between the sand grains as much oxygen as practicable whenever the filter may be at rest.

224. Bacterial Efficiency and Purification—Hygienic Efficiency.—As the function of a filter is to remove as far as possible the organic matter and bacteria of the applied water, there must be some criterion by which its efficiency in the performance of those functions can be expressed. The bacterial efficiency is represented by the ratio found by dividing the number of bacteria after filtration in a prescribed cubic unit, as a cubic centimeter, by the number which the same volume of raw water held before being applied to the filter. This is a rather misleading ratio, for the reason that the effluent water may contain bacteria of certain species which grow in the lower portions of a filter or in the drains which conduct the effluent from it. It is possible, therefore, that bacteria may be found in a filter effluent when all of the bacteria originally held in the water have been removed. Hence the ratio expressing what is called the bacterial purification arises from dividing the number of bacteria actually removed from a cubic centimeter of water by the filter by the number originally held by a cubic centimeter of raw water. The smaller the first of these ratios the higher the degree of efficiency. Extended experience, both in the filters of such laboratories as that of the Massachusetts State Board of Health and with actual filters of public water-supplies, show that under attainable conditions of operation 98 to 100 per cent of all the bacteria originally found in the water may be removed.

There is also used the term hygienic efficiency which is used in connection with slow sand filters. This means simply the per cent of pathogenic bacteria removed by the filter, and there is good reason to believe that it is at least as high as the bacterial purification.

225. Bacterial Activity near Top of Filter.—The work of removal of bacteria and organic matter has been found by extended investigations to be performed almost entirely within 6 or 8 inches of the top surface of the sand; indeed the most active part of that operation is probably concentrated within less than 3 inches of the surface. At any rate the retained bacteria and nitrogenous matter are found to decrease very rapidly within a

foot from the upper surface, below which stratum the quantity is relatively very small and its rate of decrease necessarily slow. A little of this nitrogenous or gelatinous matter is found to surround to a slight extent the sand grains found at the bottom of the filter. Some authorities have considered that the more steady uniform efficiency of the deeper filters is due to this effect.

226. Rate of Filtration. — The rate at which water can be made to flow through a slow sand filter is of economical importance, for the reason that the higher the rate the less will be the area required to purify a given quantity per day. Foreign engineers and other sanitary authorities advocate generally slower rates of filtration than American engineers are inclined to favor. The usual rate in Europe is not far from 1.6 to 2.5 million gallons per acre per day. There is also considerable range in this country, and the rate may reach 3 million gallons per acre per day. Indeed a considerable number of tests have shown that for short periods of time, at least, some waters may be efficiently filtered at rates as high as 7 to 8 million gallons per acre per day, but probably no American engineer is ready to introduce such high rates as yet. As a matter of fact the rate will depend considerably upon the character of water used. Clear water from mountain lakes and streams uncontaminated and carrying little solid material may be filtered safely and properly at much higher rates of filtration than river or other waters carrying more sediment and more organic matter. This principle is recognized both in Europe and in this country. It would appear from experience that slow sand filters at the present time with rates of 2.5 to 3 million gallons per acre per day may be employed for practically any water that may be considered suitable for a public supply, and that with these rates high degrees of both bacterial purification and hygienic efficiency may be reached.

227. Effective Head on Filter. — Inasmuch as the depth of sand ranges from perhaps 3 to 5 feet the water will experience considerable resistance in flowing through it. The distance in elevation between the water surface over the filter and that of the water as it leaves the filter measures the loss of head experienced in passing through the sand and the drainage-passages under it. It has been maintained by some foreign

authorities that this loss of head should be not more than 24 to 30 inches; that a greater head would force the water through the sand at such a rate as to render desired purification impossible. Experience both in the laboratory and with public filters in this country does not appear to sustain that view of the matter; considerably greater heads than 30 inches have been used with entirely satisfactory results both as to the removal of organic matter and bacteria. It appears to be best so to arrange the flow of water through the sand and the underdrains as to avoid in either a pressure below the atmosphere, as in that case some of the dissolved air in the water escapes and produces undesirable disturbances in the sand, resulting in reduced efficiency. No precise rule can be given in respect to this feature of filtration, but it seems probable that satisfactory results may be obtained under proper working of filters with a loss of head not greater than the depth of water on the filter added to the depth of sand in it, although that maximum limit would ordinarily not be reached. The depth of water on the filter may be taken from 3 to 5 feet. In this country it is seldom less than the least of these limits, and perhaps not often equal to the greater limit.

228. Constant Rate of Filtration Necessary.—Care should be taken in the operation of filters to avoid any sudden change in the texture or degree of compactness of the sand. At the times when workmen must necessarily walk over the surface they should be provided with special broad-based footwear, so as to produce as little effect of this kind as possible where they step. Sudden changes in the degree of compactness cause correspondingly sudden changes in the rate of filtration, and such changes produce a deterioration of efficiency. This may be due to two or three reasons. Possibly such changes may open small channels through which water finds its way too freely; or the breaking of the gelatinous bond between the grains of sand may operate prejudicially. At any rate it is essential to avoid such sudden changes and maintain as nearly uniform a rate of filtration over the entire filter as possible. Again, the age of a filter affects to some extent its efficiency. A month or two of time is required, when a new filter is started, to attain what may be called its normal efficiency. Even after that length of time the filter gains

in its power to retain and destroy bacteria. This action is particularly characteristic of filters formed of comparatively coarse sand.

229. Scraping of Filters.—More or less solid inert as well as organic matter accumulates on the surfaces of the slow sand filters, so that at t[illegible]d of proper periods of time, depending upon the character of the water filtered, this surface accumulation must be scraped off and removed together with the sand into which it has penetrated. In scraping the filter it is impossible to remove less than .25 or .5 inch of sand, and at least .5 to .75 inch is removed whenever a filter is scraped. Sometimes 1 or 2 inches may be removed. This sand may be washed and again placed upon the filter for use. The operation of scraping exhibits a fresh sand surface to the applied water. It has been held, particularly by foreign authorities, that this operation of scraping militates against the efficiency of the filter for the time being. The investigations of the Massachusetts State Board of Health and other experiences in this country do not confirm that view which is based on the assumption that the top nitrogenous film is essential to efficiency. These investigations have shown that this film is not necessary in intermittent filters; that in many instances no diminution of efficiency has resulted from a removal of the film to a depth of .3 inch; that even the presence of that film has not given efficiency to coarse sand when the coating was thick enough to completely clog the filter; and, further, that the material of this nitrogenous film is found at a depth of several inches below the surface. It is practically certain that the scraping to depths not exceeding 1 inch have no sensible effect upon the efficiency under proper management and operation of the filters. This is particularly true if the thickness of sand is from 3 to 5 feet. It is undoubtedly true that with very shallow sand filters from 1 to 2 feet in depth the scraping of the surface may have some effect upon bacterial efficiency.

It has been the custom in connection with some European filters to waste the water which first passes through after cleaning, but the usual practice in this country is to fill slowly the filter with filtered water from below and, after the sand is submerged, to permit it to stand a little while before use. Care taken in

this manner will insure an efficiency to a freshly scraped filter sufficient to avoid any wastage.

230. Introduction of Water to Intermittent Filters.—Where intermittent filters are used it is of the greatest importance to conduct the water to them so as not to disturb the sand on their surfaces. This can readily be done in a number of ways. If the shape of the filter is not oblong, it will be advisable to form a number of main drains or passages in the sand from which smaller depressions or passages near together may lead the water to all parts of the surface. The flowing of the first water through these depressions will permit the entire surface to be covered so gradually as not to disturb the sand grains, and it is essential that such means or their equivalent be employed. If the filter is long and narrow in shape, the main ditch along one of the longer sides, with depressions at right angles to it or across the filter and near together, will be sufficient to accomplish the desired purpose. Obviously when filters are not intermittently used such precautions are not needed.

231. Effect of Low Temperature.—In the early days of the use of sand filters in this country it was frequently supposed that the low temperature of the winter caused decreased bacterial purification and a decrease in power to reduce organic material. It now appears that such is not the case. The effects of low temperature, such as is experienced in winters of this climate, may be overcome by temporarily covering the filters so that heavy ice cannot form and produce disturbances in one way or another prejudicial to efficiency of operation. The agencies which operate to reduce efficiency in cold weather are no longer believed to be those due to low temperature. They are rather indirect and mechanical, and may be readily overcome by the prevention of the formation of ice.

232. Choice of Intermittent or Continuous Filtration.—The process of slow sand filtration when continuous has been shown by experience to be entirely effective for ordinary potable waters, but in those cases where the amount of dissolved oxygen may be low and where the amount of organic matter is relatively high it may be advisable to resort to intermittent filtration. Neither method, however, can be depended upon to render potable a

water which has been robbed of its free oxygen by an excessive amount of contaminated organic matter. Nor can these processes be expected to remove coloring matter produced by peaty soils or other conditions in which large amounts of vegetable matter have been absorbed by the water. The methods, therefore, have their limitations, although their field of application is sufficiently wide to cover nearly all classes of potable water.

233. Size and Arrangement of Slow Sand Filters. — Among the first questions to arise in the design of slow sand filters are their size and arrangement. The total area will be determined by the total daily draft and the rate of filtration. Rates of filtration running from 2.5 to 3 million gallons per acre per day, or even more, have been found satisfactory and are customary in this country. Having given, therefore, the total daily quantity required, it is only necessary to divide that by the rate of filtration per acre and the result will be the number of acres required for the total filter-bed surface. This net area, however, is not sufficient. Unless there is requisite storage of filtered water to meet the variation in the hourly draft for the day, the capacity of the filters must be sufficient to meet the greatest hourly rate, which must be taken at least $1\frac{1}{2}$ times the average hourly demand during the day; indeed this is only prudent in any case.

Again, it is necessary to divide the total filter surface into small portions called beds, so that one or more of them may be withdrawn from use for cleaning or repairs, while a sufficient filter-area remains in operation to supply the greatest hourly draft. This surplus area will usually run from 5 to 20 per cent of the total area of the filter-beds, although for small towns and cities it may be much more. The sizes of the filter-beds will depend upon the local circumstances of each case. It is evident that as each single bed must have its individual set of appliances and its separating walls, the purpose of economy will be best served by making the beds as large as practicable. At the same time they must not be made too large, for in that case the portion out of use might form so large a percentage of the total area as to increase unduly the cost of the entire plant. A size of bed varying between .5 and 1.5 acres is frequently and perhaps generally found in foreign filtering-plants. If filter-beds range in

area from .5 acre to 2 acres, the latter for large plants, the purposes of economy and convenience in administration will probably be well served. The grouping of the beds is an important consideration and will depend somewhat, at least, upon the shape of the plot of ground taken for the filters. It is advisable that the inlets to the different beds should, as far as possible, discharge from a single inlet-pipe or main. This will generally be most conveniently accomplished by making the beds rectangular in shape, grouped on each side of the supply-main, with their longest dimensions at right angles to it. This arrangement is illustrated by the grouping of the filter-beds in the Albany plant, shown in Fig. 7. In the case of a single oblong bed, like that at Lawrence, Mass., shown in Fig. 4, page 284, its relatively great length and small width makes it possible to run the main supply along one side, from which branch depressions with concrete bottoms enable the water to be distributed uniformly over its surface in the manner shown in the figure. It is further necessary to group the filter-beds, pumps, sand-cleaning appliances, and other portions of the plant, so that the ends of economy and efficient administration may be served in the highest degree. It is always necessary that these features of the whole filtration system should be carefully kept in view in laying out the entire plant.

234. Design of Filter-beds.—The preparation of the site for a group of filtration-beds also involves the consideration of a number of principal questions. In the first place, the depth required for the sand and underdrains will not be far from 5 feet, and there must be a suitable bottom prepared below the collecting-drains. Again, the depth of water above the sand may vary from 3 to 5 feet, making the total depth, including the bottom, of the filter proper about 10 or 11 feet, and this may represent the depth of excavation to be made. If the material on which the filter to be built is soft, it may be necessary to drive piles to support the superincumbent weight. The bottom must be made water-tight. This can be done either by the use of a layer of well rammed or packed clay, 1 to 2 feet in thickness, carrying 6 or 8 inches of concrete, or by a surface of paved brick or stone. If the sides of the filter-beds are of embankments with surface slopes, the latter may be protected in the same manner. If the

sides are of walls of masonry, concrete is an excellent material to be used for the purpose.

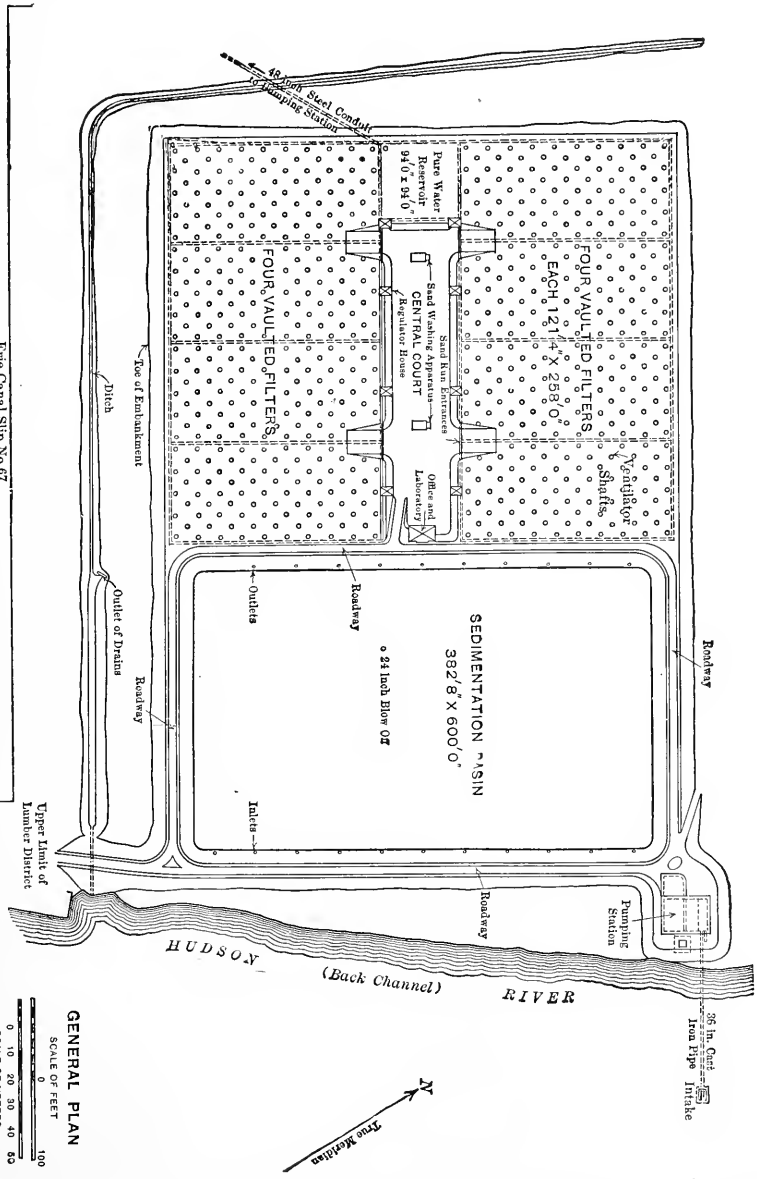


FIG. 7.—Sedimentation-basin and Filter-beds at Albany, N. Y.

In designing the sides of filters or of the piers projecting up through the sand for the support of the roof, in case there is one,

be dependent upon the areas from which they withdraw water. It is advisable to make them rather large, in order that the water may flow through them more freely. They seldom need exceed 6 or 8 inches. They are preferably made of salt-glazed vitrified pipes laid with open joints, around and in the vicinity of which are placed gravel or broken stone, the largest pieces with a maximum diameter of 1 to 2 inches. The largest broken stone or coarsest gravel is near the pipe and should decrease in size as

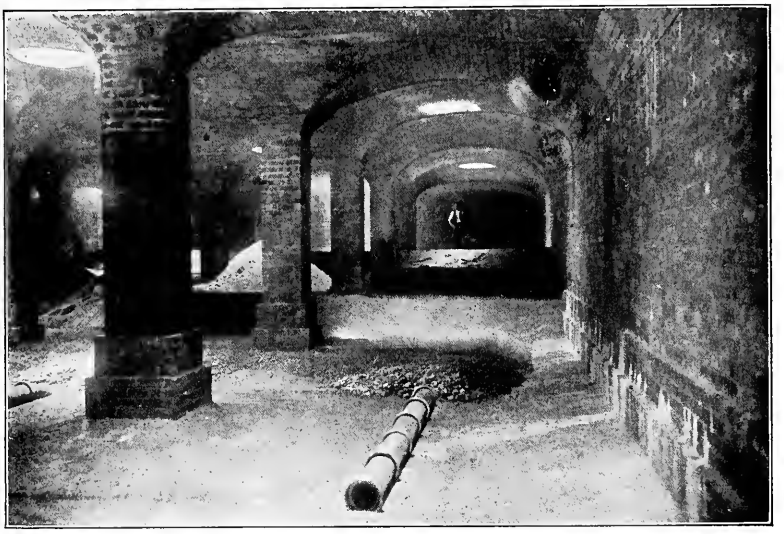
Interior of Covered Filter at Ashland, Wis.

the drain-pipe is receded from, so that the final portions of the gravel farthest removed from the drains will not permit the filter-sand to pass into it. When properly designed and arranged, the loss of head in passing from the farthest points of a filter-bed to the point of exit from the filter will not exceed about .01 to .02 of a foot.

237. Arrangement of the Sand at Lawrence and Albany.—Above this gravel is placed the filtering-sand, about 4 feet thick in the Albany filter and 3 to 4 feet thick in the filter at Lawrence, Mass. The sand in the Albany filter was specified to have not "more than 10 per cent less than .27 mm." in diameter and "at least 10 per

cent by weight shall be less than .36 mm." in diameter. Over the entire floor was spread not more than 12 inches of gravel or broken stone, the lower 7 inches consisting of broken stone or gravel with greatest diameter varying from 1 inch to 2 inches; the remaining 5 inches of the lower 1 foot was composed of broken stone or gravel decreasing from 1 inch in greatest diameter to a grain a little coarser than that of the sand above it. In all cases, sand for the filter-bed should be free from everything that can be classed as dirt, including clay, loam, and vegetable matter. Furthermore, it should be free from any mineral matter which might change the character of the water and render it less fit for use.

This filtering-sand is usually placed in position with a horizontal surface. At Lawrence, however, it was placed with



Partially Filled Covered Sand Filter showing Drain pipe.

a wavy surface, the horizontal distance between the crests of two consecutive waves being 30 feet, the concrete gutter for admitting the water being half-way between, all as shown in the illustrations. The sand of this filter was of two grades, the coarser sand having an effective size of 0.3 mm. (.118 inch) and the finer an effective size of 0.25 mm. (.098 inch). The two dif-

ferent sizes of sand are seen not to be arranged in horizontal layers, but so that the finer is over the drains and the coarser between. The No. 70 sand is capable of passing 70 million gallons per acre per day with a head on it equal to the depth of sand, while the No. 50 sand can pass 50 million gallons per acre per day with a head on it equal to its depth. There appears to be no special advantage in placing the sand in filters other than in horizontal layers with an effective size practically uniform.

238. Velocity of Flow through Sand.—The velocity with which water will flow through a given depth of sand with a known depth or head above the surface of the latter has been carefully investigated by the Massachusetts State Board of Health with the following results:

v = the velocity at which a solid column of water, whose section equals in area that of the bed of sand, moves downward through the sand in meters per day; this is practically the number of million gallons passing through the sand per acre per day.

c = a constant, having the value of 1000 for clean sand, and 800 for filter-sand after having been some time in use.

d = the effective size of the sand-grain in millimeters.

h = the head lost by the water in passing through the sand at the rate v; this is the effective head of water producing motion through the sand.

l = the thickness of the sand bed.

t = the temperature of the water in degrees Fahr.

The velocity v, as determined by experiment, takes the following form:

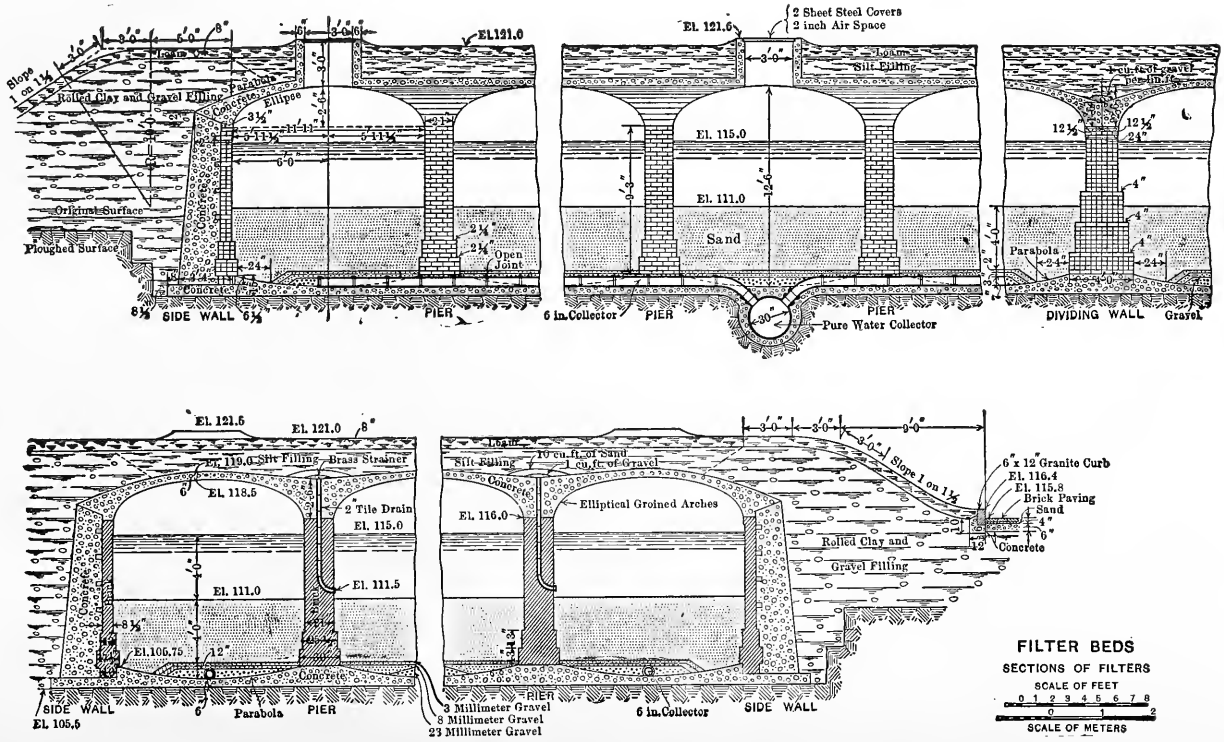
$$v = cd^2\frac{h}{l}\left(\frac{t+10}{60}\right).$$

This formula cannot be used for the flow of water through all sands of all thicknesses and under all circumstances. It is limited to effective diameters of sand between .1 and 3 mm., having a uniformity coefficient not greater than 5. h and l may be taken in any unit as long as both are expressed in the same unit, since the ratio of the two quantities will then not be affected.

If the effective head of water on the filter or the head lost is equal to the thickness of the bed of sand, the ratio of h divided by l will be 1. In case the formula is used to express the quantity of water flowing through the sand per acre per day, it must be remembered that v will be the number of million gallons and not the total number of gallons. The formula can only be used when the sand is well compacted and where the voids of the sand are entirely filled with water.

239. Frequency of Scraping and Amount Filtered between Scrapings.—The frequency of the scraping of filters will depend upon the amount of organic matter in the water and upon the rate of filtration. Between the years 1893 and 1900 the periods between scrapings of the Lawrence filter ranged generally from 20 to 32 days, although periods as small as 13 or 19 are found in the records. The quantity of water passed between scrapings varies generally from 67 million to 90 million gallons, although it fell as low as 49 millions and rose as high as 109 millions. In the case of the Albany filter-plant, up to the end of the year 1900 the shortest period between scrapings was about 15 days and the longest about 42 days, the smallest quantity of water passing through any filter between scrapings being 26,735,000 gallons and the largest 76,982,000 gallons. The operation of the Albany filters for the year 1901 shows that the average run of a bed was 26 days between scrapings, with a total of 70,000,000 gallons per acre for that period. These figures represent about the usual workings of slow sand filters at the present time, the period between scrapings running usually between 15 and 30 days, and the quantity from 30 million gallons per acre to 100 million gallons per acre.

240. Cleaning the Clogged Sand.—The clogged sand scraped from the top of the filters at the periods of cleaning is removed to a convenient point where appliances and machinery are available for washing it. This is an item of some importance in the administration of filters, as the sand which is removed and washed is at a later period replaced upon the filter-bed. Various methods have been tried for the purpose of cleaning sand efficiently and economically. The continuous ejector sand-washer, one set of which is used at Albany, is probably as efficient as any



Filters for City of Albany, N. Y.

machine yet devised. It is shown in Fig. 8. It will be observed that the dirty sand is fed to the machine at one end into a hopper-shaped receptacle. In the bottom of this hopper is a nozzle through which water is discharged from a pipe running along the entire bottom of the machine. This jet of water forces the sand upward through a suitable pipe into a reservoir which discharges the sand and water into another hopper, and so on through the series of five. Evidently there may be any number of hoppers in the series, a jet of water being provided at the bottom of each. In this manner the sand and water are thoroughly mixed together and compelled to flow upward from each hopper to the next, the dirty water overflowing also from each hopper into a tank underneath, whence it runs to waste. The clean sand and water flow out of the machine at the end opposite to that at which they entered. After the washed sand is dried it is ready to be replaced in the filter.

241. **Controlling or Regulating Apparatus.** — It is essential to the proper working of a slow sand filter that the amount of water admitted to and passing through it shall be as nearly uniform as practicable. This necessitates controlling or regulating apparatus, of which there are two general classes, the one automatic and the other worked by hand. There are a considerable number of appliances of both classes. The filtered water flows from the end of the drains to one or two small tanks formed by suitable masonry walls immediately outside of the filter-beds and rises to a level determined by the loss of head in passing through the filter. The difference in elevation between the water surface over the sand and that in the filtered water-tanks shows the effective head which causes the water to flow through the sand. The object of the controlling or regulating appliances is to keep that head as nearly constant as possible. Both the hand and automatic appliances preserve the value of that head by maintaining constant discharges through either vertical or horizontal orifices, the orifices themselves being movable. They may be rectangular or other orifices with horizontal lips or crests. If the control is automatic it is accomplished usually by a float which raises and lowers the orifice in such a way as to maintain a constant difference of level between the filtered and the unfiltered

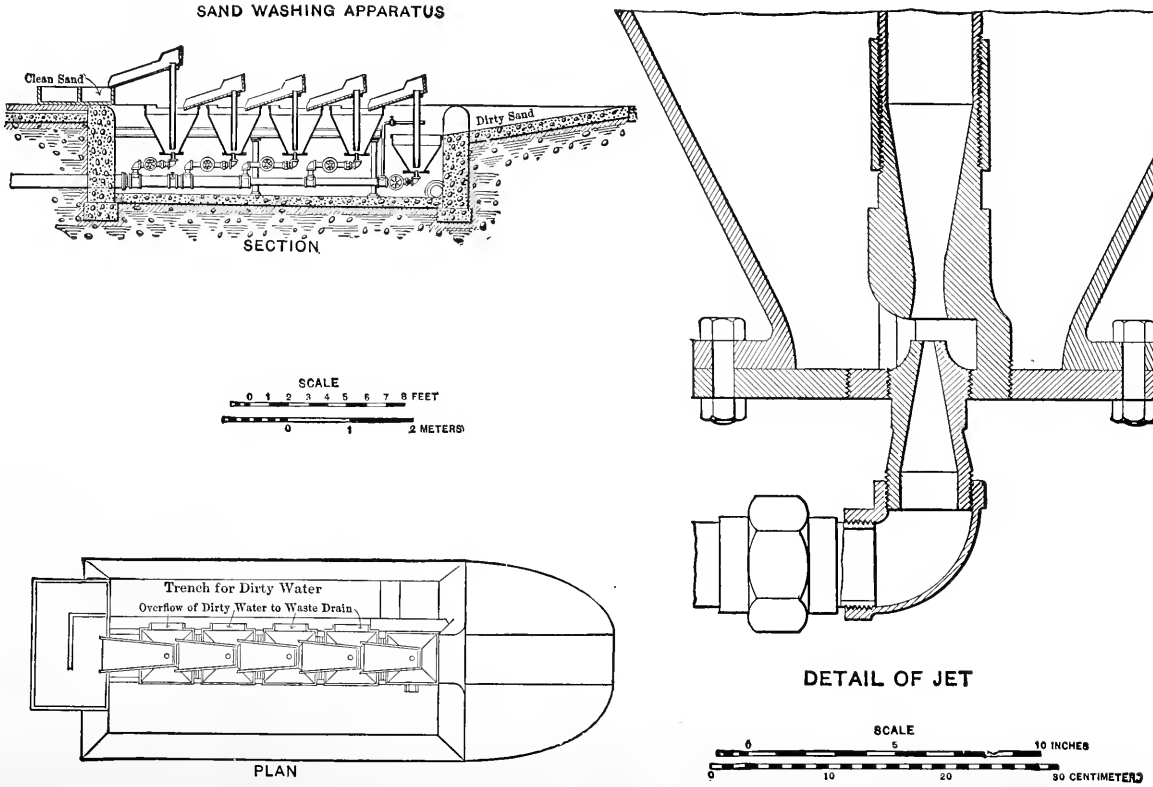


FIG. 8.—Ejector **Sand-washer.**

water. The figures illustrate both types of regulating appliances, the actions of which will be readily understood.

242. Cost of Slow Sand Filters.—The cost of both the open and covered slow sand filters will obviously vary according to the cost of labor and materials at their sites. The original cost of the Lawrence filter, about 2.44 acres in total area, was nearly $25,000 per acre. The cost of covered filters, so far as constructed in this country, varies from about $44,000 to nearly $51,000 per

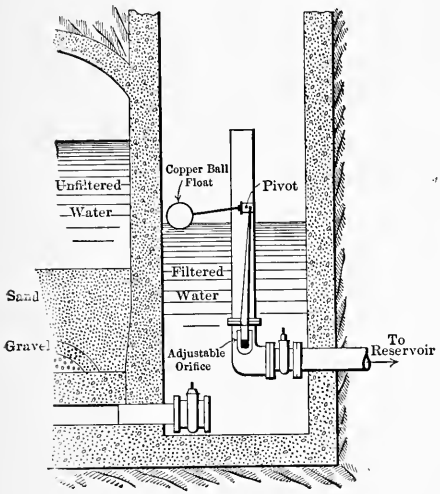


FIG. 9.—Ball-float Regulator of Rate of Filtration.

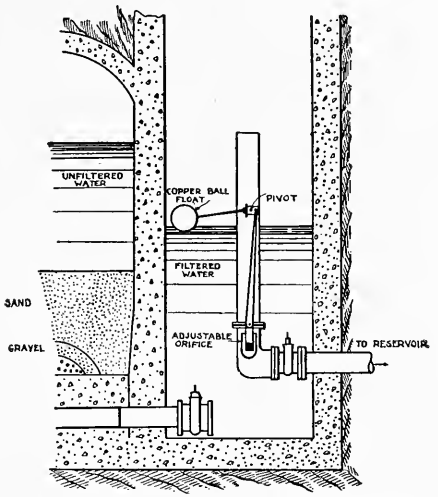


FIG. 10.—Regulating Apparatus Designed by J. H. Fuertes for the Tome Institute Filters.

acre excluding the pipe, pumping plants, and sedimentation-basins. The Albany covered filters cost about $38,000 per acre including filtering materials, but excluding excavation, pumps, buildings, sedimentation-basins, piping, and sand-washing machinery, or nearly $46,000 per acre including those items except pumps and sedimentation-basins. The roof, included in the preceding estimate, cost about $14,000 per acre. The smaller the filters the greater the cost per acre, as a rule, as would be expected. A single open filter at Poughkeepsie and three open filter-beds at Berwyn, Pa., cost respectively $42,000 and $36,000 per acre, the former being little less than .7 acre in area and the

latter having an aggregate area of a little more than one-half acre. A covered filter at Ashland, Wis., consisting of three beds of one-sixth acre each, cost at the rate of about $70,000 per acre.

243. Cost of Operation of Albany Filter.—The cost of operating the Albany filter, including only the costs of scraping, remov-

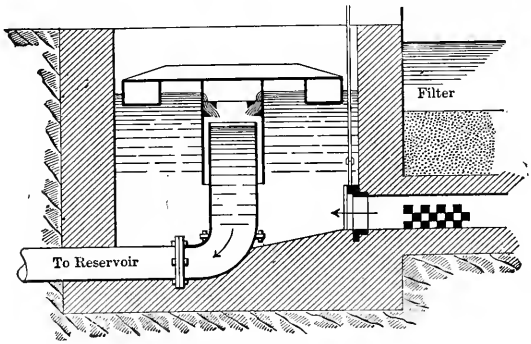


FIG. 11.—Regulator of Rate of Filtration.

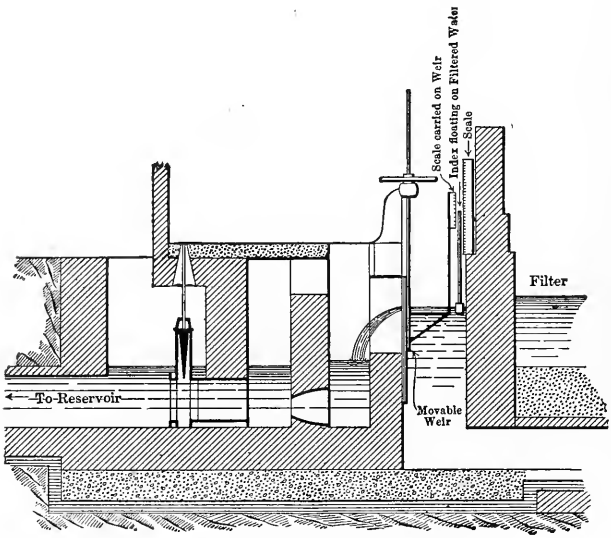


FIG. 12.—Regulator of Rate of Filtration.

ing sand, refilling, incidentals, lost time, and washing the sand during seventeen months ending December 29, 1900, was $1.66 per million gallons filtered. The cost of removing the sand (ex-

cluding scraping), washing, and refilling was $1.21 per cubic yard. The total cost of operating the entire filter-plant, including all items, for the year 1900 was $4.52 per million gallons filtered. This covers all expenses, including pumping, superintendence, and laboratory, which can be charged to the operation of the filter-plant. The average removal of albuminoid ammonia at Albany for the year 1900 was 49 per cent and of the free am-

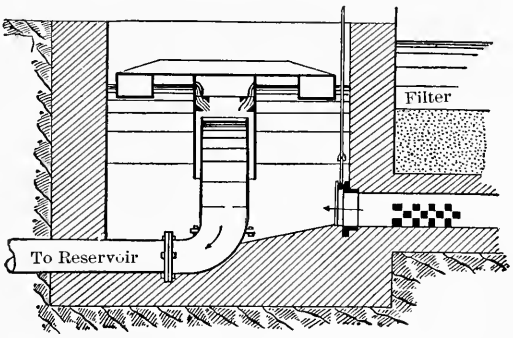


FIG. 13.—Regulator Designed by W. H. Lindley for the Filters at Warsaw, Poland.

monia 78 per cent of that in the raw water, while the average bacterial removal was over 99 per cent, running from 98.3 per cent to 99.6 per cent. The volume of water used in washing the sand was about twelve and a half times the volume of the sand. Each cubic yard of sand washed, therefore, required twelve and a half cubic yards of water.

244. Operation and Cost of Operation of Lawrence Filter.—It was originally intended that the Lawrence filter should be worked intermittently. The Merrimac River water, which is used by the city of Lawrence, was known to carry at certain periods of the year sufficient typhoid germs received from the city of Lowell to produce at least mild epidemics. The intermittent operation was considered necessary to furnish the filter with the requisite oxygen to destroy beyond a doubt all pathogenic bacteria. The increasing demands of water consumption during the years that have elapsed since filtration began in 1894 have seriously modified these conditions, so that the intermittent feature of operation of the filter is no longer very prominent. During 1898, for instance, the filter was drained only four to thirteen times per

month, with an average of eight monthly drainings. In 1899 the drainings were more frequent, varying from five to fourteen per month and averaging eleven times. Finally, in 1900, the monthly drainings ranged from three to thirteen, with an average of eight. It may be considered, therefore, that the Lawrence filter occupies a kind of intermediate position between intermittent and continuous operation.

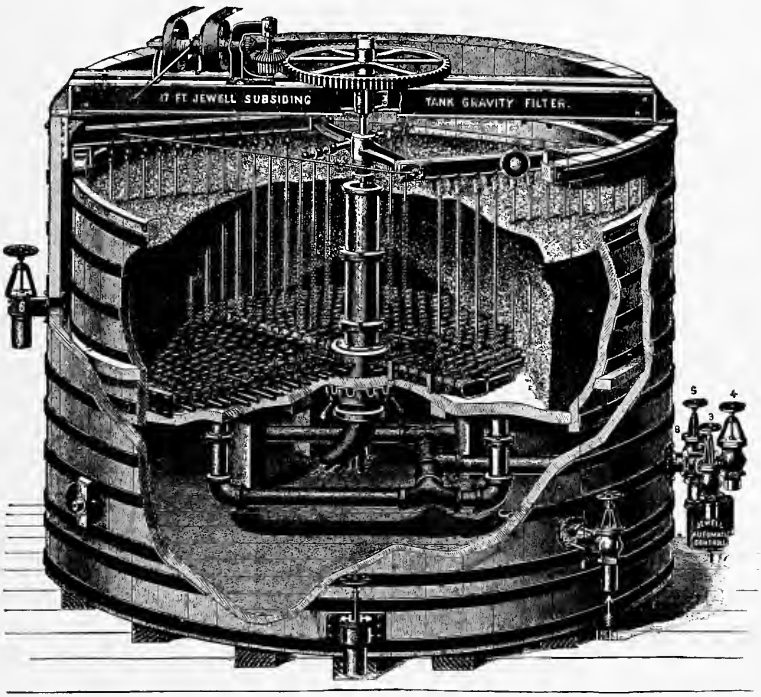
The total cost of operating the filter at Lawrence, including scraping and washing of sand, refilling, removal of snow and ice, and general items in the period from 1895 to 1900, both inclusive, varied from a minimum of $7.70 per million gallons to $9.00 per million gallons. If the removal of snow and ice be omitted, these amounts will be reduced to $5.10 and $6.90 respectively. The cost of washing the sand only in the Lawrence filter during the same period varied from 45 to 67 cents per cubic yard. The volume of water required for that washing varied from ten to fourteen times the volume of sand.

245. Sanitary Results of Operation of Lawrence and Albany Filters.—The average number of bacteria in the Merrimac River water applied to the filter during the period 1894 to 1899, both inclusive, varied from about 1900 per cubic centimeter to 34,900, and the percentage of reduction attained by passing the water through the filter varied in the same period generally from 97 to 99.8 per cent, with an average of about 99.1 per cent.

In the city of Lawrence the average number of cases of typhoid fever per 10,000 of population has been about one third, since the introduction of filtered water, of the number of cases which existed prior to the installation of the filters, and less than one fourth as many deaths. A large number of the cases of typhoid occurring after the installation of the filter have been traced to the use of unfiltered water, and it is probable that all or nearly all could be similarly accounted for.

In the city of Albany the experience had been quite similar. The average number of deaths per year from typhoid fever for ten years before the introduction of filtered water was 84, while in 1900, with the filter in operation, the total number of deaths was 39. These figures are sufficient to show the marked beneficial effect of filtered water on the public health.

246. Rapid Filtration with Coagulants.—It has been seen that the rate of filtration through open sand filters does not usually exceed 2 to 4 million gallons per acre per day under ordinary circumstances. Much greater rates would clog the sand and produce less efficient results. Experience has also shown that such methods cannot be depended upon to remove from water coloring matter of a vegetable origin or very finely divided sediment. In order to accomplish these ends it is necessary to



Jewell Filter.

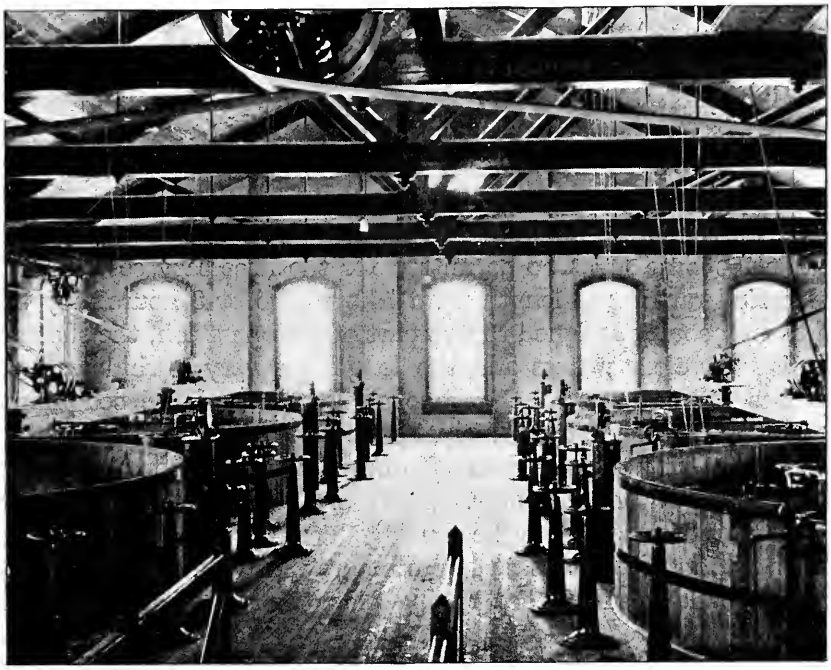
employ suitable chemicals which, acting as coagulants, may accomplish results impracticable in the open filter. Resort has therefore been made first to the adoption of suitable coagulants and then to such increased heads or pressures as to force the water through the sand at rates from 25 to 30 or even 50 times as great as practicable in slow sand filtration. These rapid sand filters are called mechanical filters. If the water is forced through

them under pressure, they consist of closed tanks in which sand is placed so as to leave sufficient volume above it for the influent water and, supported upon a platform carrying perforated pipes, strainers, or equivalent details through which the filtered water may flow into a suitable system of effluent pipes in the lower part of the filter. If water is forced through the sand by the required head, the upper part of the filter may be open, but of sufficient height to accommodate it. The same filtering material, clean sand, is used as in the slow filters; the only differences, aside from the higher rate of filtration, are the greater head and the introduction of a coagulant to the water. The depth of sand used may vary from 2 to 4 feet. The thickness of a relatively fine sand may be less than that of a coarser sand.

247. Operation of Coagulants.—The coagulant which has been found to give the best results is ordinary alum or sulphate of aluminum. If sulphate of aluminum is dissolved in water containing a little lime or magnesia, aluminum hydrate and sulphuric acid are formed. The aluminum hydrate is a sticky gelatinous substance which gathers together in a flocculent mass the particles of suspended matter in the water, and it also adheres to the grains of sand when those masses have settled to the bottom. This flocculent, gelatinous mass covers the sand and passes into its voids. As the water is forced through it the bacteria and suspended matter are held, leaving a clear effluent to pass through. Other coagulants are used, such as the hydrate of iron, but it costs more than alum and is not so effective in removing color, although it is an excellent coagulant for removing turbidity. Physicians have made objection to the use of alum for this purpose, on the ground that any excess might pass into distribution-pipes and so be consumed by the water-users to the detriment of health. While it is possible that further experience may show that there is material ground for this objection, it has thus far not been found to be so. It is, however, essential that only the necessary amount of alum should be used and that there may be a sufficient amount of alkali to combine with the sulphuric acid. Otherwise the acidulated water may attack the iron and lead pipes and so injure the water and produce serious trouble. It can only be stated that the method and operation of these mechanical filters

have thus far been sufficiently successful to avoid any of these difficulties.

248. Principal Parts of Mechanical Filter-plant—Coagulation and Subsidence.—The principal parts of a complete mechanical filter-plant in the order of their succession are a solution-tank, a measuring-tank, a sedimentation-basin, and a filter. In case of great turbidity the sedimentation may be completed in two



The Jewell Filter-plant at Norristown, Penn.

stages, the first in a settling-basin prior to receiving the coagulant, and the second in another basin subsequent to the coagulation. The tanks are usually of wood, although they may be of steel. The solution-tank is a comparatively small vessel in which the alum is dissolved. The solution is then run into the measuring-tank, from which it flows into the water at a constant rate maintained by suitable regulating apparatus. It is imperative for the successful working of the mechanical filter-plant that the coagulant be introduced to the water at a uniform rate. This

rate will obviously depend upon the character of the water. The coagulating solution runs from the measuring-tank into the pipe through which the water to be filtered flows and in which it first receives the alum. The water and the coagulating solution are thus thoroughly mixed and flow into the sedimentation-basin. The subsidence which is provided for in this basin may be omitted in very clear waters which carry little solid matter, but the operation of the filter itself will be more satisfactorily accomplished if as much work as feasible is done before reaching it. The mixture must remain in this basin a sufficient length of time to allow such subsidence as can reasonably be attained.

It appears from experience in this part of the work that it is not well to introduce the coagulant too long before the water enters the filter, especially if the water be fairly clear. In the case of the presence of finely divided solid matter, however, sufficient time must be permitted for the necessary settlement. A period ranging in length from $\frac{1}{2}$ hour to 6 or 8 hours may be advantageously assigned to this part of the operation, the shorter period for clear waters and the longer for very turbid waters. It has been suggested that two applications of the coagulant might be beneficial, the principal portion being given to the water before entering the sedimentation-basin and the other just before the waters enters the filter. The work of the filter, especially with turbid waters, may be much reduced by simple subsidence for a period of perhaps 24 hours before receiving the coagulant, the secondary subsidence taking place in the settling-basin in the manner already described. Duplicate solution- and measuring-tanks will be required in order that the process may be continuous while one set is out of use. In this process it is absolutely essential also that the coagulant should be of the best quality, inferior grades having been found to be unsatisfactory in their operation.

249. Amount of Coagulant—Advantageous Effect of Alum on Organic Matter.—The amount of sulphate of alumina will vary largely with the quality of water. In the investigation made by Mr. Fuller in connection with the Ohio River supply for the city of Cincinnati, he found that with very slight turbidity only $\frac{3}{4}$ grain was required per gallon of water, but that a high degree of

turbidity required as much as 4.4 grains per gallon, with intermediate amounts for intermediate degrees of turbidity. It was estimated that these quantities would correspond to an average annual amount of about 1.6 grains per gallon. In case there should be a period of three days of subsidence preliminary to filtration, he estimated that for the greater part of the time the amount of alum would vary from 1 to 3 grains per gallon. Occasionally more and sometimes less would be required.

Alum has some specially valuable qualities in connection with this class of purification work. It combines with coloring matter, particularly that which has been acquired from contact of the water with vegetation, and precipitates it. It seems to combine also, to some extent, with the organic matter carried by the water and thus enhances the efficiency of filtration.

250. High Heads and Rates for Rapid Filtration.—The principal work of investigation of filtration in mechanical or pressure filters has been made for the cities of Pittsburg, Cincinnati, Louisville, and Providence, R. I. In the experimental work of those investigations rates of filtration ranging from 46 million to 170 million gallons per acre per day have been employed with essentially the same efficiency. This is a practical result of great importance, particularly if in the continued use of these filters on a large scale a satisfactorily high efficiency can be reached and maintained. It was observed that the number of bacteria in the effluent varied with that in the raw water. It was also noticed that similarly to the operation of slow sand filters the rate of filtration should not be changed suddenly, as that is likely to cause breaks in the sand and militate against continued efficiency.

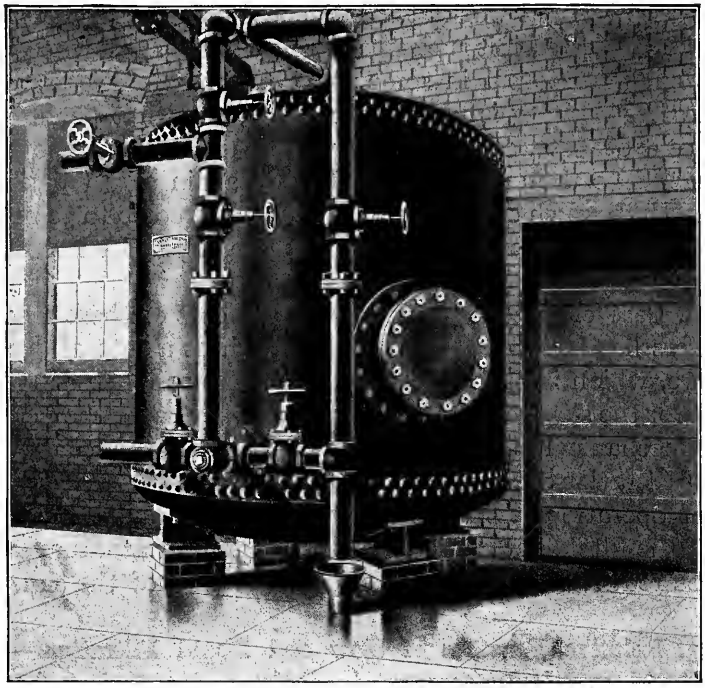
In his experimental work at Cincinnati Mr. Fuller found that with fine sand an available head on the filter of 12 feet gave economical results. He also states that "high rates are more economical than low ones, and that the full head which can be economically used should be provided. Just where the economical limit of the rate of filtration is can only be determined from practical experience with a wider range of conditions than exist here, but there seem to be no indications that the capacity of a plant originally constructed on a medium rate basis (100 million to 125 million gallons per acre daily) could not readily and eco-

nomically be increased, as the consumption demanded, to rates at least as high as the highest tried here (170 million gallons per acre daily), provided the full economical increase in loss of head could be obtained."

251. Types and General Arrangement of Mechanical Filters.— These mechanical or pressure (by gravity) filters have until lately been constructed by companies owning patents either on the process or on the different parts of the filters. The fundamental patent, however, protecting rapid sand filters with the continuous application of a coagulant has expired and the city of Louisville, Ky., is now constructing rapid sand filters different in design from those heretofore used. The types that have been most common heretofore are the Jewell subsidence gravity filter, the Continental gravity filter, the New York sectional-wash gravity filter, and others. They all possess the main feature of accelerating the rate of filtration by pressure, either in a closed tank (rarely) with comparatively small water volume above the sand or by an open filter with sufficient head of water above the sand to accomplish the high rate desired. This latter method is that now generally used, as by it the requisite steadiness of head or pressure can be secured. The closed type is subject to objectionable sudden changes of pressure which prevent or break uniform rates of filtration. The sand is supported upon a platform with a suitable system of pipes fitted with valves or gates for the withdrawal of the filtered water, the space below the platform forming a small sedimentation-chamber. They are usually constructed in comparatively small circular units, so that one or more of a group may be withdrawn from operation for the purposes of cleaning or repairs without interfering with the operation of the others. This system of small units, gives some marked practical advantages, as housing is readily accomplished, and if necessary the plant may be easily removed from one point to another.

It is obvious that with the large amount of water forced through a given area of filter-bed the sand will become clogged within a comparatively short time, requiring washing and replacing. Mr. Fuller found at Cincinnati that the periods between washings when fine sand was used in the filters ranged from 8 to

24 hours, with an average of 15, but with coarse sand the average became 20, with a range of from 6 to 36 hours. The time required for washing the sand at Cincinnati was 20 minutes for coarse or 30 minutes for fine. At Providence Mr. Weston found that the average time of washing was about 11 minutes. The cleaning is accomplished partially by stirring the sand with revolving arms, as shown in the accompanying figures, but generally by



Continental Filter.

forcing the water in a reverse direction through the sand and allowing the wash-water either to run to waste or to be again purified. The filters are designed for the purpose of cleaning by the reversal of the direction of the flow of water. Latterly the sand has been cleaned by forcing compressed air at a low pressure through it and the superimposed water. The passage of the air or water upward through the sand produces such a commotion among the grains that they rub against each other and

clean themselves of the adhering material, allowing it to be carried off by the water above the sand. Both methods are much used and are satisfactorily effective for the purpose.

It was found at Cincinnati that 4 to 9 per cent, with an average of 5 per cent, of filtered water was required for washing the fine sand, and only 2 to 6 per cent, with an average of 3 per cent, for the coarse sand of the mechanical filters used in Mr. Fuller's experiments. Mr. Weston has found about the same figures in his experimental work at Providence. The wash-water need not be wasted at all if it is pumped back into the subsidence-tanks.

It has been found in some cases that the efficiency of the filters after washing is not quite normal, and that possibly 2 or 3 per cent of the water must be wasted unless it is allowed to run back into the subsidence-tanks and again pass through the filter. Under such circumstances it has required 20 to 30 minutes of operation of the filter after washing to regain its normal efficiency.

252. Cost of Mechanical Filters.—The cost of these mechanical filters has been found to range as high as a rate of $500,000 per acre, which is probably about ten times as much as the rate of cost for the slow sand filters. On the other hand, the efficiency of the mechanical filters may be as high as the other class, with a rate of filtration from thirty to fifty times as great, and with a cost of operation less than that of the slow sand filters. The cost of the filters per million gallons of filtered water may, therefore, be reduced to perhaps one fourth of that of the slow sand type.

253. Relative Features of Slow and Rapid Filtration.—It is premature, even unnecessary, to make a comparison between the slow and rapid sand filters. The former are well adapted to a large class of potable waters in which there is not too much or too finely divided solid matter and in which the coloring from organic origin is not serious. They have the advantage of requiring no chemicals and are capable of attaining a high degree of efficiency. The average rate of filtration may be taken about 3,000,000 gallons per acre per day. The rapid sand filter, on the contrary, requires the application of a coagulant, but has thirty to fifty times the capacity of the other class. It is better adapted

to the removal of turbidity and color, and when properly operated it gives a high efficiency. A sufficiently extended experience has not yet, however, been attained to enable a complete statement to be made as to the entire field to which they may be adapted. They have certainly been shown to possess valuable qualities in a number of respects, and they are undoubtedly destined to play an important part in the purification of waters.