out that attention had already been drawn to the considerable part played by the ventilation-system in the design and construction of the Mersey tunnel. It was inevitable that the newness of the problem should have brought many anxious moments to the engineers responsible, whilst the great dimensions and layout of the tunnel made the problem more difficult. It had been wisely decided to await the opening of the Holland tunnel and to profit as far as possible by the experience that would then become available, but even so the essential differences between a pair of one-way tunnels and a single tunnel of large diameter had left a problem requiring careful examination. The decision to complete as rapidly as possible a 1,000-foot section of the tunnel under Hamilton square and to carry out therein full-scale tests had made it possible to arrive at a complete solution. By dint of hard work on the part of all concerned, little or no delay had resulted before the tunnel was opened for traffic. In carrying out the experiments at Hamilton street three issues presented themselves. Firstly, the proper manner of coursing the air-currents through the traffic space had to be determined. Secondly, the most efficient method of admitting air into the traffic-space had to be found; and, thirdly, it was necessary to discover what was the best type of ventilating fan to use. Professor Hay.

Under the first heading the principal question had been as to whether or not the full transverse system, with top ceiling-duct, Professor Hay. used in the Holland tunnel was essential or desirable at Liverpool. The upper duct made no difference to the dilution of noxious gases obtained with a given fresh-air admission ; it spoilt the appearance of the tunnel, was costly to build, and required considerably more power in use. At Liverpool an additional annual cost of about £4,000 a year for electricity would have been entailed. It appeared to have some advantages in case of fire, but in a large-diameter tunnel those advantages were not so apparent. The decision had therefore been taken to omit the ceiling-duct, and experience gained during the past 18 months had confirmed the wisdom of that step. It was, in fact, doubtful whether its use was justified even in a small-diameter tunnel.

With regard to the second point, experiments had been carried out at Hamilton street to determine the best design of air-admission slot through the road-deck; various model slots had been set up in lengths, and the resulting mode of air-admission tested, until an even and smooth flow of air had finally been obtained. Pressure losses in the air-ducts and slots and at bends had been measured, and as a result modifications had been made in the duct-system to reduce losses to a minimum. It was rarely realized how much power could be lost at a badly-designed bend. Actual losses of 80 horse-power at a single right-angled bend had been measured under full-quantity conditions, so that the care taken in streamlining bends wherever possible was fully justified.

Finally, it had been a cause of great regret that the compact type of axial-flow or propeller fan had proved to be too inefficient and noisy. At the time the tunnel had been built the design of such fans had been in too early a stage for commercial adoption on the large scale required; since the opening of the tunnel, however, design had proceeded rapidly and commercial experience had been gained, and in future tunnels the propeller fan would demand consideration. Its adoption would effect large savings in the building space and duct-system required.

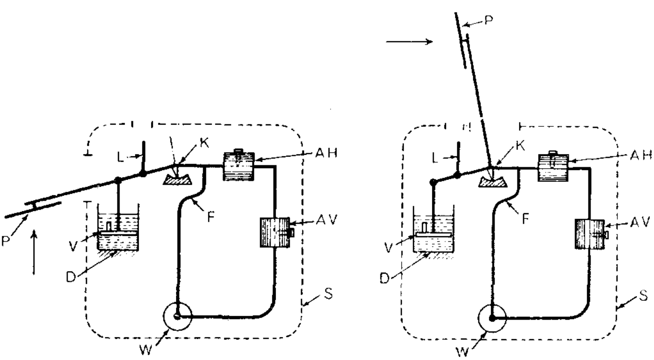
The care taken in considering the design of the ventilation-system and the costly experiments made had, however, justified themselves by the results. The ventilation-system had given no trouble, and its maintenance over a period of years ought to be low. The experience gained at Liverpool would be of great advantage in the design and construction of future tunnels; it was likely that the road tunnel might prove popular in the future, not only in solving cross-river-transport problems but for meeting land-transport problems in densely-populated areas.

Mr. Hodgson. Mr. J. L. HODGSON observed that the meters he had designed for measuring the air-flows in the various ventilation-ducts of the tunnel were similar to those which he had previously designed for measuring the ventilation-air in the ducts of the Mount Victoria tunnel in New Zealand. In the case of the Mersey tunnel, the air-flow was measured at sixteen points in the ducts, indicated electrically in the six fan-control rooms, and recorded electrically in the central control room. Mr. Hodgson.

The meters were of the impact-plate weight-controlled type. Movements of the arm carrying the impact-plate operated an electrical potentiometer to which the indicating and recording instruments were connected. The range of accurate flow-measurement was 1 to 5. The size of impact-plate used varied with the maximum air-velocity to be measured so as to ensure approximately the same operating force at the same fraction of full flow in all cases. The maximum force on the plate was about 1 lb. Five sizes of plate,

Figs. 15.

(*a*) (*b*)



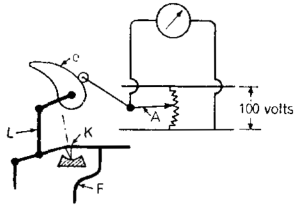
Alternative Types of Impact-Plate Transmitters.

ranging from $8\frac{1}{2}$ inches to 17 inches in diameter, were used to cover a range of maximum air-velocities varying from 15 to 60 feet per second. The impact-plate type of meter was used in preference to a Pitot tube and an oil-sealed bell on account of the ease with which it enabled the low air-velocities to be measured with accuracy. (The Pitot head corresponding to an air-velocity of 3 feet per second was only about $\frac{1}{500}$ inch of water, whereas the force on an impact-plate was about $\frac{1}{25}$ lb.)

There were two designs of the impact-plate transmitters, one for the vertical and the other for the horizontal ducts, as illustrated diagrammatically in *Figs. 15*. P was the impact-plate, W was the pendulum-weight, AH and AV were the horizontal and vertical adjustment-weights respectively, and K was a knife-edge on which the frame F carrying the above parts operated. The contact-surfaces of the knife-edge and its bearing were covered with mercury

Mr. Hodgson. (not shown) in order to keep them free from grit and dust. A valve V enabled the damping of the dashpot D to be readily adjusted. The whole of the mechanism was enclosed in a metal shield S. The arm carrying the impact-plate projected through a slot in the shield, and its angular movement was about 11 degrees on either side of the mean position. The variation of the flow-coefficient of the plate with angularity of presentation, and with the VDW/μ value of the plate and duct, was allowed for on the cam C shown in *Fig. 16*. The cam, which was connected to the frame F by the link L, operated a potentiometer arm A, and the cam and potentiometer were enclosed in a dust-tight box. The electrical circuit for the non-summation instruments was shown in *Fig. 16*. A voltage-controlled motor-generator maintained a constant difference of potential across the terminals of the bus-bars to which each of the indicating and recording instruments were connected. The use of the variable

Fig. 16.

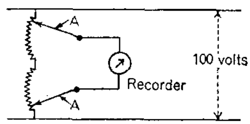


POTENTIOMETER AND CONNECTIONS.

pendulum-weight W enabled larger plates to be used at the higher maximum velocities than would otherwise have been possible. It was desirable to have as large plates as possible at the high velocities in order to ensure that the "impact" forces depended upon the size of plate in use, rather than upon the air-resistance of the arm to which the plate was fixed.

When installing the meters, many new problems had to be faced, as the flows had to be metered both immediately after bends and immediately after fan-outlets. The general method adopted had been to choose from the drawings those measuring stations which seemed to be most suitable, and then to check the positions by actual inspection of the sites. Removable Pitot tubes on permanent brackets had been installed at points about 10 feet upstream of each of the chosen stations. At each of those points the duct to be calibrated had been divided into squares about 2 feet across by means of wires attached to its walls, so as to define the positions at which the air-velocity was measured. The removable Pitot tube had then been calibrated with the air flowing through the duct at several velocities for each of the two fans provided. Any variation in the fan speed during a test had been shown by a variation in the reading of the removable Pitot tube, and all such variations had been corrected for before working out the velocity coefficient of the removable Pitot tube for the particular measuring station. Having ascertained that the measuring station chosen was a suitable one, and having calibrated the removable Pitot tube with each of the two fans in operation, it was an easy matter at any subsequent date to install and adjust the impact-plate transmitter. Mr. Hodgson.

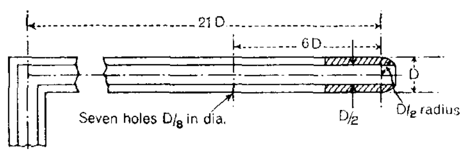
Fig. 17.



SUMMATION CIRCUIT.

Out of the fifteen measuring stations that had been so chosen, only one had proved to be unsuitable. In that case a permanent eddy, giving negative velocities, had formed on the one side of the duct. Also, the direction of the air-velocity in the tunnel itself had been found to affect the velocity at the chosen measuring point owing to the measuring point being too close to the exhaust-ceiling. As that particular duct branched higher up, measuring points in each of the branches were chosen, the potentiometers of the transmitters installed in the branches being connected in series as shown in *Fig. 17*.

Fig. 18.



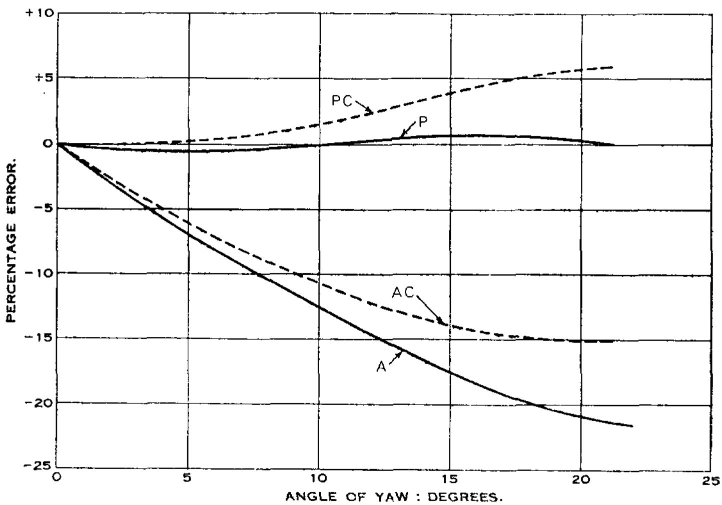
SPHERICAL-ENDED PITOT TUBE.

As the air-flow in the ducts was seldom parallel to their axes, the type of Pitot tube chosen (*Fig. 18*) was an adaptation of the spherical-ended Pitot tube described by Messrs. Ower and Johansen.[1] That type of Pitot tube had very small yaw-errors, and had been recommended by Mr. Hodgson for the original calibrations on which the size of the Mersey tunnel fans had been based. It had been found that when the readings of that Pitot tube were compared with those of certain anemometers commonly used in mining practice, very

[1] E. Ower and F. C. Johansen, "The Design of Pitot-Static Tubes," Technical Report of the Aeronautical Research Committee. R. & M. No. 981. H.M. Stationery Office, 1927.

Mr. Hodgson. considerable discrepancies occurred owing to those anemometers not being insensitive to yaw-error. To prove that it was the anemometers that were in error, he had had both the anemometers and the Pitot tube checked in a pulsating fan outlet, the intake air to the fan having been measured by means of a large plate-orifice for which the coefficient had been determined by his previous work. *Fig. 19* showed the results of those tests. Curves P and A showed the inaccuracies of the velocity measurement for the Pitot tube and the anemometer respectively when tested at various angles of yaw. Curves PC and AC showed those inaccuracies corrected for the cosine error, so that the measured velocity was resolved parallel to

Fig. 19.

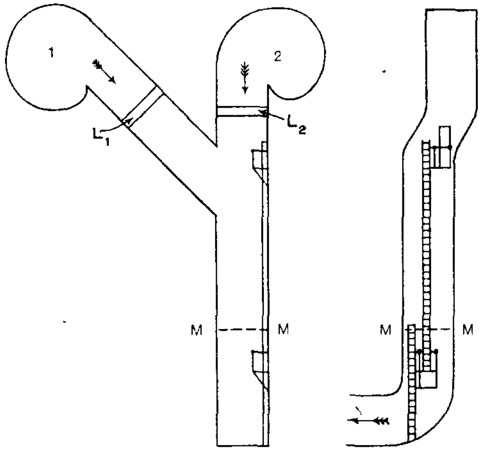


YAW-ERRORS FOR PITOT TUBES AND ANEMOMETERS.

the axis of the duct. Those curves indicated that even when the anemometer error was 10 per cent. (as was frequently the case), the spherical-ended Pitot-tube error would only be about 1·0 per cent. The matter was of considerable importance in connection with mine-air and fan measurements, as the anemometers tested had been of types approved and relied upon by mining experts. The reason why that large discrepancy between Pitot tube and anemometer readings had not previously been discovered was that anemometers were calibrated in wind-tunnels from which eddies and flow-irregularities had been carefully eliminated. The air-flow in the ducts had been frequently very gusty, variations of from 8 to 10 per cent. during 30 seconds in the velocity at a particular point being of common occurrence. Very often when the velocity rose at one point in the cross

Figs. 20.

Mr. Hodgson.

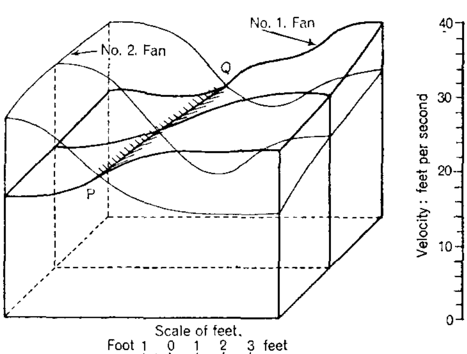


TAYLOR STREET BLOWING FANS AND DUCTS.

section of the duct, it fell at another. In spite of that gustiness, it was found that, by taking average readings over a period of time, very consistent results could be obtained, both when calibrating the standard Pitot positions, and when setting the impact-plate transmitters against the standard Pitot-tube readings.

A further difficulty which had had to be overcome had been that of using one transmitter at a measuring section such as MM (*Figs. 20*), where either of the fans 1 and 2 might blow through the louvres L_1 and L_2 respectively. He had overcome that difficulty by plotting velocity-distribution surfaces for the duct for the same total air-

Fig. 21.



AIR-VELOCITY CONTOURS OBTAINED AT MM IN *Figs. 20*

Mr. Hodgson. flows (*Fig. 21*), and then placing the impact-plate of the transmitter somewhere on PQ, the line of intersection of those surfaces.

The traversing Pitot tube had been carried at the end of a 12-foot bamboo pole, and could be adjusted so as always to face the flow. It could thus be kept well upstream of the observer. The importance of that point had been brought home when calibrating some of the smaller ducts, where the presence of the observer had affected the flow-distribution to such an extent that the final readings had had to be taken without any observer being present in the duct. The interference which might be caused by the body of an observer was often not sufficiently realized when making air-measurements in mines.

Mr. Neelands. Mr. A. R. Neelands had been associated with the preliminary work at the Mersey tunnel and had kept in fairly intimate touch with the progress of the work. He pointed out that the decision of the engineers to adopt cementation had met with a certain amount of criticism, but if the problem which confronted them at the outset were carefully considered, it would be seen that the decision had been justified. Certain information as to the amount of water pumped during the construction of the Mersey Railway had been available, and it had been known that 9,000 gallons per minute had been pumped from headings driven at a higher level than that of the proposed road-tunnel. Bunter Sandstone was notably capricious in its yield of water, and therefore at that time it had been practically impossible to assess what pumping capacity would be required to keep the workings dry. It had been known from the records of several shaft-sinkings that Red Sandstone could be successfully treated and from 85 to 95 per cent. of the water sealed, and cementation was therefore an insurance at a comparatively small cost (2·7 per cent. of the total cost) against possible delays and increased expenditure in all directions due to the difficulties of permanent construction in the presence of continuous and heavy feeders of water.

The restrictions imposed upon the pressure allowed had created an interesting problem for the cementation contractors. In shaft-sinking to depths of 1,000 feet or more in Red Sandstone, pressures up to 2,000 lbs. per square inch had been used. The permissible pressure at the Mersey tunnel had been 50 lbs. per square inch plus the static head. It would be seen therefore that the technique of cementation had had to be altered considerably to meet the new conditions. Generally that alteration had taken the form of increasing the volume of chemicals and decreasing the volume of cement; that expedient had been successful, although the results had not been so satisfactory as those obtained where there were no pressure restrictions.

It might be of some interest to assess the value of the process when operated with pressure restrictions. The total residual feeder from the shaft excavation, after cementation with no artificial pressure limits, had been found on 24 September, 1930, to be 32·5 gallons per minute. Information as to the quantities pumped during the excavation of the adjoining Mersey Railway shaft was not precise, but about 5,000 gallons per minute appeared to have been handled. Mr. Neelands.

The total length of the drainage heading was approximately 1,500 feet. Partial cementation had been carried out after driving from chainage 300 feet to chainage 565 feet, and pre-cementation from chainage 736 feet to chainage 862 feet, a total of 265 feet plus 126 feet, or 391 feet. In those lengths the residual water had been weired where possible, and measurements giving a value of about 0·6 gallon per minute per foot-run had been obtained. The total residual flow from the heading had been 4,000 gallons per minute or 3·4 gallons per foot-run over the untreated parts. If the make of water over the drainage heading had been uniform after excavation the percentage which had been sealed by restricted cementation and silicatization was 77·5.

The Author gave a figure of 4,200 gallons per minute as the quantity pumped from the Liverpool shaft at one period. As the drainage heading feeder was 4,000 gallons per minute, the total from the tunnel and shaft excavation proper had been 200 gallons per minute, which did not appear an unduly large quantity when the size of the excavation was considered. The method appeared to have been justified by the results, and the Mersey tunnel operations certainly contributed to an improved knowledge of the possibilities of restricted-pressure cementation and silicatization in New Red Sandstone.

He thought that the conclusion of the last paragraph on p. 478 left some doubt as to the purpose of cementation and the reason for its discontinuance. He would like to make it clear that there had never been any suggestion that the cementation would render unnecessary the installation of a waterproof lining. The results expected from the cementation were: (1) that the quantity of water from the ground would be reduced to such an extent that the residual feeder would not affect the safety or the progress of the constructional operations, and (2) that the consolidation and strengthening of the rock, particularly in the roof, would give greater protection from any fall or from any inflow from the river. After the headings had progressed a certain distance from the river-bank the exploratory boreholes had indicated sound and dry rock; the necessity for cementation no longer arose and it had therefore been stopped. The exploratory drilling had continued in case there was any change in the

Mr. Neelands. strata, and the cementation plant had been retained in readiness to deal with any bad or wet ground that might have been encountered.

The figure of £153,000 given as the cost of cementation included the exploratory boring both in the treated and untreated ground, and the cube of ground treated included 1,000 yards of the excavated tunnel on a diameter of 46 feet 3 inches, plus a further 10 feet in radius minimum treatment to provide a protective surrounding.

The Author. The AUTHOR, in reply to various points raised at the Meeting and not dealt with at the time, and in reply to the Correspondence, stated that the explanation of the apparent contradiction between various speakers as to whether or not there was a longitudinal air-flow in the Holland tunnel might be that at times the flow would be affected by a strong wind blowing into the portals.

With regard to the air-velocity in the north and south air-ducts at the Mersey tunnel, the maximum speed was about 30 miles per hour, but at one time a speed of about 40 miles per hour had been considered when the supply of even greater quantities of fresh air had been contemplated. At a point half-way between George's Dock and the bulkhead at the mid-point under the river the speed was half that given above. Both " clean " and " dirty " mists had been experienced in the tunnel, but the mist was usually " dirty." The visibility-apparatus was sensitive to both types of mist. The apparatus had not been planned to actuate the tunnel lighting. The reasons why air-flow meters of the impact type had been chosen in preference to the Pitot tube type were given by the late Mr. Hodgson (p. 653). The impact type as installed was accurate to within $\pm 2{\cdot}5$ per cent. at minimum readings, which was quite sufficient for operating purposes.

With regard to the cementation process, the Author did not agree with the figures put forward by Mr. Neelands, but he quite agreed that it had never been suggested that the cementation process would render unnecessary the installation of a waterproof lining. The cementation process was useful and had been adopted for the reasons given, and it had been discontinued as soon as the engineers considered it advisable to do so.

He would point out that the references on pp. 496 and 497 to the Mount Victoria tunnel and Holland tunnel were incomplete. The statement with regard to the Mount Victoria tunnel should have read: "For the Mount Victoria tunnel in New Zealand, a formula was given which, when reduced to similar terms, . . ." The full reference to the formula given by Mr. Singstad was " Ole Singstad, "Ventilation of Vehicular Tunnels." World Engineering Conference, 1929, vol. ix, p. 381. Tokio, 1931.

NOTE: For Index, see end of Volume 3, 1935-36.