Discussion.

'he President. The PRESIDENT, in moving the vote of thanks, remarked that the Paper dealt with a subject that was not very amenable to mathematical treatment. As the Authors said, any results calculated in the way such treatment indicated could only by accident be reasonably accurate. The Paper was a record of patient investigation by competent investigators, and it would prove to be a mine of knowledge of great worth to designers in the future.

Mr. Binnie. Mr. W. J. E. BINNIE remarked that the value of the Paper was enhanced by the fact that it was couched in simple and clear language, without the use of higher mathematics, so that it could be readily understood. Many problems connected with water defied mathematical solution and required the making of model experiments. Not the least interesting part of the Paper was that dealing with the scale to which models should be constructed in order to give results applicable to a full-size structure by means of the laws of similarity. With regard to the advantages of the use of siphons, it was necessary to limit the extent to which the water could rise in a reservoir, in order to avoid endangering the structure. Reservoir dams might be either masonry structures or earth embankments. In the former case it was usual to allow the water to escape over the top of the dam, and where the length of the dam was considerable there appeared to be no particular object in introducing siphons unless it was essential that the level in the reservoir should vary within only narrow limits; but in the cases of short dams in narrow gorges, where there was not much room for an ordinary spillway, a siphon discharge was of great benefit. If it was necessary to limit the rise of level in the reservoir to about 2 feet above the overflow-weir, the mean velocity of discharge would be about 5 feet per second. If a siphonic discharge were substituted, it would be possible under the best practical conditions to get a velocity at least five times as high as that; and consequently, for every unit of length of the weir, assuming that a depth of 2 feet of water was passing over the throat of the siphon, five times as much water would be discharged as would pass over a weir—neglecting the necessary partitions between siphons. In the case of an earth embankment it was even more necessary to prevent the water from rising above a certain limit, because if it overtopped the bank the earth would be swept away and the reservoir would vanish. The principal reason put forward against the adoption of siphons in this country had been the risk of their being blocked by ice. He had recently attended the World Engineering Congress at Tokio, and he had there taken the opportunity of discussing that point with engineers from various countries who had constructed siphons in regions where the climatic conditions were much more severe than in the British Isles; and as far as he had been able to ascertain they had not been troubled with blocking by ice. That point required consideration, and an engineer would be very bold to introduce siphonic discharge in Arctic regions if failure of the structure would involve disaster. In considering the question of blocking by ice, he would first assume that the reservoir was just on the point of overflowing. The entry to the siphon could be made as far below the water-surface as was desired, the governing factor being the depth of the water in the reservoir at that particular point. It was obvious that under those conditions no trouble would be caused by ice formed on the surface. Assuming next that the water-level in the reservoir had fallen to 6 feet below the overflow-level, that the siphon-inlet had been carried down 6 feet, that the level then remained stationary, and that ice formed on the surface of the reservoir; if a flood then occurred and the water began to rise, the ice in the reservoir would break, but the entry to the siphon might remain blocked by ice. Under such circumstances, as the water-level rose to the crown, the ice seal at the entrance to the siphon would be under the pressure of the water in the reservoir on one side and open to the atmosphere on the other, and, assuming that the area of the entry to the siphon was about 9 square feet—which was a very moderate size—there would be a distributed pressure of about $1\frac{1}{2}$ ton on the ice formed in the entrance, which would be sufficient to burst ice not exceeding about 3 inches in thickness, so that the siphon would come into action. In providing for conditions where frost might occur, the siphon should be designed in such a way that the entrance was well below the top water-level and was of large area. The question was far more than a mere academic one. In 1929 the Manchester Corporation applied to Parliament for permission to introduce siphons in connection with their reservoirs in the Longendale Valley which had been constructed many years previously, before the intensities of floods had been much studied, so that the lengths of the waste weirs provided were not sufficient to ensure the safety of the embankments. Mr. Binnie.

Mr. Binnie. Stockport, the County Council, and other bodies who would have suffered very severely if the reservoirs burst, had opposed the introduction of the siphons on the ground that siphons were dangerous to construct. He did not know quite what was meant by that; but it had been maintained that they were liable to be blocked by ice; and unless there was a consensus of opinion of engineers in this country in favour of the introduction of siphons there would be great difficulty in getting the necessary powers to construct them. An interesting point in the Paper, illustrated in Tables XIII and XIV, was that water passed over the throat of the siphon as a free vortex, the product of radius and velocity being practically constant except where the filaments of water were immediately in contact with the walls. The consequence was that the velocity varied very widely. Table XIII showed that the maximum velocity was about 1·6 times the mean velocity, and the same ratio held good in Table XIV. A practical question was, what velocity could be worked to at the throat of the siphon without the occurrence of cavitation at the point of high velocity? Cavitation interrupted momentarily the flow of water and set up very serious and destructive vibration in the whole structure. As far as he had been able to discover, the limit of velocity was about 27 feet per second at ordinary barometric pressure, whereas if there were not that possibility of cavitation it might be possible to work to 40 or 42 feet per second. The Authors had worked with very moderate heights of discharge, but a waterworks engineer was frequently faced with the problem of having to discharge water over the top of a high dam. In such circumstances the siphon would have a very long lower leg, and there would consequently be cavitation unless that leg was so arranged as to cause back pressure and thus prevent the formation of a vacuum in the throat. Alternatively the siphon could be arranged so as to discharge into the air at a level above the base of the dam; but that would lead to difficulty in providing for the fall of the mass of water. No doubt the Authors had considered the point, and he would be glad to hear what form of design they would recommend under such circumstances. That difficulty had actually presented itself at Manchester, where a very long leg would have had to be provided to carry the water down into the valley below the embankment, and a gradually diminishing cross-sectional area had been proposed for the downward leg in order to avoid forming a vacuum at the throat.

Mr. Buckley. Mr. A. B. Buckley desired to endorse Mr. Binnie's observations with regard to the application of siphons in this country. As an example of what might be done, he referred to the Ashop river

Mr. Buckley.

diversion.[1] There the offtake-channel was protected by a side weir, 116 feet long, which discharged 246 cusecs with a depth of about 8 inches over the sill. The Bagnolo siphon in Italy, which was about 8 feet long and had a head of 8 feet 9 inches, discharged more than double the volume discharged by the Ashop offtake-weir. That constituted a very striking comparison. About 15 years ago he had had to investigate the question of a dam at the outlet of Lake Tsana in Abyssinia, approximately circular and 30 miles in diameter. It was about 14 days' trek to that lake from the nearest railway, so that a reliable automatic spillway there would be extremely valuable, and he had therefore studied the subject of siphons. He visited a number of siphons in Italy and obtained a list of about eighty that had been constructed, working under a head ranging from a minimum of 1 metre up to a maximum of 12 metres. That fact, he thought, was rather striking, considering that the theoretical maximum head was only about 10 metres. He believed that the largest installation of the kind was in Norway, and discharged 600 cubic metres (21,190 cubic feet) per second, or more than the discharge of the Thames in maximum flood. From the results given in Table I the Authors concluded that the coeffixient of discharge increased appreciably with the working-head, but he thought that perhaps another factor, which was only touched upon in the Paper, might be material. To illustrate what was in his mind he would refer to the way in which those siphons actually worked. If anyone watching a siphon, such as the one at Bagnolo, were asked to say why it began to flow, he would probably answer, "For no apparent reason." That siphon had a depth of about 3 feet and primed as soon as the water rose about 1 per cent. of the depth of the throat. He knew of a siphon which was 2 metres 10 centimetres in depth and began to prime with a head of 2 centimetres over the sill. If the Authors had found that a head of one-third of the depth of the throat was required to prime the siphon, that seemed to indicate that possibly the models did not quite accurately reproduce the action of their prototypes in that respect, because in practice it had been found that 1 per cent. was usually ample.[2] Therefore, as the siphon began to work, after

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[1] Minutes of Proceedings Inst. C.E., vol. 229 (1930), p. 394.

[2] The following references give instances of siphons that have been known to prime with a siphonic head above the lip of the throat of about 1 per cent. of the throat depth.

(i) Trans. Am. Soc. C.E., vol. 55 (1922), p. 1141. Mr. E. S. Lindley states: "As a demonstration, a second gate was opened until the flow of the

Mr. Buckley. the water had risen 1 or 2 centimetres above the sill, the observer would find that the water-level fell until it might be 5 or 6 centimetres below the lip, rushing up into the siphon in a remarkable curve accompanied by considerable noise, which started as a murmur with the flow and increased in loudness. Anyone who had heard a 12-inch pump beginning to draw air would be able to imagine the kind of noise that might be expected from a pump discharging 14 tons of water per second, as the siphon in question did, if the water fell to within a few inches of its suction or below it. That noise was due to the drawing-in of air, and it indicated inefficiency in the siphon. Referring to the Authors' tests, he had prepared *Fig. 12*, which illustrated the degree of immersion of the inlet of the siphon for the five tests discussed in Table I, and it was evident that the immersion of the inlet differed in each test; in the fifth test the water-level was actually below the lip, and in that respect he would ask the Authors whether it would be possible to repeat the five tests, varying the head, but maintaining the same depth of immersion upstream, as well as downstream, for each experiment It would mean providing a separate model for each experiment. Possibly in a model the noise made by the suction of air would not be so striking, and it might even be inaudible. In the first test given in Table I the depth of immersion was 23 per cent. of the head, but in the fifth the water-level was 9 per cent. of the head below the outlet. One would expect it to fall below the lip, but not to that extent; because 9 per cent. of the head in a full-size siphon might represent 18 inches or more below the lip, and he doubted whether that could actually happen: in that respect the model had probably been assisted by capillary action and similar factors. The Authors compared a coefficient of 0·806, obtained with a head of 0·629 foot

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siphon was broken, and then adjusted until the canal was at the same level. The gate was then closed, and within 30 seconds the siphon was again flowing, the maximum rise having been 2 centimetres above the lip." Mr. Lindley refers to a siphon with a throat-depth of 2·10 metres.

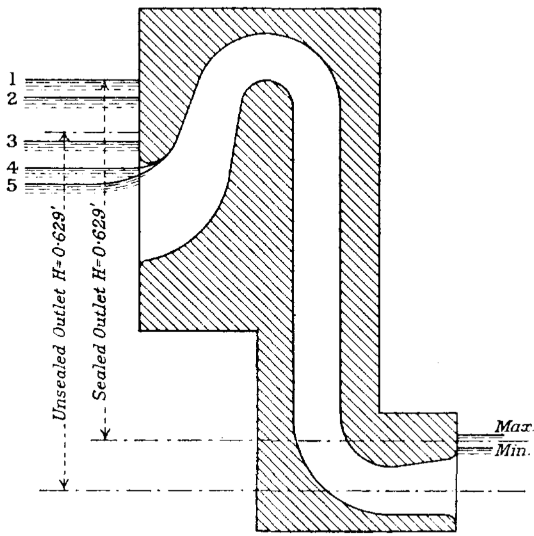
(ii) "Sifoni Autolivellatori," by E. Gregotti (Mortara, Italy, 1909). In a certificate given by Mr. T. Tittoni for a siphon at Sannazzaro de' Burgondi operating with a head of 2 metres and having a discharge of 1 cubic metre per second, it is stated that a rise of only 2 centimetres above the normal level of the canal was sufficient to start siphonic action.

(iii) Pamphlet describing self-priming siphons, by E. Gregotti (Mortara, Italy, 1912). A list of 130 siphons is referred to, with capacities ranging up to 250 cubic metres per second. It is stated that siphonic action starts with a siphonic head of 2 to 7 centimetres.—A. B. B.

Mr. Buckley.

in a test with a sealed outlet, with a coefficient of 0·640 obtained with the same head but with the outlet unsealed; but Mr. Buckley suggested that the two tests were not strictly comparable, because in the former the inlet was sealed by a depth of water equal to 23 per cent. of the head, whereas in the other it was sealed by a depth of only about 6 per cent. That might possibly account for the difference in the coefficients. He suggested that until such experiments as he had mentioned had been made, it could not be concluded that the effect of sealing the inlet could be disregarded. He also suggested that calculation of the coefficients on the throat-area of the

Fig. 12.



Scale: One-Quarter Full Size.

siphon might lead to misunderstanding. If the discharge-coefficients exceeded unity, and they might be as high as 2, it would be evident that they provided no direct indication of the siphon's efficiency, because a siphon with an efficiency of 200 per cent. would be an impossibility; but he thought that in a case like Table I, where the coefficients were less than unity, the figure 0·806 might be taken to indicate an efficiency of 80·6 per cent., which apparently was not the fact. In order to compare those coefficients with the coefficients of the Italian siphons given in the Paper, he had calculated them on the mean cross-sectional area of the siphon and not upon the throat-

Mr. Buckley. area (Table IA). The revised figures in the fifth column seemed to provide a fair basis for comparison of the efficiency of the respective

TABLE IA.

Test No.	Head.	Immersion of Inlet.	Coefficients Computed.		Difference.
			At Throat.	On Mean Section.	
Tests with Sealed Outlets.					
	Foot.	Per Cent. of Head.			Per Cent.
1	0·629	+23·0	0·806	0·735	9·7
2	0·585	+18·0	0·788	0·716	10·0
3	0·530	+6·5	0·765	0·695	10·0
4	0·471	−3·0	0·756	0·684	10·5
5	0·444	−9·5	0·753	0·684	10·0
Test with Unsealed Outlet.					
—	0·629	+9·0	0·640	0·572	12·0

siphons. In Table VA he had computed the coefficients for the first group of experiments recorded in Table V. Those results

TABLE VA.

	Model.	Head.	Co-efficients of Discharge.		Ratio of Coefficients.
			On Throat.	On Mean Section.	
		Feet.			
Original models with 1 in 8 outlets, 20 inches and 5 inches long . . .	Large	2·40	1·107	0·986	1·25 : 1
	Small	0·60	0·910	1·790	

seemed to indicate that the Authors had proved that the large model was big enough, as it had an efficiency of 98·6 per cent., which was as high as could be wished for in a model. On the other hand, the small model was apparently too small, and that seemed to be an important result. In the small model, capillarity, surface tension, and viscosity appeared to influence the results adversely. It was obvious that the Authors' models had a much higher real efficiency than had the Italian models, and he attributed that to, among other things, the length of the inlet-leg. That being the case, it

Mr. Buckley. might be natural always to aim at making the inlet-leg long; but in practice that would, he thought, seldom be possible, because the siphon would continue to work until the water was below its lip. In a storage-reservoir that would involve the waste of too much water. Such conditions in the forebay of a hydro-electric station would probably allow air to be drawn into the pressure pipe; in an irrigation-canal the fluctuations would be too great; and even in a navigation-canal they would be objectionable. Therefore he did not see that in practice it would ever be possible to provide a siphon with a long inlet-leg; and unless some arrangement were discovered for excluding air from the inlet, he did not think that in practice a higher efficiency than about 0·5 would be possible. [Mr. BINNIE pointed out that the vacuum was broken when the water fell to the level of the air-vent.] He agreed that in a siphon such as was illustrated in *Fig. 6* (A), where the lip was lower than the prescribed water-level, the stoppage of the siphonic action would be governed by the level of the air-vent. The area of the latter had however to be considerable to break down the siphonic action, and the siphon would therefore lose efficiency by sucking air through the air-vent. If it was desired to maintained a constant upstream level, the inlet-leg could therefore not be lengthened. As such siphons were usually installed where it was required to limit the variation of upstream water-level to a few inches, and as an adequate depth of immersion of the siphon-inlet or of the air-vent was essential for efficient working, in actual practice there seemed to be little probability of attaining any very high efficiency, except where large variations in upstream water-level could be tolerated. He suggested that higher efficiencies might possibly be attained by lengthening the horizontal lip shown at the inlet of *Fig. 6* (C), and he hoped that the Authors might see their way to make such experiments as might throw light on that. He doubted, however, whether the long horizontal lip would prove structurally economical; he was unaware of any other alternative for increasing efficiency in that respect, and a coefficient of 0·47 seemed about the highest attained in Italian practice. The Authors referred to the Yuma siphons. Those seemed to have been constructed across a canal as part of a regulating-bridge, one-half of which was fitted with sluices and the other with siphons; and by providing a certain area of sluice-opening the water could be caused to flow through the siphons. Under those conditions he thought that the velocity of approach must have some influence upon the problem. He had lived for some 25 years in a general atmosphere of canals, flowing brimful, and always more or less liable to burst; any information of the nature of that given

Mr. Buckley. in the Paper was extremely valuable to him, and he was glad to have the opportunity of expressing his thanks to the Authors.

Professor Dixon. Professor S. M. DIXON observed that, though siphons had been in use for a considerable time, their characteristics were not yet thoroughly understood, and the Authors' work was filling that gap in a very satisfactory way. It was only by means of experimental work on them that siphons could be actually designed. Mr. Buckley had stated that it was probably impossible to make a siphon with an efficiency higher than 50 per cent. The Glens Falls siphon, to which the Authors referred, had under certain conditions an efficiency of over 60 per cent. That was an actual siphon, and he had no doubt that engineers would succeed in increasing the efficiency of siphons, but not by proceeding along the lines of the Italian siphons. He would like to mention some unpublished results obtained in 1926 and 1927 by Mr. K. C. Wu, who was at present Professor of Hydraulic Engineering at the University of Chekiang, in experiments carried out on siphon spillways at the City and Guilds (Engineering) College. Mr. Wu had experimented with a model of the Glens Falls siphon (*Figs. 5*, p. 215) made to a scale of one-twelfth. The results were not as good as those obtained by the Authors, but good enough to show the importance of experiments with models; the best discharge had been obtained when the siphon was just sealed—a difficult condition to carry out always in practice, because it would mean maintaining a constant level of the tail water. The coefficient of discharge found by Mr. Wu for the model was 0·66, which unfortunately was higher than that under the same conditions at Glens Falls, for which the figure given was 0·61. In part that discrepancy was no doubt due to the smoothness of the model. The Authors' discussion of dynamical similarity as applied to siphons and the effects of viscosity was very important, and was published for the first time. Unfortunately, it was impossible to apply the criterion given on p, 221 to Mr. Wu's experiments because the variation in vd in his experiments had been only from 0·15 to 0·45. The experiments had led to very similar results to those obtained by the Authors, and Mr. Wu had found by measuring the pressures that he should modify the outlet-leg in the way the Authors mentioned. The outlet-leg of the Glens Falls siphon was cut back very much as in the Authors' small model, and Mr. Wu had found very irregular losses of head, so he had built two new models. In one of them the outlet-leg was straight and in the other curved backwards towards the upper basin, in each case with constant cross section, and increased coefficients of discharge were obtained in each case. Experiments in priming had also been carried out on the three models. Mr. Wu had thus found that he could improve the wooden model and get a much better coefficient of discharge. A glass plate had then been fixed in the same way, as the Authors had done, and it had been possible to observe the smoothness of the flow and freedom from eddies. He was very grateful to the Authors for bringing forward this very important topic, because at the colleges there was a general endeavour to experiment upon models, and it was desirable to show that such experiments were of real service to engineers. Professor Dixon.

Mr EVAN PARRY remarked that one of the most uncertain quantities in hydraulics hitherto had been the coefficients of discharge of siphons, that was to say, excepting the coefficient of friction proper. No one knew with certainty just why those coefficients varied so widely—from, say, 0·3 to more than 0·9 ; but he thought that as a result of the Authors' work it could be said that all uncertainty had now been dispelled, and that it would be possible to predict the discharge of a siphon with a very fair degree of accuracy by means of the information contained in the Paper. A rather interesting point that had already been referred to by Mr. Binnie was the determination of the velocities in the bend. The mechanics of fluids passing round bends had been deduced a very long time ago by the late Professor James Thomson, F.R.S., and according to his theory any fluid in passing round bends assumed the character of a vortex. That principle had been amply demonstrated later by a model—which he thought was still in existence at Glasgow University—of a bend in an open channel, and Professor Thomson had been able, by means of the application of that principle, to explain fully all the phenomena observable at the bends in rivers and channels. He thought it worth while to call particular attention to that principle, because it was very often assumed by engineers that the velocity at the outside of the bend was higher than at the inside, as exemplified by the rotation of a cart-wheel. As far as he knew, the Authors were the first to demonstrate that principle in its application to a closed conduit, and it was rather remarkable that the approximation to a true vortex was so close. He would have expected a wider departure from the true vortex, owing to the influence of friction at corners, and he would much like to see similar readings and observations obtained upon bends in round pipes, where he expected there would be a much wider departure from the true vortex. He suggested that if the Authors had the time they would be able to combine such an investigation with, say, the formulation of a rational theory of the losses at bends in pipes of round section. Mr. Parry.

Mr. Halcrow. Mr. W. T. Halcrow remarked that the information given in the Paper would be a great help to engineers who had to design and build siphons and to watch them in operation. A further important advantage of siphon spillways, which Mr. Binnie had not mentioned, was that there were no working parts; and siphons were therefore to be preferred to mechanical devices, whether automatic or controlled. The Authors' work had clearly demonstrated that auxiliary priming-siphons could be eliminated. They were a bad feature of some existing siphons, as they were liable to be choked by floating matter. He had to deal with conduits protected by gratings in some of the Scottish water-power schemes, where large quantities of floating vegetable matter frequently choked the screens; were priming-siphons employed in such conditions, difficulty might arise from that source. It appeared that, where the long leg of the siphon had to be vertical, the simplest method of priming was to form a shelf on the inner wall, if a right-angled outlet-bend was necessary, and when it was not possible or desirable to have a water-seal. In the abstract[1] of the Paper there was a statement, under general conclusion No. 7, which he had not fully understood; it was said that a siphon spillway having the outlet turned through a right angle so as to discharge horizontally would usually prime with a free outlet. He would be glad if the Authors would say whether in that case no auxiliary siphon at the top was necessary. He had recently been considering the design of some siphons for a comparatively high dam, and one of the problems was to reduce the erosive effect of the fall of water discharged from the siphon on to the rock downstream of the dam. He had been considering various methods of destroying the energy of the water. Did the Authors consider that a jet disperser fixed to the outlet-end of the siphon would have any effect, either good or bad, upon the discharge-capacity of the siphon?

Mr. Naylor. Mr. A. H. Naylor observed that the Authors had performed some very valuable pioneer work. They assessed the value of a design by the coefficient of discharge, but it seemed to him that the coefficient of discharge did not give a true measure of the efficiency of the siphon. As an instance, it was possible to have a siphon which had a very low efficiency and which yet had a coefficient of discharge exceeding unity. The object of a siphon spillway was to get the maximum possible intensity of discharge over the crest, so that the height of the dam, and consequently its cost, could be kept as low as possible. The ideal case, which was of course unattainable,

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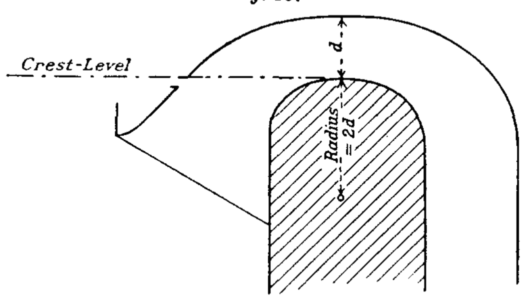
[1] Inst. C.E. "Sessional Notices," 1930-31, p. 51.

would be that in which there was a perfect vacuum at the crest, and consequently a velocity of 47 feet per second over the crest-area. He would call that an efficiency of 100 per cent. In actual practice, as had been pointed out by the Authors, a vortex was formed at the crest; the pressure was lowest on the inside radius, and that minimum pressure must not be less than a vacuum of about 28 feet of water. That meant that in any siphon the average velocity over the crest could not exceed a certain figure. In the Authors' design—and in any other design in which the radius of the crest was about half the depth of the crest—the maximum possible average speed obtainable at the crest was about 24 feet per second, and he would be inclined to say that such a siphon could have a maximum efficiency not exceeding about 50 per cent.; because the discharge could not exceed an average speed of 24 feet per second over the crest, as against 47 feet per second in the ideal Mr. Naylor.

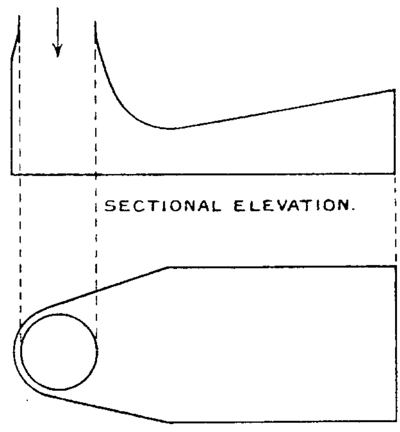
Fig. 13.



case. If the radius of the crest were increased to twice the depth of the throat, according to the vortex theory an efficiency of 75 per cent. would be possible. It appeared that the maximum efficiency of a siphon was limited almost entirely by the design of the crest; and the full efficiency for any particular form of crest could generally be attained by providing a suitably divergent suction-tube and outlet. About a year ago he had designed a large siphon according to that principle. The radius at the crest was about twice the depth of the throat, as shown in *Fig. 13*. As the tube receded from the crest it gradually increased in depth, the mean velocity decreased correspondingly, and consequently it was possible to reduce the radius of the bottom of the tube as it approached the vertical legs. With such a design it would be possible to get an efficiency of 75 per cent., according to his definition of efficiency, provided that a suitable divergent outlet could be formed. Perhaps the most significant

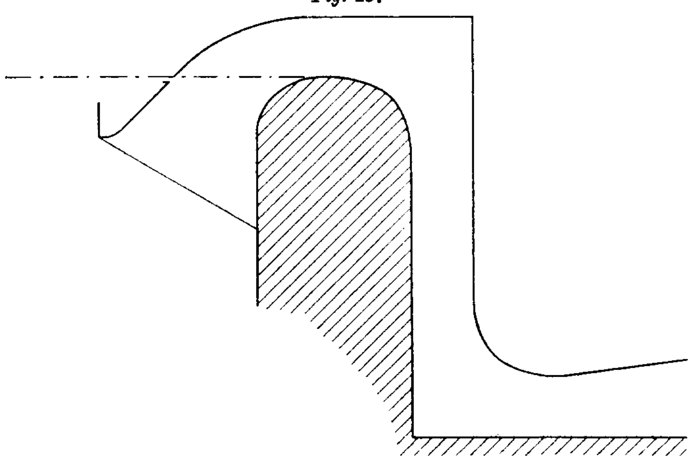
Mr. Naylor. part of the Paper was that dealing with the lower bend. Sharpening the outer curve had increased the coefficient of discharge from

Figs. 14.



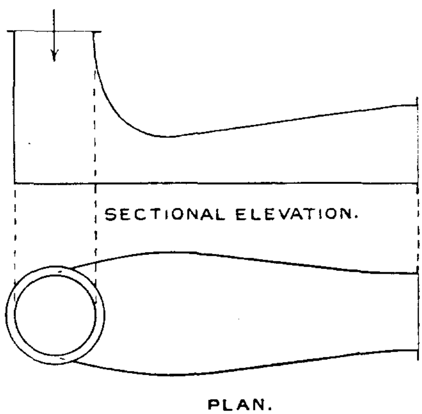
0·688 to 0·747 in the case of the submerged outlet. That meant that the loss at the bend was reduced by 0·32 times the velocity

Fig. 15.



head. In the original bend the radius was about equal to the depth of the tube at the bend, and the loss in such a bend would be between 0·4 and 0·5 of the velocity head. Thus sharpening the curvature of the outer surface and slightly increasing the depth had reduced the loss at that point to less than half, which was very satisfactory. He had come across a similar thing in connection with turbine design. Some makers of large water-turbines in Sweden used a suction-tube having a sharp right-angled bend in the outer wall, as shown in *Figs. 14*. That was evidently the most efficient form of suction-tube. It seemed to be remarkable that a sharp corner had the effect of reducing the loss at that bend; but the Authors' experiments appeared to point to a similar conclusion. He would appreciate any information the Authors could give as to the reason for that. If sharpening the lower bend reduced the frictional loss, why should not the same thing be done at the top bend? Arguing by analogy, the adoption of the design shown in *Fig. 15* would Mr. Naylor.

Figs. 16.



further reduce the losses in siphons, and he would like to hear the Authors' comments on that suggestion. The most important deduction from the facts just stated was that the ordinary standard pipe-bend ought to be arranged as shown in *Figs. 16*; the area of the throat would be the same as the normal area, but the section would be wider and shallower. If it were possible by such a design to halve the loss at every right-angled bend in a municipal installation, a great saving would result.

Mr. H. W. S. Husbands observed, with reference to the original experiments of which particulars were given on p. 207, that it was stated: "When the tail water-level is lowered sufficiently to unseal the outlet, the outlet stream breaks away from the upper surface at the beginning of the outlet-bend, which runs only partly full. Mr. Husbands

Mr. Husbands. In computing the coefficient of discharge under such circumstances, the working-head has been measured to the centre of the outlet." Measurements under the head giving a coefficient of discharge of 0·806 (which was a head of 0·629 foot with the outlet sealed) showed a value of 0·640 with the outlet having a free discharge. It appeared that the depth from the crest of the siphon to the middle of the outlet was 0·72 foot, which was more than the head mentioned. Presumably the head that was meant was the working-head, not the head of the upstream level over the crest; but if the upstream level was only just over the crest when the outlet was sealed, the head was bound to be greater when the outlet was free. The Authors and others had pointed out that the highest efficiency was obtained with the outlet just sealed. That was curious, because the head would be higher if the outlet were free. Would the Authors explain why they had come to that conclusion ? In the case of the models dealt with in Tables XX and XXI, there was a higher head with the outlet unsealed, but, in addition, the coefficient of discharge was higher with the outlet free than with the outlet sealed. Those models had no bottom bend, and eliminating the bottom bend had increased the coeffieient of discharge in both cases ; it therefore appeared to be better not to have a bottom bend. The last series of experiments dealt with in Table III, with the divergent outlet, showed that having the top surface horizontal and the bottom surface sloping down gave a better coefficient of discharge. It was curious that, although that siphon had a bottom bend, it would not prime automatically, and yet there were siphons without any bottom bend—only just a slight kink in the channel—that primed perfectly. There might be some other reason for that, and since Series No. 7 in Table III had a better coefficient than the others, it might be advisable to try an experiment with both top and bottom surfaces of the outlet slightly divergent. A difficulty in taking advantage of the higher coefficient obtained by eliminating the bottom bend, when it was necessary to seal the outlet, was the risk of trouble due to ice which might block the siphon at the outlet.

Professor Gibson. Professor GIBSON, in reply, on behalf of himself and his colleagues, thanked the members for the way in which they had received the Paper. Ice would be a very real trouble if the climatic conditions were severe enough and if due precautions were not taken in the design of the siphon ; but the fact that such siphons were working successfully in Canada and the United States, where the conditions were much more severe than they could ever be in this country, indicated that there was no real reason to fear troubles due to ice. As was shown by the experiments described in the Paper, and

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incidentally by experiments upon the Maramsilli siphons, described[1] by Mr. P. Davies, Assoc. M. Inst. C.E., the velocity at the throat of the siphon approximately obeyed the free-vortex law. The velocity was highest where the pressure was lowest, and the pressure was always low at the inner radius. That explained many of the apparent anomalies found in considering the coefficients of discharge of the two Italian siphons (A and B, *Figs. 6*) and of the siphons used by the Authors. The coefficients of the Italian siphons were very low, being 0·31 and 0·36, and although there was reason to suspect that there was leakage of air through cracks in the crown of the siphons, yet even if air leakage were disregarded the design would lead one to expect an extremely low coefficient of discharge. The very small radius of the top of the crest indicated that, if the free-vortex law was obeyed at the crown section, the velocity near the crest of the siphon must be very high and the pressure must be very low. Siphons of that type could not be expected to run at any but the lowest of heads without air gradually accumulating and forming a partial air-lock, and that was probably the major explanation of the very low coefficients of discharge. If a siphon for which experimental data were available was examined, it would be found, almost invariably, that when the coefficient was extremely low all the radii of curvature would be small. Mr. Naylor had emphasized that fact, and the design shown by him, having a crest with a very large radius, was excellent and would probably lead to higher coefficients of discharge than had been obtained in the experiments described in the Paper. He saw no reason, except the cost of the additional material put into the siphon and the necessity for a thicker crest, why that type of design should not be used. With reference to the limit of velocity at the throat of the siphon the maximum velocity should not be higher than would cause a negative pressure greater than about 24 feet of water. Assuming the reservoir level to be substantially the same as that of the crest of the siphon, that would mean that the velocity near the crest should not exceed about 40 feet per second. With that maximum velocity, the mean velocity at the throat would depend upon the radius of the bend. The bigger the radius, the more nearly could the mean velocity be allowed to approximate to the maximum velocity. The reduction in the loss at a bend due to the shortening of the outer radius was now a well-established fact. He thought that it had been discovered first by Professor V. Kaplan that losses in all bends could be considerably reduced by making the bends of

[1] Minutes of Proceedings Inst. C.E., vol. 224 (1927), p. 39.

Professor Gibson. the particular form just described, and that had been verified by other investigators. The draught-tube shown by Mr. Naylor was really a modification of the original Kaplan draught-tube. The effect of an outlet bend of the Kaplan type in increasing the discharge was due not only to the reduction of loss in the bend itself, but also, as explained in the Paper, to the fact that it reduced the tendency of the outlet bend to run partly empty. When, as in the Authors' large model, the outlet bend terminated in a divergent outlet of greater or less length, that also more readily ran full when preceded by a bend of the Kaplan type; and since there was a very appreciable gain of head with such a divergent outlet when running full, due to conversion of kinetic into pressure head, the beneficial effect of the Kaplan bend was largely due to that factor. The same was the case, but in a smaller degree, even when the divergent outlet was submerged, since by reducing the inequality of velocity across the section at entrance, it reduced the contra flow near the sides and the eddy-formation which was a feature of the motion in a divergent pipe, and thereby increased its efficiency as an energy converter. It had been suggested that such a bend might be used with advantage at the crown of a siphon. It would be interesting to try this experimentally, but there was a strong probability that difficulty would be experienced in getting rid of the air from the upper part of such a crown bend when priming the siphon. He was unable to agree that no siphon could have a working-efficiency of more than 50 per cent. An example in that connection was the Glens Falls feeder siphon. There was no reason why in practice any siphon, large or small, should not be so designed as to have an efficiency of discharge of 70 or 80 per cent. He had been greatly interested in Professor Dixon's observations about the experiments of Mr. Wu, and he remembered having seen some of the experimental work being carried out at the time; he was glad that that work had been so successful and that Mr. Wu's results agreed generally with the Authors'. With all the siphons used in the experiments described in the Paper that had an outlet-bend, priming was found to be possible with a free outlet. If a jet disperser were used at the outlet the pressure at the outlet would be raised; and consequently the pressure throughout the siphon, and therefore at the crown, would also be raised. If it were desired to increase the pressure at the crown so as to prevent it from approaching an absolute vacuum, he would, as had been suggested, arrange for the cross-sectional area at the outlet to be smaller than that at the crown, so that the velocity would be less near the crown than in the outlet-leg. There did not appear to be any agreed

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definition of the "efficiency" of a siphon—a term which several speakers had used—and the Authors had preferred for that reason to compare coefficients of discharge. If, by the most efficient siphon, was meant one which gave the maximum discharge with a given throat-area and a given head, that was also the siphon giving the *maximum coefficient of discharge.* The idea of calculating the coefficient of discharge on the mean sectional area of the siphon did not appeal to the Authors. The mean sectional area of many siphons was a very vague quantity, whereas the area at the crown was at least definite and easily determined. With regard to the statement that many large siphons would prime with a head not exceeding 2 centimetres over the crest, it was not clear whether or not the siphons to which reference was made had "baby" siphons incorporated in the design. Also it was not clear whether or not the lower edge of the air-vent was higher than the crest of the siphon, as was the case in many of the Italian siphons. In either of those cases the head necessary to produce priming was less than in a design of the type tested by the Authors. It would not be a difficult matter, however, so to modify that design as to enable it to prime with a head much less than one-third of the throat height, if that were an important consideration. Mr. Buckley's remarks as to the upstream levels in the tests of Table I were based on a misunderstanding. Actually, the upper edge of the outlet in those tests had been submerged to a depth of approximately 1 inch, so that the inlet had been fully submerged in all the tests. Experiments showed that, with a siphon running full, the effect of increasing the depth of submersion of both inlet and outlet, keeping the working-head constant, was negligible. Also that the effect of lowering the depth of the inlet by increasing the length of the inlet leg, keeping all other factors the same, was to cause a very slight reduction in discharge, such as was readily accounted for by the slight increase in frictional resistance.