*Discussion on Paper No. 6830**

The Bretby tunnelling machine

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Mr H. J. B. Harding (Past President) congratulated the Authors on having developed such a sophisticated machine. It was encouraging to think that this experience was available so that if a Channel Tunnel project was started a British firm could compete with rivals in offering boring machines.

108. During the study on the Channel Tunnel, Mr Harding had visited a number of tunnelling operations where the tunnelling machines used had been the K and M Drum Digger, the Marietta in the French coal mines, two Robbin's machines at Oahe in South Dakota, the Bretby machine, the tunnels at Mangla bored by Robbin's machines, and the Robbin's machine on the Metro extension in Paris.

109. He did not agree entirely with the Authors in the suggestion that the main problem was the hardness of the rock. This could be overcome by spending enough money. What mattered was the nature of the ground, whether it was folded or fissured or full of water, or whether it changed suddenly from rock to soft ground, as well as the diameter and the length of tunnel which were functions of great importance.

110. The Robbin's machines at Oahe were 32 ft 6 in. in diameter and all the auxiliary machinery was housed in a steel box about 8 ft clear of the invert; this was in two levels with conveyors above and hydraulic and other electric machinery below. The material was composed of alternate beds of shale and sandstone.

111. In earlier models an outer face rotated in an opposite direction to an inner face, but this had been discarded in favour of single rotation. The machine was designed for lifting and building rings of steel joists at about 4 ft intervals. Rails were placed on stools welded to the ribs for carrying the tail of the machine. Bogies ran on the rails and were connected to the tail of the machine by jacks. The machine was propelled forward by double jacks pushing on the ribs.

112. Mr Harding had obtained figures from the American contractors at Oahe and some rough figures for tunnels at the Mangla Dam. In the former case there were seven shafts and the machine was lowered down each shaft in turn. In one particular tunnel it bored 100 ft in the first week.[3] In the next week the drive was 200 ft with a 48 h delay through a fall of rock, and the third week 500 ft had been bored; in the fourth week another 500 ft with a 24 h delay due to falls of rock. The five Mangla tunnels were 36 ft in diameter and progress seems to have been slower; however, the excavations in both cases seemed to be about 112 cu. yd per working hour.

113. At Oahe the total delays for one tunnel had been 390 h with an operating time of 280 h. At Mangla he was told that the total delay in one tunnel was 610 h and the operating time 500 h.

114. At Bretby three engineers and an industrial staff of 12 were employed. In deciding on the use of such a machine in hard rock, it had to be decided whether

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it would be economical to use, rather than whether it was possible to do so. The advantage of a tunnelling machine was that it was non-cyclic, compared with drilling and blasting with the pause for clearing the air; however, in hard rock with the method of drilling and blasting using the ladder method which had been developed in Sweden and which was being popularized by Atlas–Copco, one man could work two drills simultaneously. At Stalon in North Sweden, seven men with 16 drills had cut 29 ft 6 in. of tunnel in 24 h.

115. In the Litani River Project in the Lebanon the ground had consisted of a layer of limestone with marl underneath and cemented sand, all lying at a dip of 30° to the line of the tunnel. After 2 miles of tunnelling when passing from the marl to the cemented sand, water was tapped and eventually 70 000 cu. m of sand completely filled the tunnel and ran out of the adit. With Mr Kell, he had been sent by the World Bank on a mission to advise on the problem. This had been a 14 ft diameter tunnel which might have been considered quite suitable for tunnelling by machine if boring ahead and grouting had been carried out, which was not the case. The mountain was 3000 ft high above the tunnel and it was found that a bed of water (at over 1500 ft head) between the two strata had been punctured; the water had eroded the weak sandstone and carried the sand down the tunnel. This had since been completed by injections[3] following the advice of the mission.

116. There had been other cases of tunnels which had passed from good rock to broken rock mixed with decomposed rock similar to the kaolin from decomposed granite. When tunnelling in soft ground where blasting could not be carried out it was important to be able to follow up the cutting edge of a machine as far as possible with protective measures in time of need. The Authors might perhaps explain how they could do this with their machine where access to the face seemed very difficult.

117. Mr Harding said that at present there was much pressure to use rotary tunnelling machines in soft and alluvial ground in cases using compressed air only between the revolving face and the ground. Many experienced tunnel engineers had their doubts on the wisdom of such a procedure. In some cases the cost of a rotary machine with all its equipment was ten times that of a standard tunnel shield and it was an expensive tool if it failed to fulfil its purpose.

Mr B. L. Metcalf (formerly National Coal Board) said that he had been associated with the Bretby tunnelling machine development from the early days. When the Board had set up the Central Engineering Establishment in 1955 to develop and prove new machines for the mining industry, it had been very important to find some project which would put the establishment on its mettle from the start and would help to attract and recruit engineers from outside. At that time the Board had been faced with a very large tunnelling problem and the speed of hand produced tunnelling had not been as great as the Board wanted. It had therefore been decided to start to build a tunnelling machine similar to the one described by the Authors.

119. The Paper dealt rather briefly with the economics of the venture, probably because it was difficult to assess what the value would have been to the industry had it been successfully deployed. The Paper said that a 20% saving would result from the increase in the rate of tunnelling, but this was a somewhat vague statement. The cost saving was related to a £5 million pit. In fact, very few new pits cost less than £10 million. It was a saving on the interest charges on the capital spent on the pit which the Board had hoped to recoup by a faster means of tunnelling, because a pit did not begin to pay off until coal was produced. Mr Metcalf did not think that the Authors were in a position to give more information about the economics, but they could have made out a very good case on the original project assessment for this development. It was unfortunate that the machine had not yet been in service underground in the mining industry.

120. Mr Hughes had touched on an interesting philosophy of development to which engineers should give some thought—the necessity for a careful project assessment, followed by stage-by-stage development. But it was necessary to assess how long a customer could wait and how long it was possible to convince him that this stage-by-stage development would perhaps produce a quicker result in the long run. The gamble entailed in producing the finished article in one go should be considered. Considerable background studies had been made on the prevention of dust, the carrying away of heat, and many other points, and these had taken time although they had been carried on in parallel with the main development progress.

121. He recalled arguments on how to eliminate the heat at the face, whether to use water or compressed air, and the final benefits which had been found from using compressed air. There was also the difficulty of taking a man to the rock face. The Authors would be able to describe the steps which had been taken; they had asked for volunteers to be carried back from the face on a stretcher to see whether anyone could be carried through the machine.

122. Work had been done on the conveyor itself and the Authors had been amazed to see it work because of its very tortuous path through the machine. Considerable information had been obtained, however, on all these elements before they had been finally incorporated in the machine. In Table 1 reference was made to the chisel bit and the rotary type of bits. Could the Authors elaborate on these designs?

123. For the Bretby machine roller bits had been selected but in the machine in Lincolnshire where the rock was much softer, would it be possible to use some form of pick? The Coal Board had been developing picks at slow speeds for their road headings and these were in advance of any other work along these lines. In a new design, would the Authors incorporate such methods if the rock measures were softer?

124. The Authors stated in § 27 that it had been found expedient to advance the machine at a constant rate, and in §§ 57 and 58 they had given the methods adopted to control the rate of advance in order to keep the power produced by the motors at a constant value. Was this another of the features which could be jettisoned in practice? Obviously in trials it was found that a constant rate of advance was all that was required.

125. As had been seen in the film shown by the Authors, methods of preventing the machine from rolling in the tunnel had been adopted. Mr Metcalf asked the Authors to elaborate on these methods.

126. Could the Authors say more about how they had overcome the problem which had arisen when the bits began to wear and the diameter of the tunnel became smaller, so that there was a tendency for the machine to jam in the tunnel?

Mr O. Dawson (Director, Mitchell Construction, Kinnear Moodie Group) said that the driving of a tunnel had always been a back-breaking repetition job. There was no doubt that explosives had eased the burden, but mechanization seemed to offer the greatest future in the development of tunnelling techniques. The driving of a tunnel mechanically was a continuous process, and the excavated ground was left relatively undisturbed, which was not always the case when explosives were used. As a consequence, over the last 100 years engineers had sought to develop tunnelling machines.

128. Fig. 10 was an illustration of the Beaumont tunnelling machine. In 1863 Major Beaumont, of the Royal Engineers, had developed a tunnelling machine and this had been tried in a water-supply tunnel for the City of Dublin. After 9 months of struggle the rock had proved too hard for the machine. However, Beaumont appeared again as the designer of a machine which drove the pilot tunnel for the Channel Tunnel in 1881. The machine had been successfully employed to drive over 1 mile of tunnel in hard chalk. Work had been stopped by an injunction in

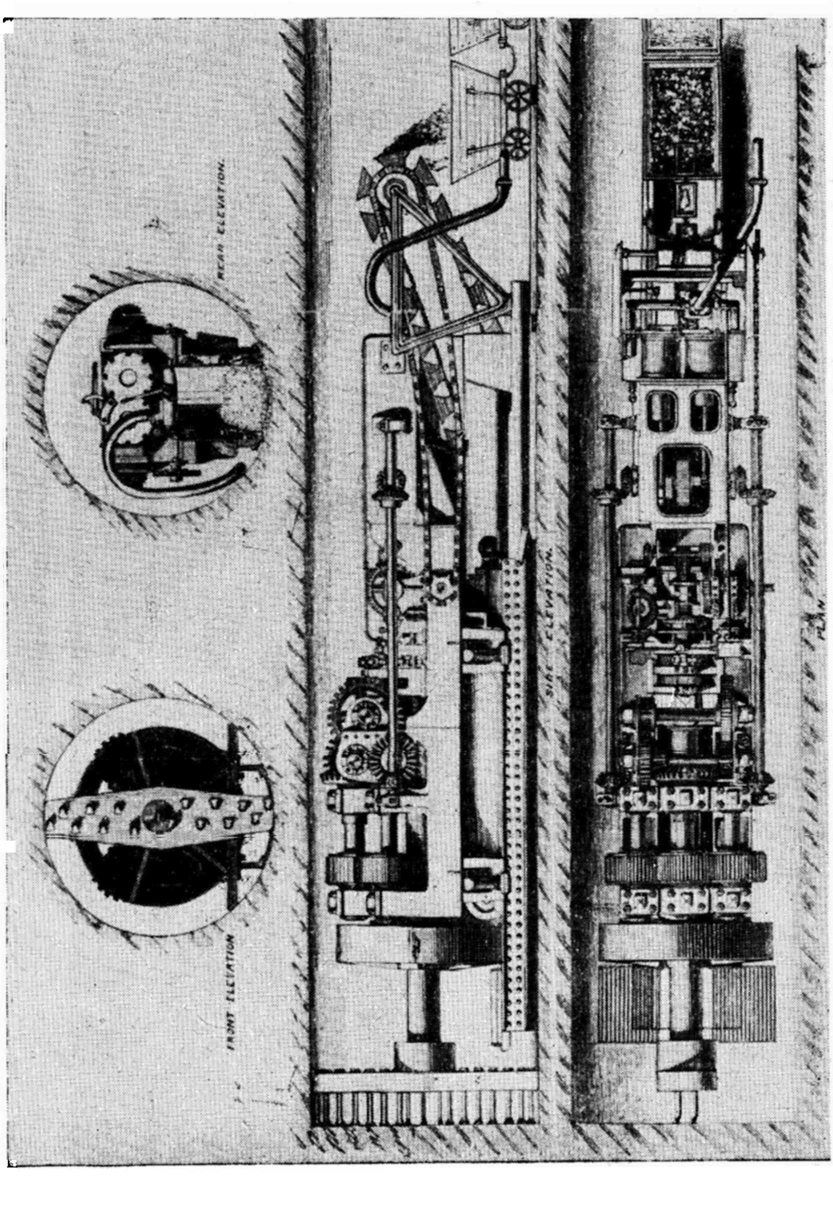

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FIG. 10: BEAUMONT AND ENGLISH'S COMPRESSED-AIR TUNNELLING MACHINE

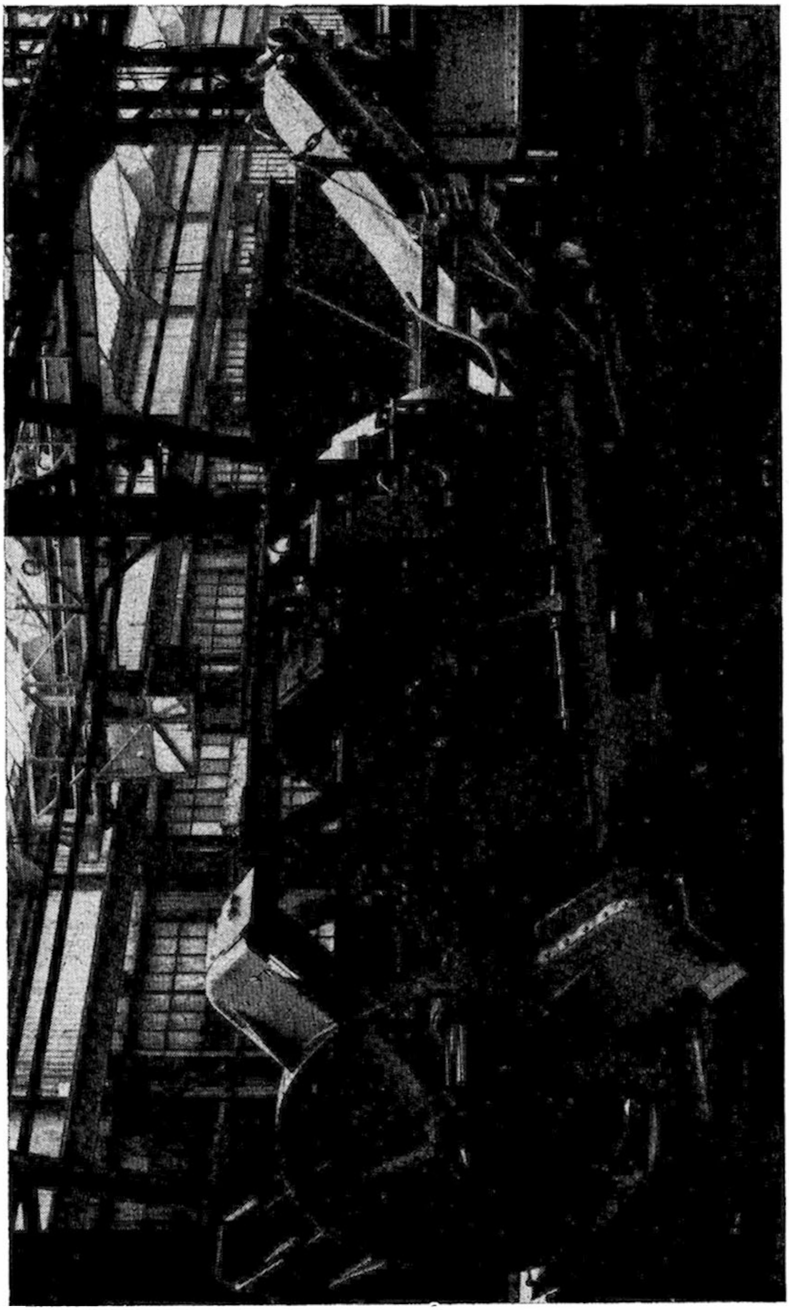

FIG. 11: THE WHITTAKER TUNNELLING MACHINE

the Houses of Parliament. Still Beaumont, who had been a Member of Parliament, had been undeterred and had carried on tunnelling. In 1883 he had driven tunnels with his machine in the red sandstone for the drainage and ventilation of the Mersey Railway tunnel. Speeds of up to 200 ft a week had been obtained, compared with 50 ft a week for hand-driven tunnels. Red sandstone had offered a challenge for tunnel machine makers, and Fig. 11 showed the Whittaker machine designed in the 1920's. The contractors, Edmund Nuttall, had used it in the same red sandstone for the Manchester main drainage. The operation of the machine had been successful, but unfortunately it had had to compete with the output from six hand-worked faces. As there had been sufficient labour available, the contractors had abandoned the machine because it had been acting as a restriction on the overall output of the contract. The builders of the machine were Sir William Arrol & Co. Ltd.

129. In the 1950's German engineers started developing machines required principally for the soft rocks, shales, and salt found in the potash mines. The Bade machine was one of these and was virtually a vertical hole-boring machine which had been turned on its side and pulled forward by cable threaded through a centre drill-hole. Mr Dawson believed that the Bade company had since developed more sophisticated machines which were self-propelled.

130. About the same time James Robbins, in America, had been developing tunnelling machines. He had successfully developed a machine for medium-hard rock. Unfortunately he had been killed in an accident, but his son had taken over his ideas and had brought them to early fruition in the work for the Tasmanian hydro-electric authority in 1961. Distances of over 400 ft a week had been reported. It was interesting to compare these with Beaumont's achievement of 200 ft a week.

131. A more recent example was the Mangla Dam machine, using disks instead of the rollers as in the Bretby machine, for the cutting mechanism. All tunnelling machines seemed to have the basic appearance of a rotary head mounted on a sturdy carriage. A drum digger machine for soft ground had been used successfully by the Metropolitan Water Board and more recently on the Victoria Line tunnel. Basically, it employed a rotating drum mounted inside a tunnel shield, and its design was an example of the co-operation between the mechanical and the civil engineer, using the civil engineer's experience of the ground through which the machine was to be driven.

132. The special requirements must have imposed quite a limitation on the design of the National Coal Board machines and must have added to their cost. The machine had to be flameproof and sparking had to be carefully avoided in the cutting head. Presumably there had been limited steering facilities because of the special requirements of a straight tunnel for mine development.

133. Mr Dawson considered the future basic requirements of a tunnelling machine. First, it should have minimum breakdown time. The only productive part of a tunnel was the working face, and the breakdown time was a vital part of the cost of a tunnel. Second, there should be access to the working face to move obstructions and for maintenance. Third, there should be access to the working parts, and it should be possible to change them in the tunnel relatively easily in the event of a breakdown. The machine should be versatile because the ground through which a tunnel had to be driven varied even within the same tunnel.

134. It had been suggested that engineers should consider the development of rock tunnelling machines when designing tunnels. It had also been suggested that the machine should not grind the material into small pieces. This was true within limits, but it was essential to have reasonably-sized material for the conveying and elevating machines. The use of explosives in a tunnel had made this apparent, and it was remarkable how special machines had been developed to load different sized pieces of rock.

Mr G. Innes (Vickers Ltd, North-East Works) read some notes on behalf of his predecessor, Mr Houghton.

136. Very little could usefully be added as regarded the design of the machine without going into details inappropriate to the discussion. However, it might be of interest that originally it was intended to drive the cutter heads, not through epicyclic gears but by means of V.S.G. variable speed hydraulic drives. This method would also have had the advantage of being able to stall under an overload, whilst maintaining full torque, without overloading the motors or the driving mechanism. There would have also been advantages in giving complete hydraulic control.

137. During the course of the design, however, it was decided that in average coal-mining conditions the heat generated by the machine was a critical factor, and the efficiency of the hydraulic drive—about 75%—would permit too much waste heat in the circumstances. The epicyclic gearing was therefore adopted, but in the light of subsequent experience and taking into account the overall efficiency, Mr Houghton was not sure that there was a significant decrease in heat loss. In a machine for normal tunnelling the V.S.G. hydraulic drive would most certainly be considered by the constructors of the machine.

138. As regards the main thrust bearings referred to in §§ 38 and 39, he agreed that as far as was known the thrust roller rings in a vertical plane were an innovation, but the long experience of the Constructors with thrust rings for cranes, swing bridges and heavy gun mountings made them confident that they would be successful as designed. The action described in § 39 was just what was to be expected; as long as the weight of the race on the inner head involved more friction than its own inertia in the absence of thrust, then the race would revolve with the inner head; but as the thrust increased above a small fraction of its normal value, the rolling friction would cause the race to assume its proper function and revolve at approximately half the algebraic difference between the speeds of the two roller paths. The results given in § 39 were as predicted by the Constructors' design staff.

139. The Authors had not emphasized the exceptional difficulties which had to be overcome in the design of the machine because of the onerous conditions of coal mining, and the necessity to limit the dimensions and weights of every portion, or sub-assembly, so as to pass down a mine shaft. The requirements of flameproofing alone caused much trouble and delay; certain metals were forbidden, and the need to include a large number of bulky accessories led to many serious problems and much delay.

Mr A. M. Muir Wood (Partner, Sir William Halcrow & Partners) said that the first point which had struck him about the Paper had been the question of economics. The National Coal Board had an advantage in being able not only to predict what it would cost them to drive a tunnel, but also the economics of the end product that promoted its construction. This was a position in which a civil engineer very rarely found himself. All too often tenders for a contract were explained to the contractor in terms of the importance of time and cost but he was not told what relative value to put on time. It seemed to Mr Muir Wood that this should be taken into account. For instance, in tunnels for roads one should be able to make cost studies to see the benefits that would be obtained from completing a road tunnel more quickly by one method than by another. It would then be possible to consider whether it was worth paying for more expensive methods. This would be no advantage in tunnels for power stations where invariably the programme of the civil engineer was confused by the complexity of developments carried out simultaneously by the electrical and mechanical engineers.

141. The specifications gave an accuracy of 1 in 200 for the machine, which was not readily understandable. Presumably it meant that it would deviate from the intended true axis at this rate, but the Paper did not give the rate at which it would be possible to recover the axis.

142. The steering of the tunnelling machine, in the same way as a shield, depended not only on keeping the centre of the machine on the axis of the tunnel but also on the

angular position of the machine or the shield relative to the tunnel. It appeared that the angular position could be achieved by some form of inertial system without much difficulty, but keeping precisely on line by any entirely automatic system appeared to be a much more difficult problem to solve. Mr Muir Wood wondered whether the Authors had considered the problem and if they had found a solution to it.

143. With a tunnelling shield, for instance, there was often a tendency for the shield to settle as it was being driven, and it had to be given a 'look-up' in order to keep it on the line. This was not quite the same problem as with a tunnelling machine, but presumably it also tended all the time to be driving the tunnel slightly further downhill than was intended.

144. Mr Harding had commented on the lack of support to the tunnel near the face. As far as Mr Muir Wood could recall, a figure of 38 ft was mentioned before the ribs could be erected. Obviously there was a problem with a machine as bulky as this in being able to put a support closer to the face. Had the Authors considered the solution which Bade had used for some of his machines in which he had a telescopic roof support in the form of a comb rather like the expansion joint in a road bridge? Half the comb moved forward with the advancing face cutters, and the other half remained behind with the anchored part of the machine. This appeared, at least theoretically, to provide an opportunity of continuous support.

145. Mr Muir Wood would be far happier using a machine such as this if there were an opportunity to make use of roof bolts close to the driving head, but as far as he could see, that would be prevented by interference with the massive frame of the Bretby machine.

146. He had not understood the point about ventilation because it seemed to him that the amount of heat developed by the machine working at full power of over 600 h.p. would require much more than 10 000 cu. ft/min of air to remove it. There was a question of water supply for the coolers; did this mean that water was used for cooling? But what was the heat balance? Presumably a certain amount of heat came out with the spoil but this would surely be small. Presumably the sludge pump removed the wet dust.

147. There was mention of the amount of out-of-balance which could be accepted on the driving head. Could the Authors give any figures for this? They could no doubt choose the measures through which they drove to make sure that the ground was relatively homogeneous, but that was rarely a civil engineer's position. If a machine like this were being used on hard rock in the crown and shale in the invert, would there be restricted progress in order to keep the load on any part of the face smaller than the maximum design load?

148. The pitch of the cutter teeth seemed very coarse for ground as hard as this sandstone. Bade had used cutters with a much smaller pitch. Presumably the amount of wear on the teeth was roughly proportional to the amount of tangential movement, and this must depend on the pitch between the teeth.

149. Could the Authors say whether the dust removal had been completely satisfactory? Had there been any dusting behind the machine? With the amount of dust going into the invert some must have failed to be taken out by the apparatus.

150. There appeared to be a certain amount of over-break caused by the machine, but lack of over-break was usually given as one of the advantages of this method. Would the Authors say more about the use of compressive strength as the sole parameter for determining the rate of progress of a machine such as this?

Mr Knowles (Tasman Highways) said that the Tasmanian machine had been successful. Two miles had been driven through the tail-race tunnel and then the head-race tunnel was driven at a rate of 761 ft a week.

152. After the head-race and tail-race tunnels were finished, the machine had been used to enlarge the main line tunnel of the railway between Hobart and Launceston. This had been a tunnel of about 11 ft in diameter which had been a bottleneck.

Working only at week-ends between the last train on a Friday and the first train on a Monday, 3200 ft had been driven in 12 week-ends.

Mr D. Jelley (Bruce Peebles) asked Mr Wrathall about the electric controls. Mr Wrathall had indicated that nowadays one would generally use transistorized circuitry if one were providing an electronic control of such a machine. He had also said that because of this there would not be the same necessity to make the equipment flameproof and that one would apply the principles of intrinsic safety. In view of experience with other mining equipment and the National Coal Board's attitude towards the difficulties of ensuring that circuits were intrinsically safe in complicated systems did the Authors still feel that the right approach was flameproofing or intrinsic safety?

154. There had been a mention of d.c. electricity for the motors for variable speed drive; no doubt this could be done reliably. Could the Authors say if the relative economics and efficiency of hydraulic drive and d.c. electric drive had been considered from the point of view of providing variable drive?

The following contribution was received in writing:

Mr P. Arklow (Mott, Hay & Anderson) raised the following points. Even allowing for the high distribution voltage of 3·3 kV, he suggested that there must be a distance from the main supply point beyond which starting current voltage drops became inconveniently large. Mr Arklow asked what this distance was and if it could be increased (subject to financial considerations) by having a larger copper section in the 3·3 kV cables, or possibly tap changing on the 3·3/0·55 transformers. Obviously if a machine similar to the one described in the Paper was envisaged for the Channel Tunnel, a radius of 15 miles with a negligible voltage drop would be required. However, because of the non-hazardous area of operations, 11 kV could be supplied to 11/3·3 transformer points which were 5 miles apart.

156. In developing an expression for the horse power a number of parameters did not appear to influence the equation directly. These included: the coefficient of friction between the roller cutter material and the rock face (this was not necessarily proportional to the hardness of the rock); the relative hardness between the cutter and the rock, and the cutter tooth angle. All these parameters influenced the depth of penetration for a given power thrust. The Authors' comments would be appreciated.

157. It was assumed that the rock failure with the roller cutter was by compressive failure. Mr Arklow suggested that the wedge loading produced failure by localized tensile failure at right angles to the direction of travel, because of the compressive resilience in that direction. If this was so, was it correct to express the capacity of the machine in terms of rock compressive strength? Fig. 12 showed the effect of friction and the wedge angle on the loading.

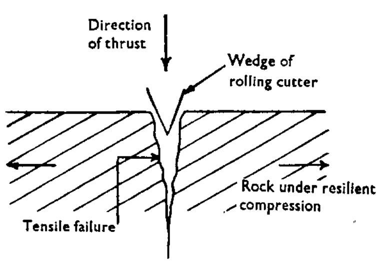

FIG. 12

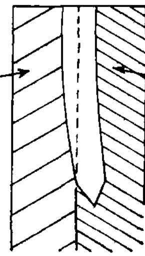

FIG. 13

158. It was well known that if two plates, one hard and one soft, were clamped together and an attempt was made to drill a hole along the plane of contact, the drill, because of its elasticity, would inevitably wander into the softer material. If there was a considerable difference in the rock strengths, such as that mentioned in the Paper in the new iron ore mine, would there be a tendency for the drill to wander into the softer areas (Fig. 13) because of its own resilience and in spite of the guiding arrangements?

159. Since rake angles have to be carefully controlled in lathe cutting tools, was there an equivalent 'rake angle' on this unit which could vary according to the rock hardness, and how could such a feature deal with the variations over a cross section? For instance the machining of a steel surface with copper inserts was a very difficult case to handle.

The Authors in reply said that the machine had originally been designed for experimental work but it was capable of operation in a coal mine after the trials. Mr Harding had given interesting information about the problem of strata and had referred to a number of other tunnelling machines working in stone. The Authors knew about these machines but they would have liked more information about the strata conditions and strengths. They had aimed at producing a machine which would drive through the hardest strata and their design had been influenced by the experience gained in coal measures in the U.K.

161. Comments on picks and disks had been interesting. The Authors had again thought of trying to use disks, but roller cutters had proved their ability to cut in stone up to 32 000 lb/sq. in., whereas the machines mentioned by other speakers had not cut in stone of that strength.

162. They had been asked about support of the tunnel behind the cutting head, and in fact this had been provided. Behind the fixed head (Fig. 2) a hydraulic roof support was followed by a long fixed canopy through which roof bolts could be set in advance of the permanent tunnel rings. These supports had been located right behind the cutting rotating head of the machine in the prototype. The facility built into the machine for rock bolting could be varied to provide a method of ground stabilization by forward injection methods.

163. The machine has been controlled by experienced engineers who had learnt their tasks without specialized training.

164. Access to the machine was to be specified. An exercise had been carried out on the prototype to confirm whether, in the event of an accident, a person could be brought from the working face through the cutting head structure to a stretcher on which he could then be taken through the machine to vehicle transport back along the roadway. The exercise had been successful, and although the machine was congested normal access to the face was not impossible.

165. The dust removal had been extremely successful. There had been a rubber seal behind the cutting head so that an operator could get close to the head and not be affected. There had been a slight rise of dust where the invert fill was extracted from the face debris to make up the road level, but that had been the only place. The seal combined with air extraction had provided an excellent dust control.

166. On the question of over-break, after early problems when difficulties of tunnel reaming had had to be overcome, there had been no over-break in the limestone at Bretby. The information supplied by a surveyor working on the project had enabled them to keep the machine aligned to within $\pm\frac{1}{4}$ in.

167. Questions had been asked about the removal of heat at the face. Heat due to working went into the rock itself and the roller cutters did not get heated. The heat went into dry rock and the majority came out in the debris. It was the Authors' experience that the heat problem was less difficult than had been expected and this had been confirmed by the experience of the Robbins machine in Tasmania.

168. The original Robbins machine had been equipped with chisel bits and conical roller bursters. These bursters came behind, between kerfs and spalled off the material. Mr Robbins and his son had supplied about 20 tunnelling machines which had worked on various contracts, some with great success, and they had developed their techniques by abolishing the chisel bit and using the disk both for cutting the kerf and shearing the rock. This seemed one answer for the immediate future.

169. Other machines had been tried with roller cutters, but some of these had run into trouble in the method of removing the rock, because they had relied on flushing it out with water. This had not been successful and the machines had been abandoned. The Authors preferred the system handling dry debris and loading it out mechanically, and this method had been successful.

170. Suggestions had been made to use picks at the Dragonby iron ore mine. The rock was certainly softer than at the trial site in general but, as Mr Muir Wood remarked, it was hard in the roof and soft in the invert. The top half of the face contained limestone of about 13 000 lb/sq. in. compressive strength, whereas the lower half of the face was a mixture of iron-ore and clay which did not exceed 6000 lb/sq. in. There was no doubt that roller cutters could deal with both the top and the bottom, and progress at Dragonby since the presentation of the Paper had confirmed this. Moreover, the cutting head was so rigidly held that it had no tendency to wander in the tunnel.

171. Questions had been asked about machine advance at a constant rate. The machine had been designed so that the rate of advance was governed by a load control on the main motors. In practice it had been found that controlling the advance of the machine was fundamental to successful operation and a pressure control on the advance cylinders was added, but neither of these devices was satisfactory. The method evolved to keep adequate control of the machine was to control the rate of advance manually, and the machine at Breedon had been set up in this way.

172. In the early stages of the external survey the machine rolled slightly in the tunnel but it was noticed by the surveyor and rolled back on line with the use of jacks. Thereafter, a transverse water gauge had been added to detect roll; a technique of slightly rocking the machine backwards and forwards with the thrust cylinders was devised to correct roll and re-align, so that heavy jack work could be dispensed with.

173. The roller cutters on the face had given no serious problems except those at the gauge of the outer head. Initially there had been no reaming cutters. The gauge of the tunnel had been cut by the outside cutters of the outer head, and the backs of these cutters had worn and bent. The Authors had put cutters on the periphery of the machine, with their axes parallel to the machine so that they cut the wall and not the face. With careful positioning these reaming cutters worked satisfactorily; they maintained the size of the tunnel and protected the backs of the gauge cutters. Even so, debris falling to the bottom could still accumulate under-

neath the backs of the gauge cutters and cause these to bend so these cutters had been shrouded. Much of the development time had been spent in finding ways of operating the reaming and gauge cutters and maintaining tunnel gauge.

174. The specification had laid down that the maximum gradient to be driven by the machine should be 1 in 200, and it was required to transfer from level to this gradient in 200 ft. Since the front support pad was 10 ft 6 in. back from the face and the anchor pads at the start of the stroke were 10 ft 6 in. behind that, any adjustment of the front support jacks would be doubled at the cutting head. At Dragonby it was possible to improve on the specification and the machine was fed into an upward gradient of 1 in 60 from level driveage over a distance of 30 ft.

175. The spacing of the cutter teeth was the standard for Hughes medium formation cutters, which term covers rock in the range met at Breedon. (Soft formation cutters have teeth more widely spaced and hard formation cutters have them closer together. Extremely hard formation cutters do not have conventional teeth but projecting spherical buttons of sintered tungsten carbide.) As has been explained, the roller cutters outside the 30 in. central boss could not achieve true rolling and should scuff; this obviously contributed to tooth wear. With cutters rolling correctly, and with tooth spacing suited to producing the most effective tooth loading on the rock surface, the chief contributor to wear would be a lack of thrust. In the particular case where the teeth had become dulled, unless they had adequate loading they would not penetrate the rock and would wear without productive work. In soft rock, of course, too much thrust would lead to foundering, and excessive speed also contributed to excessive wear. Thus, the requirement for efficient working was a high thrust and a slow speed rather than vice versa.

176. Further to Mr Arklow's contribution, Fig. 9 showed that each tooth entering the rock was subjected to two forces: a reaction at right angles to the radius from O and the friction between the tooth and the rock. The tip of the tooth probably moved in a small trochoidal loop which assisted in shearing a fillet of rock off the surface so that it might have a second reaction directly opposite to the friction. Otherwise, the coefficient of friction was taken into account and was represented by $\tan \theta$. It should be noted that the expression given in Appendix 2 was for 'rotational horsepower', i.e. that required for the motors to rotate the head. More horsepower was required from the thrust mechanism: it was, of course, proportional to the thrust and the rate of advance. Progress would depend on the hardness of the rock and the angle and spacing of the teeth. However, this horsepower was much less: § 41 and Fig. 5 showed that four 160 hp motors had been installed for rotation but only one 15 hp pump motor for advance, although it was this motor which had to provide for the drag of the machine, the sledge, and the towed ancillaries, as well as for attacking the rock.

177. The Authors' view on the action of rotary cutters was that the cutting edge (whether a tooth or the periphery of a disk) first indented and (as the thickness of the wedge increased) then sheared off the rock between the wedge and the free face formed by the previous indentation or kerf. With roller cutters this might be assisted by any trochoidal movement of the tips of the teeth. Rock was weaker in shear than in compression and it was the shear that gave the major failure. If the rock was weaker, larger pieces could be sheared off and less work was required; moreover, the cutting was more efficient if larger pieces were sheared off. The value of the compressive strength of the rock was important because it gave an indication of the general strength of the rock. Moreover, the experimental work at Bretby indicated that the best cutting index for a tool (i.e. the best ratio of the rate of removing stone to the power used) bore a fixed ratio to the compressive strength of the rock. It might be noticed that the cutting index was not only an index of the efficiency of cutting, but that its dimensions reduced to the inverse of the dimensions of stress. In practice, it was difficult to segregate the cutting power from that dissipated in debris removal and general congestion in the hole. A rule for the roller cutters used had been suggested

as follows: cutting index (cu. in./min/hp) × compressive strength of rock (lb/sq. in.) = 800 000 for boreholes or 1 200 000 for large tunnels. Alternatively, the rate of removing stone was proportional to the power and inversely proportional to the compressive strength of the rock: thus, more power (and consequently a larger and heavier machine) was required to maintain the output in harder rock.

178. Concerning Mr Jelley's question on intrinsic safety and flameproofing as to the possibility of making electric equipment intrinsically safe, it was essential to do so mainly because of the cost; flameproof equipment was much heavier and more difficult to handle.

179. A rather complicated position was developing with the Mines Inspectorate on the subject of intrinsically safe equipment. The stage was being reached in which multiple intrinsically safe circuits were being used. Usually engineers needed them in a common cable, but if they wanted the equipment to be certified there was at present no alternative to completely segregated circuits.

180. Until the Ministry of Power could produce some new form of certification, which was neither flameproof nor intrinsically safe, there would be complications with intrinsically safe equipment where multiple circuits were involved. The Ministry had indicated that at some time in the future they would probably provide a new form of certification by which multiple circuits could be used in cables or junction boxes provided that first contact tripping was used. In other words if there were two or more intrinsically safe circuits in a cable, then on the first contact between any of these circuits the whole of the supplies should be tripped. If this were to be done then the individual supplies would still have to be intrinsically safe in themselves. The Ministry had also indicated that they would probably require some form of methanametry in the situation in which these circuits would work.

181. The best way of ensuring that voltage drop on cables feeding the machine did not become excessive was to ensure that the supply voltage was sufficiently high. In the use envisaged in coal mines 3·3 kV would be quite adequate since the driveages involved would not be large. New collieries where the tunnelling machine would have been used most were on a supply voltage of 6·6 kV making the problem much easier to overcome without feeder cables becoming too large. In cases where the tunnels were longer than those for which the machine had been originally designed, there was still no bar against going to 11 kV. The only difficulty in this case would be the installation of the supply if it did not already exist at the particular colliery, although the intake supply of many collieries was 11 kV.

182. Since the presentation of the Paper the Authors had received information on the completion of a tunnel drive in New Mexico, U.S.A., by a machine built by the Hughes Tool Company, U.S.A.

183. This tunnelling machine had incorporated many features in design which the Authors had reported as necessary modifications to be included in the construction of the next machine, using principles basically similar to the Bretby machine.

184. The important advances in design built into the Hughes machine were as follows:

(*a*) roller cutters specifically designed for the task, incorporating straddling brackets with double bearings for the roller shaft which are sealed and require no compressed air supply;

(*b*) adjustable reaming cutters on the periphery of the cutting head and shrouded gauge cutters; adjustable outer roller cutters positioned on the cutting head permitted a variation in size of the tunnel between 19 ft 10 in., 20 ft 10 in. and 21 ft 2 in.; this variation allowed the cut diameter to be changed according to rock formation where the inclusion of supports was specified;

(*c*) a single cutting head unit;

(*d*) smaller size anchor pads and a more flexible facility for machine steering;

(*e*) greater thrust.

185. It was reported that the machine started work on the Navajo Indian Irrigation Project, near Aztec, New Mexico, at the end of June 1965. By 27 October, 1965, 3262 ft were stated to have been driven in a tunnel approximately 20 ft in diameter. By April 1966 the length had been extended to 1½ miles, and the total distance to be driven was 2 miles.

186. An indication of the cost for this machine, which had the ability to vary its cutting diameter in the range of 18 ft to 20 ft was £300 000.

Reference

3. HALWANI S., JANOD A. *and* LAJEAT J. P. Le percement du tunnel d'Awali de l'aménagement du Litani au Liban. *Travaux*, 1965, **365** (May), 247–260.

Corrigenda

The following alterations should be made to the original Paper.

(1) Page 658, § 36: add after the last sentence
'Each cutter has a face width of 5 in. and a mean diameter of 8 in.'

(2) Page 667, § 83: the fifth sentence should read
'On this basis λ works out at 0·0808 in. for the outer head and 0·035 in. for the inner head.'

(3) Page 669, § 88: the third sentence should read
'Power supplied to the outer head motors was 85 kW and the inner head motor 55 kW when the forward thrust pressure was between 1500 and 1700 lb/sq. in., and the rate of advance 2½ ft/h.'