

both units were later used for removing coarse sand only, the supply of raw sand being divided between them. It was found that the excess of fine sand could be effectively removed by skimming the sand in the filter-beds after backwashing gently. The grader worked by a process of elutriation, the fine sand being carried up the central pipe and the coarse sand falling to the bottom. In the unit illustrated, the upward velocity was about 0.33 foot per second. A larger central displacer was used in the lower half of the vertical pipe than in the upper, in order to compensate for the quantity of water coming in from the feeding ejector. The flows were adjusted by trial to give the desired grading. The best adjustment having been found, the heads on the various overflow sills were noted and thereafter worked to. It was found that shut-offs generally resulted in choked pipes. The waste water, which flowed into a nearby filter, was therefore allowed to run continuously day and night. The grader did not give quite so sharp a separation of the sizes as had been hoped, or could even have been achieved by sacrificing output. Nevertheless, a sufficiently high degree of uniformity was attained (see *Fig. 15*, p. 222). The rejected coarse sand averaged about 57 per cent. of the input; a further 7 per cent. of fine sand was subsequently removed by skimming the sand in the filters. Thus, approximately 36 per cent. of the slow sand filter sand was utilized, instead of about 45 per cent. available within the selected size limits.

APPENDIX IV.

SUPPLIERS OF COMPONENTS.

Suppliers of some of the main components employed in the construction of the works described were:—

The Harland Engineering Co. Ltd., Alloa	Pumps, electrical machinery, and wiring.
The Dorr-Oliver Co. Ltd., London	Flocculator equipment.
The Jewel Filter Co. Ltd., London	Filter-rate controllers, and control tables.
Messrs. Guest & Chrimes Ltd., Rotherham	Hydraulic and manual valves, Venturi meter, etc.
J. Blakeborough & Sons, Ltd., Brighouse	Reflux and flap valves.
The Stanton Ironworks Co. Ltd., near Nottingham.	Cast-iron pipes and specials.
The Paterson Engineering Co. Ltd., London	Dry feeding equipment for lime.
Edgar Allen & Co. Ltd., Sheffield	Grinding-mills.
Bell Bros. Ltd., Manchester	Limestone powder feeding equipment.
G. & T. Earle, Ltd., Hull	Cement.
The Hilton Gravel Co. Ltd., Derby	Sand and gravel.

Discussion.

The Author introduced the Paper with the aid of a series of lantern slides and a film. He said that waters which were treated for public supply purposes could vary greatly in turbidity, chemical composition, colour, and bacterial purity. He would, therefore, disclaim that the plant

which he had described in the Paper was one which could be installed in every case. The plant had been designed to suit the conditions obtaining at Bamford, and all he would claim for it was that it had been successful in doing that.

In 1937 he had found very little information about the details of filtration plant, particularly rapid gravity filters, in available English literature, but he had obtained a great deal of help and information from American sources. He thought that was due to the fact that in the United Kingdom most filtration plants were designed by specialist firms. Water engineers probably had a less detailed technical knowledge of the conditions which had to be met in water treatment, but they had an intimate knowledge of the plant for which they were responsible and the conditions that it had to meet, and they had not the same inhibitions in publishing the details as a commercial firm might have. In the United States it was apparently quite usual for consulting engineers to design filtration plants, and they published the results. Moreover, a large amount of research work had been done which had also been published very fully.

He stressed the usefulness of a pilot plant, which did not cost very much and might give most valuable information.

He had mentioned in the Paper the question of the loss of head in sand which was being expanded by the reverse flow in washing. He had certainly found out experimentally the facts which he had given in the Paper, but they were not entirely novel, because, since writing the Paper, he had found them stated in a very useful Paper by Fair and Hatch published by the American Waterworks Association in 1933.¹

Whilst he had not mentioned any turbidity figure greater than 15 parts per million on the silica scale, the figure at Bamford was occasionally very much higher, and for a short period in November and December of 1947 turbidities had ranged between 100 and 150 parts per million. In those circumstances the sedimentation tanks had proved extremely valuable, and without them great difficulty would certainly have been experienced. With their help it had been possible to produce a good filtered water without undue choking of the filters.

Sir Jonathan Davidson said that he admired the way in which the Author had set out to acquire his own data for the design and operation of the plant and to check the particulars that he had obtained from present-day American practice.

He thought it was likely that in the course of the discussion some comparison might be made between the rapid filters at Bamford and the contemporary installation of the Metropolitan Water Board at Hampton. He did not propose to discuss the relative merits of the two plants, which differed considerably in design and in mode of operation, but it should be understood that the purpose of the plants and the conditions under which

¹ "Fundamental Factors governing the Streamline Flow of Water through Sand," J. Amer. Waterw. Assn, vol. 25 (1933), No. 11, p. 1559.

they worked were not identical. The Author's problem had been to produce complete purification in one stage and to remove colour, for which purposes he used a coagulant. At Hampton the process of purification was carried out in two stages, the effluent from the rapid filters being passed to slow sand beds which operated at a higher rate than usual, so that the rapid filters there were really roughing or primary filters. Also, as no colour problem existed at Hampton, a coagulant was not used.

Another important difference was with regard to the water to be treated. The Author had stated that there was no algal trouble at Bamford, whereas at Hampton the water was sometimes so highly charged with algae as to be almost unfilterable with slow sand beds.

One of the most striking differences between the two plants was that the Author relied on a high-velocity wash for cleaning his beds, whilst at Hampton an air scour followed by a lower rate of upwash had been adopted. The question whether air scouring was desirable was a controversial one. Mr. T. D. Key had recently stated¹: "The benefits to be derived from air scouring have been largely overrated, and in certain cases its use may cause more harm than good." As a result of the experience in operating the Hampton plant, it had been definitely found that the omission or the partial application of the air scour had resulted in imperfect cleaning of the sand. The difference from the results obtained by the Author, however, might be accounted for mainly by two factors. First, the area of the beds at Hampton was more than twice the area of those at Bamford, and, secondly, the sand was much coarser at Hampton. The Hampton sand had an effective size of 0.84 millimetre, as compared with 0.45 millimetre at Bamford, and a uniformity coefficient of 1.8, as compared with 1.32 at Bamford.

The Author had referred, in the introductory section of his Paper, to "a superfluous clear-water reservoir." Why was it "superfluous"? Surely such a reservoir would assist materially in maintaining a constant rate of flow through the slow sand beds, which was a most desirable thing at which to aim.

Mr. H. F. Cronin referred to the Author's choice of the third of three courses which had been open to him, namely:—

- (1) Pressure filters and coagulation.
- (2) Rapid gravity filters and the existing slow sand filter beds.
- (3) Rapid gravity filters and coagulation.

The reason for discarding the second was not given, but Mr. Cronin suspected that it was the desire of the Author to abolish the slow sand filters, a type of plant which often gave trouble and which was expensive to operate.

¹ T. D. Key, "Cleaning of Filter Sands," J. Instn Civ. Engrs, vol. 29, 1947-48 (February 1948), p. 326.

The water from which the supply for London was drawn was very different from that in the Derwent Valley reservoirs. The staff of the Metropolitan Water Board had tried (so far unsuccessfully) to use rapid filtration with a coagulant because the capital cost of slow sand filters was high and they were difficult to operate, as well as expensive to clean. The chief reason why coagulation had failed was that the algae, particularly the blue-green algae, developing in the reservoirs caused the floc to float instead of to settle in the tank.

To further research in that matter the Board had approved an expenditure of £55,000 on an experimental plant with four types of basin for coagulation and two rapid gravity filters. Each filter would deal with about 250,000 gallons per day, so the installation would be on a practical scale. The plant was now being constructed but, as it had only been possible to secure W.B.B. priority for it, the rate of progress was not very high.

Air scour was still used in London and had been found quite satisfactory, but the Metropolitan Water Board's engineers had not been able to carry out the experimental work on the subject which had been done by the Author, because they had been engaged on other work.

Mr. Cronin described the arrangement adopted by the Metropolitan Water Board for compressing air without the use of a power-driven compressor. The wash-water tank was at the top of a tower in the filter building and was fed by a supply from the pumping mains. Underneath the tank was a closed steel compression cylinder about the size of a Lancashire boiler. When the bed had to be cleaned, compressed air was first passed through the filtering medium, followed by the wash water. The compressed air was obtained by letting water down from the wash-water tank into the compression tank, and when that tank was partly full of water and the top part was full of air, the water-valve was closed. The air-valve on the top of the compression tank was then opened and the air was allowed to pass through the bed. After that the wash-water valve was opened, and as the wash water discharged from the compression tank it drew a charge of air in through a non-return valve, and thus left the cylinder full of air ready for compression when the next bed required washing. That arrangement involved no moving parts, but it necessitated a larger capital expenditure than would be required in the case of air-compressors.

The first air-compressors used by the Metropolitan Water Board were of the reciprocating type and a certain amount of trouble had been experienced with oil from them getting into the under-drains. The Board had no experience with the rotary type of air-compressor, which was placed on the market at a later date.

Mr. Cronin made reference to the deposit which formed upon the grains of sand in the primary filters after some years' running. The sand was Leighton Buzzard sand, originally sharp and clean, but in due course it

acquired the appearance of coffee grains, rounded and covered with calcium carbonate, which was easily removed by hydrochloric acid. Had the Author found any growth on the grains of sand in his filtration plant, and further, if the sand grains did grow as he had just described, would that upset the Author's washing arrangements and cause greater expansion, and perhaps result in sand being carried over with the wash water ?

Mr. Cronin then showed lantern slides illustrating the interior of the primary filters at Walton, Kempton Park, Stoke Newington, and Hampton. At Walton the effluent from the filters flowed over a weir and the rate of filtration was controlled by a float operating a double-beat valve. It was a very simple and robust control, the only objection to it being the noise of the water falling over the weirs. As there were eight filters in the filter-house the noise was somewhat excessive.

The same type of control apparatus had been used at Kempton Park, where there was a white-tiled channel down the middle of the house through which the water flowed, giving the staff visual indication of the state of the water leaving the filters. The disadvantage, however, of the white-tiled channel was that dirt and deposit adhered to the tiles, the cleaning of which became difficult in consequence. In that case also there was the noise of the water falling over the weirs, but there also the control apparatus was robust and easy to examine and to adjust.

The interior of the primary filters at Stoke Newington was rather like that of those at Bamford. All pipes, channels, etc., were located below the floor-level and the movements of valves were operated from a control table at the side of the centre aisle. The outlet control was by Venturi meter and there was no noise and nothing to see. One of the disadvantages of the apparatus at that works was that the indicators were operated by wires which required a good deal of attention, and there was also some difficulty in keeping the control valves in order.

There was also a central channel in the Hampton primary filtration plant, but in that case the outlets were controlled by Venturi meters and the water was discharged into the channel without any noise.

The choice of the design of the control gallery and the interior of a primary filter-house presented some difficulty, as the water in the filters behind the side walls, and any water which might be present in channels inside the building, caused condensation, and, in addition, when the water became cold it was not easy to keep the building warm.

Mr. Cronin then drew some comparisons between the stations at Walton and Bamford, which had very similar outputs. The works at Walton had a designed output of about 24 million gallons per day. Water from the river was pumped into storage reservoirs, circulated in them, then passed through primary filters, and finally filtered through six slow sand filter beds.

With regard to the question of capital cost, he thought that the works at Bamford cost about £94,000, and if that were reduced to 1938-39

figures, it would be about £73,000. With an output of 23 million gallons per day, the capital cost was £3,200 per million gallons per day.

The filtration works at Walton, together with the roads, etc., cost £173,000 in 1926, which worked out at a capital cost of £7,200 per million gallons filtered per day.

Four more slow sand filter beds were being constructed at Walton and the price for those was extremely high. Each of the existing filter beds had cost about £21,000, whereas each of the four new ones that were being constructed would cost about £70,000, which he considered very expensive, although it had to be admitted they were slightly more elaborate than the older filter beds.

During 1947 the Walton works operated at a rate of about 23 million gallons per day and the cost per million gallons filtered was 27 shillings, that was, the cost of labour and materials, but chiefly labour. The Author had not given his costs, but, assuming that chemicals cost £5,000 per annum and labour £1,000, Mr. Cronin believed that the cost at Bamford would be about 17s. 6d. per million gallons filtered. It therefore seemed that the rapid filter working with coagulation was considerably cheaper than the dual filtration method using slow sand filter beds.

As a minor matter of detail, Mr. Cronin thought that the Author should have expressed the dose of aluminium sulphate in the table on p. 235 as parts per million and not as grains per gallon.

Mr. R. W. Aitken, referring to the question of high-velocity upwash and air scour, said that the practice in America was to use high-velocity upwash only, without any air scour, and that had led American water engineers to attach very great importance to pre-treatment, that was to say, treatment before the water actually reached the filter. There could be no doubt that, when the water was adequately treated chemically, conditioned, and settled, so that the floc that was formed in the water going on to the filter was of a non-adherent type, the filter would be satisfactorily cleaned by upwash only. If, however, complete pre-treatment was not always available, the use of upwash alone tended to cause trouble. That seemed to be the experience at Hampton when air scour had been omitted.

The main difficulty when upwash only was used was "mud balling" or the formation of mud zones in the filter. That occurred because most of the dirt removed from the water was concentrated near the surface and tended to cause the sand grains to stick together. When the bed was upwashed, the surface layer broke up into particles larger than the individual sand grains. Those larger particles then settled down into the expanded bed to form mud balls. That was one type of mud ball and was usually found at the side walls of the filter. In another type of "mud balling" the particles were relatively small and, because of the binding material, the specific gravity of the whole was less than that of the sand grains. Those relatively small particles tended to remain on top of the

filter and had to be scraped off occasionally ; otherwise the filter would become choked.

Such troubles did occur with high-velocity wash, and there was a considerable amount of literature in the American journals on methods of dealing with them. In 1940, the American Society of Civil Engineers had published a manual on the design of water treatment plants, which recommended the use of surface washing of the sand with high-velocity jets projected down on to the sand bed. The object was to break up the surface layer before the bed became a quicksand and the larger particles could sink into it. As a matter of interest, the breaking up of the surface layer before the sand bed became a quicksand was exactly the function of air scour.

About 30 years ago both air scour and the jet method of breaking up the surface layer had been used in the United Kingdom. On the whole, air scour was used more often nowadays, because it had been found to be more efficient than the water jet.

The Bamford filters worked at an upwash rate to give 50 per cent. expansion, and a great deal of trouble was taken to maintain that rate. It would be interesting to know how that particular rate had been arrived at. It was seldom found, when upwash only was used, that there was any advantage in increasing the rate beyond that which suspended all the working sand. The cleaning action of the water on the sand grain was the shearing force of the water when flowing past it, and that reached a maximum when the grain was suspended. If upwash were increased beyond that, all that happened was that the sand grains moved apart, and the same velocity past the grains was maintained.

It was necessary, when high-velocity wash only was used, that all the working bed should be suspended. If it were intended to remove dirt, using the whole of the fine sand layer, then the whole of that layer would have to be suspended ; otherwise dirt might be found adhering to the surfaces remaining in contact in the lower layers. If all the particles of sand were of the same size, that was, infinitely close grading, it would be possible to suspend the whole of the sand bed without expanding it at all. That did not happen in practice, so that if the bottom of the sand bed were suspended it was necessary to expand the top of the bed. For that reason it seemed that the degree of expansion of the bed depended on the relation of the maximum and minimum sizes of the sand particles used. At Bamford those limits were fairly close and yet a fairly high percentage expansion was used, which Mr. Aitken believed would be more than was necessary to expand the sand at the bottom of the bed.

With regard to the terms " effective size " and " uniformity coefficient," used to describe a particular sand, he thought that before those terms became too common a means of describing a filter sand, more attention might be paid to what they really meant. They had been originally invented by Hazen, who was a master of the empirical formula, as para-

meters in empirical formulae which he produced for calculating certain phenomena when using natural sands or hydraulically graded sands. Hazen had not intended them to be used where closely graded sands were to be employed, and Mr. Aitken considered that a maximum and minimum size would have been a more satisfactory way of describing a closely graded sand.

Mr. Julius Kennard observed that when Mr. Edward Sandeman had been responsible for the construction of the original Bamford filters, some 40 years ago, slow sand filters had been the vogue. Rapid filters had only just been introduced, and Mr. Sandeman had probably adopted a somewhat revolutionary practice in installing roughing filters. There could be no doubt, however, that those filters had proved to be very successful, because the yield of the original plant, as stated in the Paper, had been fully 12,000,000 gallons per day, and, if Mr. Kennard's arithmetic was correct, it would tend to show that, with one bed out of commission for cleaning, the flow of 12,000,000 gallons per day was equivalent to a rate of 3.13 gallons per square foot per hour, which was more than 50 per cent. in excess of the commonly accepted rate of 2 gallons per square foot per hour. Therefore the roughing filters had definitely done very good work.

He would like the Author to elaborate his reasons for choosing the particular filtering method from those available to him. The Yorkshire Bridge filters, which were mechanical filters of the pressure type, had a yield of 9,000,000 gallons per day, and the ultimate yield of the Derwent works was about 30,000,000 gallons per day, now that the Ladybower reservoir had been constructed for compensation water, so that the Author had had to consider the problem of providing an additional filtering capacity of about 21,000,000 gallons per day; and Mr. Kennard was pleased to see that the Author had, in fact, installed a plant of a capacity of 23,000,000 or 24,000,000 gallons per day.

Mr. Cronin had referred to the cost of the Bamford works, which was given in the Paper as £92,500, but Mr. Kennard had expected Mr. Cronin to go a little farther and express his view on that cost, because the construction of a treatment plant with a capacity of 23,000,000 or 24,000,000 gallons per day at a cost of £92,000, even allowing for the additional cost of paving the filter-house eventually, meant that the cost was less than £4,000 per 1,000,000 gallons treated, which, in his view, was very low indeed, notwithstanding the advantages which the Author had had in being able to make use of the available filter beds and other works. It was interesting to note that the original filters had cost £105,000, which worked out at about £9,000 per 1,000,000 gallons per day treated, and that was at pre-1914 rates.

The Author had mentioned, in his introductory remarks, that it was unwise to generalize in matters of the kind in question, and Mr. Kennard would therefore like to refer to three cases with which he had been associated recently.

In case A the authority concerned had already had in operation four slow sand beds, with a capacity of about 2,000,000 gallons per day, which was equivalent to a rate of 2 gallons per square foot per hour. An additional impounding reservoir had had to be constructed, which increased the yield and the quantity of water to be treated by a further 1,000,000 gallons per day and, after some consideration, the conclusion had been reached that the method of double filtration employed by the Metropolitan Water Board was to be preferred in that case. Rapid gravity filters had been installed with a rate of 100 gallons per square foot per hour, and, by the water being passed through those filters first, it had been possible to increase the rate to something over 4 gallons per square foot per hour through the existing slow sand beds. The cost was £5,000 per 1,000,000 gallons per day treated. There were some special expensive construction items, although there was no chemical plant required.

In case B, where 4,000,000 gallons per day of somewhat polluted water was obtained from the gathering ground, the rate of flow through four slow sand beds was 1.866 million gallons per day at 2 gallons per square feet per hour. It was decided that it was desirable to scrap completely the existing slow sand beds and to install new rapid gravity beds, and that work was under construction. Coagulation would be adopted and there would also be lime correction. The cost would be about £10,000 per 1,000,000 gallons per day. That was a high figure and was due to the cost of some expensive generating plant which would be operated by high-pressure water from one of the reservoirs.

In case C the water was river water where the colour at times was as much as 300 parts and the turbidity 400 parts per million. The maximum rate of abstraction was about 10,000,000 gallons per day. Part of the water was pre-treated before storage in subsidence reservoirs, then passed to rapid gravity filters, and finally to slow sand beds; the other part was conveyed direct to a clarifier before being dealt with by rapid and slow sand filters. The treatment consisted of dosing with alum up to 4.3 grains per gallon, activated carbon 1.34 grain per million, and chlorine 2.6 parts per million. The water eventually produced was satisfactory, after passing through nearly all the operations known to water engineers. It was now proposed to introduce improvements by constructing an additional conditioning plant and clarifier, which should allow for an increased rate of flow through the slow sand beds.

Mr. N. J. Fugh said that during the course of the discussion much stress had been placed on filters, but he wished to refer to the other part of the treatment which was taking place at Bamford. Before doing so, however, he would like to ask what was the *pH*-value of the water produced from the Bamford works. The Author had mentioned various *pH* values in the Paper, but had not given the *pH*-value of the final water at Bamford.

He shared the Author's preference for non-corrodible material in the base of any form of filter. There was great danger in using anything which

was not practically indestructible if it was to be buried and to remain buried for a very long time. The deterioration of corrodible materials, unseen and possibly undetected, might lead to great trouble in filter beds. Mr. Pugh agreed with the Author's plea that that aspect should be very seriously considered wherever new plant was being installed.

It could be quite easily seen that the Author's approach to his problem at Bamford had been influenced, if not dominated, by the existing structures, of which he had to make the best possible use. He had been limited for head on filters, the available head being 10 feet 6 inches, and that had, no doubt, influenced certain other aspects of his work. He had also had a number of filters which were going to be surplus, and it appeared as though he had said to himself: "I may as well use these somehow. What about a little sedimentation before we put this water on to the filters?" He had therefore tackled the problem of sedimentation and had improved his results by flocculation. In those beds, which Mr. Pugh imagined were not very expensive to construct or difficult to operate, the Author had obtained a 50-per cent. improvement in colour and a 75- to 80-per cent. improvement in the bacteriological quality of the water. Was that bacteriological improvement influenced by pre-chlorination, and, if not, could not that device probably produce a settled water free from the greatest danger in water, namely, bacteriological impurity?

If the Author had approached his problem entirely anew, without the background of the existing works to influence his approach, would he not have tried to get even better results by the first stage of his treatment, namely, sedimentation? Mr. Pugh very strongly advocated the greatest safety at the earliest possible moment as the first principle of the treatment of water for a public water-supply. If the bacteria could be removed in the first stage, even if the water were not so good, so far as colour was concerned, as at the end, at least it was safe. If the final sterilization and dealing with the most-to-be-feared element in impurity, namely, bacteria, were left to the last, that was not consistent with "safety first," which should be one of the axioms in water treatment. He would therefore like to ask whether the Author could remove the impression that the first stage, the sedimentation, had been regarded as merely preparing the water in a fairly crude way for the filters.

The Author had stated that he did not mind if the sedimentation was not quite so effective at certain times, as it maintained the work of the filters, and perhaps he would enlarge on the question whether filtration was necessarily the major or principal stage in all questions of treatment. Might not it sometimes be a supplementary stage rather than the principal stage? Was not it better to look at water treatment as consisting of stages, every one of which was important and might have more advantages than the other stages? It might be that filtration was not always the stage from which the greatest benefit would be obtained.

The Author, in reply, said that the clear-water reservoir at Bamford

had been termed superfluous because it had never been used as a clear-water reservoir. As soon as the original plant was put into use the reservoir had been filled with filtered water, and he had been informed that the water promptly turned a bright green colour. It had then been found that the reservoir was not necessary and that a uniform flow down the aqueduct could be maintained quite easily by regulating the slow sand filters. Therefore the reservoir had been used as a store for sand, and later it had been turned into a settling tank for the dirty water from the filter washing. If ever needed as a clear-water reservoir it should have been roofed over.

The reason why rapid gravity filters had been adopted with sedimentation tanks, instead of rapid gravity filters followed by slow sand filters, was that, owing to the position of the filters on an aqueduct, they would have encroached on the head for the siphons either upstream or downstream if the works had been arranged in any other way. Rapid gravity filters could have been put at the inlet to feed into the slow sand filters, but that would have encroached on the siphon upstream. Additional slow sand filters would have had to be constructed, and on that hillside site they would have been very costly. Further, since the required removal of colour involved the use of a coagulant, complete purification could be effected without using slow sand filters at all. Therefore it appeared that the best course to adopt would be to make the rapid gravity filters the main part of the plant and to use sedimentation tanks formed out of the old slow sand filters as a preliminary.

The sand grains in the Bamford filters and in the filters at Yorkshire Bridge became coated with a kind of varnish of iron and alumina, but the sand grains in the Bamford filters were certainly not acquiring that coating at anything like the rate at which those in the pressure filters had acquired it. In five years the coating had not become great enough to effect the flotation of the grains perceptibly. It would be noticed that Table I, which showed the grading of the sand, included two series of tests, made in 1934 and 1936, and that those indicated very little change in the grading. A certain quantity of fine stuff had been washed out, but there had been nothing to suggest that the sand grains had become appreciably bigger.

Mr. Kennard had pointed out that the old filter plant had cost more than £100,000 in pre-1914 days, and to some extent it had been possible to use part of that value in the new plant, reducing the cost below what it would have been if the new works had been started on a completely undeveloped site. It was rather difficult to say exactly how much should be added to make the pre-1939 figure of £70,000 into something rather larger, representing the total cost of the plant as it now stood. With regard to the operating cost, in 1947 an average of nearly 21 million gallons per day had been filtered, and the overall cost, including the capital cost of the original filters and the new ones, had been about 0.85*d.* per 1,000 gallons. It was difficult to divide certain costs accurately between York-

shire Bridge and Bamford, because limestone was ground at Bamford for Yorkshire Bridge and the lime was put in at the Bamford filters for both plants. In view of that, the operating costs at Bamford should be put at a little below 0.85*d.* per 1,000 gallons.

In reply to Mr. Aitken, the first indication of a filter not being sufficiently washed was that the sand started to crack away from the sides of the filter. It was a very good plan to draw the water right down to the sand occasionally or, better still, as a routine matter once every week or two, to make sure that the dirty bed, after it had run but before it was washed, was not showing a parting away from the side. If it was, the sand contained an appreciable amount of silty material, and the way was open to the formation of mud balls. The Author had tried washing with a little less than 50 per cent. expansion and had found that symptoms of that sort were beginning to appear; therefore he had reverted to 50 per cent. expansion. At that rate he had, in fact, managed to keep the sand remarkably clean during the period of nearly 5 years during which the plant had been operating.

There might be some substance in Mr. Aitken's point that if the sand were not so uniformly graded a different rate of expansion might be appropriate; but the grading that had been used was about as close as could be obtained, practically speaking, and, for dealing with a large bulk of sand and that type of grading, 50 per cent. expansion seemed to be a very good working rule.

The Author found himself unable to agree with Mr. Aitken's view that there was no advantage in increasing the rate of wash beyond that necessary to suspend all the sand. As the rate was increased beyond that point, the greater space between the sand grains allowed freedom for movement and vigorous agitation resulted throughout the full depth of the bed. There were irregular and constantly changing currents, both vertically and horizontally, and those caused the grains to be rubbed vigorously one against another, so dislodging adhering dirt in a way that streamline flow around the grains could not equal.

Where the water contained much silt or had not been effectively pre-treated by sedimentation, air scour was, no doubt, an effective method of breaking up the mud layer at the surface of the bed, but, in the Author's view, it did little to cleanse the bulk of the sand.

After the water came from the filters it had a *pH*-value of approximately 6.0, but after the lime had been added, that was to say, before the water was sent down to the aqueduct, the *pH*-value was raised to 8.0. The aqueduct had lengths of cut-and-cover, then siphons, and then more cut-and-cover, and the *pH*-value of the water decreased slightly in passing over it.

The question raised by Mr. Pugh, as to how much reliance should be placed on the filters and how much on pre-treatment, was a matter for decision in each particular case. A great deal of the purification could be

effected by means of efficient sedimentation tanks, and at lower cost. However efficient such tanks might be, they would require to be supplemented by filters if water of high clarity were required.

The water at Bamford was not liable to have any dangerous bacterial pollution, and the chlorine put in after filtration was really intended to make doubly sure of the water being free from bacterial impurity. The water was practically sterile when it came from the rapid filters. The degree of colour removed had also proved to be a very reliable indication of bacterial efficiency.

Paper No. 5640.

“ Drag Velocity in relation to Production of Turbulent Energy and Loss of Head in Pipes in the V^2 -Law Region of Flow.”

By JAMES WILLIAMSON, M.I.C.E.

(Ordered by the Council to be published with written discussion.)†

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INTRODUCTION.

IN a Paper presented to The Institution in 1939,¹ the Author advanced reasons for considering that the Manning formula $V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}$ (metre-

† Correspondence on this Paper may be accepted until the 15th September, 1948, and will be published in a Supplement (obtainable on request) to the Institution Journal for October 1948. Contributions should be limited to about 600 words.—SEC. I.C.E.

“Consideration on Flow in Large Pipes, Conduits, Tunnels, Bends, and Siphons,” J. Instn Civ. Engrs, vol. 11 (1938-39), p. 451 (Apr. 1939).