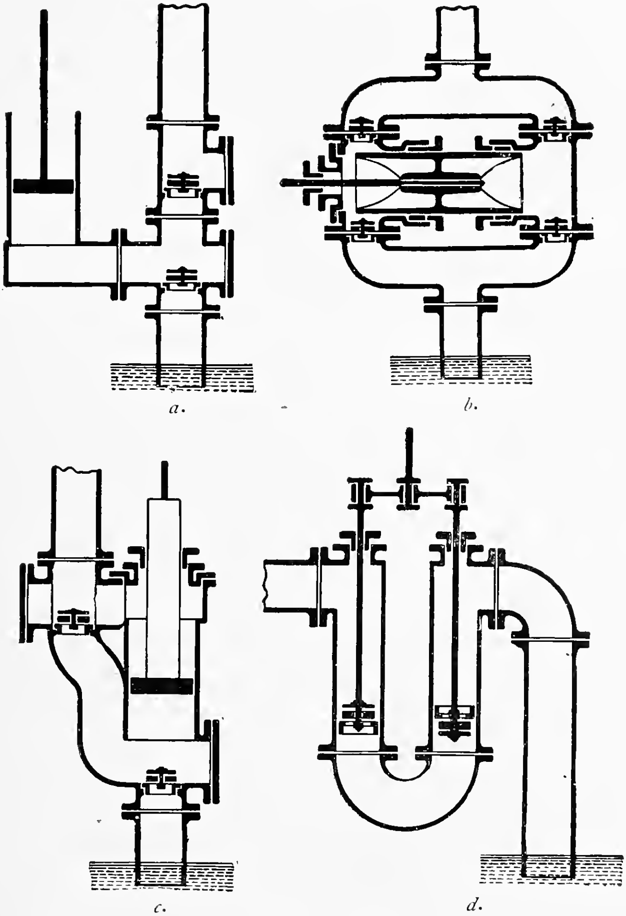
CHAPTER XVIII.

195. Pumping and Pumps.—When it is impossible to secure water at sufficient elevation to be delivered to the points of consumption by gravity, it is necessary to resort to pumping in order to raise it to the desired level. Indeed it is sometimes necessary to resort to pumping in connection with a gravity supply in order to deliver water to the higher parts of the distribution system, the lower points being supplied by gravity. This combination of gravity supply with pumping is not unusual. That part of New York north of Thirty-fourth Street between Lexington and Fifth avenues, north of Thirty-fifth Street between Fifth and Sixth avenues, north of Fifty-first Street between Sixth and Ninth avenues, north of Fifty-fifth Street between Ninth and Tenth avenues, north of Fifty-eighth Street between Tenth and Eleventh avenues, and north of Seventy-second Street between Eleventh Avenue and the North River, with elevation of 60 feet or more above mean high tide-water, is supplied from the high-service reservoir near High Bridge, the water being elevated to it from the Croton supply by the pumping-station at the westerly end of the bridge. The elevation of the water surface in the High Bridge reservoir is 208 feet, and that of the large reservoir in Central Park 115 feet, above mean high tide-water. Some specially high points on the northern part of Manhattan Island are supplied from the High Bridge tower, whose water surface is 316 feet above mean high tide.

The pumps employed for the purpose of elevating water to distributing-reservoirs are among the finest pieces of machinery built by engineers at the present time. They are usually actuated by steam as a motive power, the steam being supplied from suitable boilers or batteries of boilers in which coal is generally used as fuel. The modern pumping-engine is in reality a combination of three classes of machinery, the boilers, the steam-engines, and the pumps. There are various types of boilers as well as of engines and pumps, all, when judiciously designed and arranged, well adapted to the pumping-engine process. The pumps are



Skeleton Pumps.

generally what are called displacement pumps; that is, the water in the pump-cylinder is displaced by the reciprocating motion of a piston or plunger. These pumps may be either double-acting or single-acting; in the former case, as the piston or plunger moves in one direction it forces the water ahead of it into the main or pipe leading up to the reservoir into which the water is to be delivered, while the water rising from the pump-well follows back of the piston or plunger to the end of its stroke. When the motion is reversed the latter water is forced on its way upward through the main, while the water rises from the pump-well into the other end of the water-cylinder. In the case of single-acting pumps water is drawn up into the water-cylinder from the pump-well during one stroke and forced up through the main during the next stroke, one operation only being performed at one time. The pump-well is a well or tank, usually of masonry, into which the water runs by gravity and from which the pump raises it to the reservoir. For the purposes of accessibility and convenience in repairing, the pump is always placed at an elevation above the water in the pump-well, the pressure of the atmosphere on the water in the well forcing the latter up into the pump-cylinder as the piston recedes in its stroke. The height of a column of water 1 square inch in section representing the pressure of the atmosphere per square inch is about 34 feet, but a pump-cylinder should not be placed more than about 18 feet above the surface of the water in the pump-well in order that the water may rise readily as it follows the stroke of the plunger.

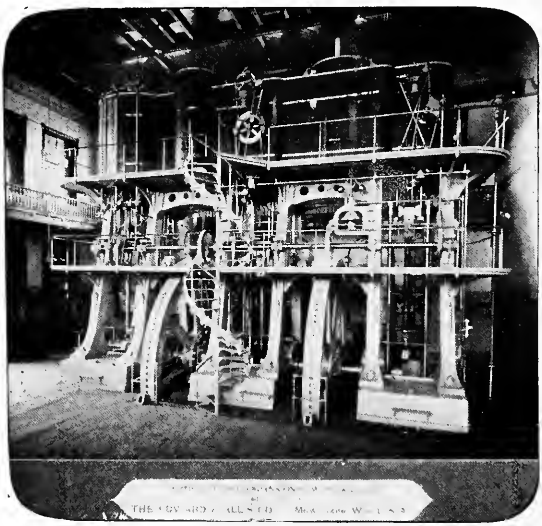
In the operation of the ordinary pump the direction of the water as it flows into and out of the pump-cylinder must necessarily be reversed, and this is true also with the type of pump called the differential plunger-pump, which is really a single-acting pump designed so as to act in driving the water into the main like a double-acting pump, i.e., both motions of the plunger force water through the main, but only one draws water from the pump-well into the pump-cylinder. Valves may be so arranged in the pump-piston as to make the progress of the water through the pump continuous in one direction and so avoid the irregularities and shocks which necessarily arise to some extent from a reversal of the motion of the water.

The steam is used in the steam-cylinders of a pumping-engine precisely as in every other type of steam-engine. At the present time compound or triple-expansion engines are generally used, among the well-known types being the Worthington duplex direct-acting pump without crank or fly-wheel, the Gaskill crank and fly-wheel pumping-engine, the Allis and the Leavitt pumping-engines, both of the latter employing the crank and fly-wheel and both may be used as single- or double-acting pumps, usually as the latter. The characteristic feature of the well-known Worthington pumping-engine is the movement of the valves of each of the two engines by the other for the purpose of securing a quiet seating of the valves and smooth working.

One of the most important details of the pumping-engine is the system of valves in the water-cylinder, and much ingenuity has been successfully expended in the design of proper valve systems. These pump-valves must, among other things, meet the following requirements as efficiently as possible: they must close promptly and tightly, so that no water may pass through them to create slip or leakage; they should have a small lift, so as to allow prompt closing, and large waterways, to permit a free flow through them with little resistance; they must also be easily operated, so as to require little power, and, like all details of machinery, they should be simple and easily accessible for repairing when necessary.

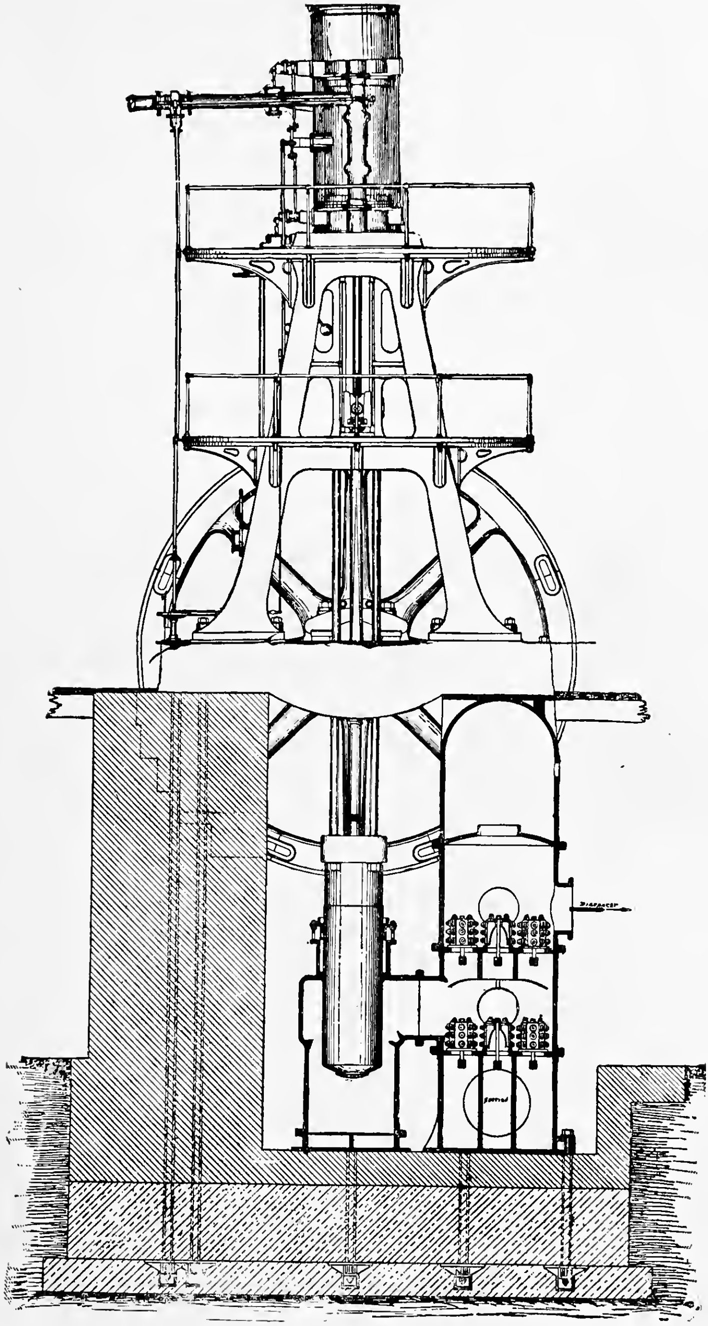
As steam is always used expansively, its force impelling the plunger will have a constant value during the early portion of the stroke only, and a much less value, due to the expansion of the steam, at and near the end of the stroke, while the head of water against which the pump operates is practically constant. There is, therefore, an excess of effort during the first part of the stroke and a deficiency during the latter part. Unless there should be some means of taking up or cushioning this difference, the operation of the pump would be irregular during the stroke and productive of water-hammer or blows to the engine. Two means are employed to remove this undesirable effect, i.e., the fly-wheel and the air-chamber, or both. In the one case the excess of work performed by the steam in the early part of the stroke is stored up as energy in the accelerated motion of the fly-wheel and given out by the latter near the end of the stroke, thus producing the desired equalization. The air-chamber is a large reservoir containing air, attached to and freely communicating with the force main or pipe near its connection with the pumps. In this case the excess of work performed at the beginning of the stroke is used in compressing the air in the air-chamber, sufficient water entering to accomplish that purpose. This compressed air acts as a cushion, expanding again at the end of the stroke and reinforcing the decreasing effort of the steam.

196. Resistances of Pumps and Main—Dynamic Head.—Obviously the water flowing through the pipes, pump-cylinders, and pump-valves will experience some resistance, and it is one purpose in good pumping-engine design to make the progress of the water through the pump so direct and free as to reduce these losses to a minimum. Similarly the large pipe or main, called the force-main, leading from the pump up to the reservoir into which the water is delivered, sometimes several thousand feet long, will afford a resistance of friction to the water flowing through it. The head which measures this frictional loss is given by equation (10) on page 239. All these resistances will increase



Allis Pump.

rapidly with the velocity with which the water flows through the pipes and other passages, as do all hydraulic losses. It is obviously advisable, therefore, to make this velocity as low as practicable without unduly increasing the diameter of the force-main. This velocity seldom exceeds about 3 feet per second.



Section of Allis Pumping Engine.

The static head against which the pumping-engine operates is the vertical height or elevation between the water surfaces in the pump-well and the reservoir. The head which represents the resistances of the passages through the pump and force-main, when added to the sum of the static head and the head due to the velocity in the force-main, gives what is called the dynamic head; it represents the total head against which the pump acts. If h represents the static head, h' the head due to all the resistances, and h'' the head due to the velocity in the force-main, then the dynamic head will be $H = h + h' + h'' = h + f\frac{l}{d}\frac{v^2}{2g} + n\frac{v^2}{2g} + \frac{v^2}{2g}$, in which f has a value of about .015 and n is a coefficient which when multiplied by the velocity head will represent the loss of head incurred by the water in passing through the pump-cylinder and valves. The latter quantity is variable in value; but it is seldom more than a few feet.

197. **Duty of Pumping-engines.**—It is thus seen that the collective machines and force-main forming the pumping system afford opportunity for a number of serious losses of energy found chiefly in the boiler, the engine, and the pump. The excellence of a pumping-plant, including the boilers, may obviously be measured by the amount of useful work performed by a standard quantity, as 100 pounds of coal. Sixty or more years ago, in the days of the old Cornish pumping-engine, the standard of excellence or "duty" was the number of foot-pounds of work, i.e.,the number of pounds lifted one foot high, performed by one bushel of coal. As early as 1843 the Cornish pumping-engine reached a duty, per bushel of coal, of 107,500,000 foot-pounds. These pumping-engines were single-acting, the steam raising a weight the descent of which forced the water up the delivery-pipe.

At a later date and until about ten years ago the usual standard or criterion applied to pumping-engines for city water-works was the amount of work performed in lifting water for each 100 pounds of coal consumed; this result was also called the "duty" of the engine. In order to determine the duty of a pumping-engine it was thus only necessary to observe carefully for a given period of time, i.e., twenty-four hours or some other arbitrary period, the amount of coal consumed, the condition of the furnace-fires at the beginning and end of the test being as nearly the same as possible, and measure at the same time the total amount of water discharged into the reservoir. The total weight of water raised multiplied by the total number of feet of elevation from the water surface in the pump-well to that in the reservoir would give the total number of foot-pounds of useful work performed. This quantity divided by the number of hundred pounds of coal consumed would then give what is called the "duty" of the pumping-engine.

198. Data to be Observed in Pumping-engine Tests.—Obviously it is necessary to observe a considerable number of data with care. No pump works with absolute perfection. A little water will run back through the valves before they are seated, and there will be a little leakage either through the valves or through the packing around the piston or plunger, or both sources of leakage may exist. That leakage and back-flow represent the amount of slip or water which escapes to the back of the plunger after having been in front of it. In well-constructed machinery this slip or leakage is now very small and may be but a small fraction of one per cent. Inasmuch as the amount of work performed by the steam will be the same whether this slip or leakage exists or not, the latter is now frequently ignored in estimating the duty of pumping-engines, the displacement of the piston or plunger itself being taken as the volume of water pumped at each stroke.

Again, in discussing the efficiency of the steam portion of the machinery the amount of partial vacuum maintained in the vacuum-pump, which is used to move the water of the condensed steam, is affected by atmospheric pressure, as is the work which is performed. Hence in complete engine tests it is necessary to observe the height of the barometer during the test. It is also necessary to observe the temperature of feed-water supplied to the boiler, and to use accurate appliances for ascertaining with the greatest exactness practicable the weight of dry steam used in the steam-cylinders and the amount of water which it carries. It is not necessary for the present purpose to discuss with minuteness these details, but it is evident from the preceding observations that the complete test of a pumping-engine involves the accurate observation of many data and their careful use in computations. The determination of the duty alone is but a simple part of those computations, and the duty is all that is now in question.

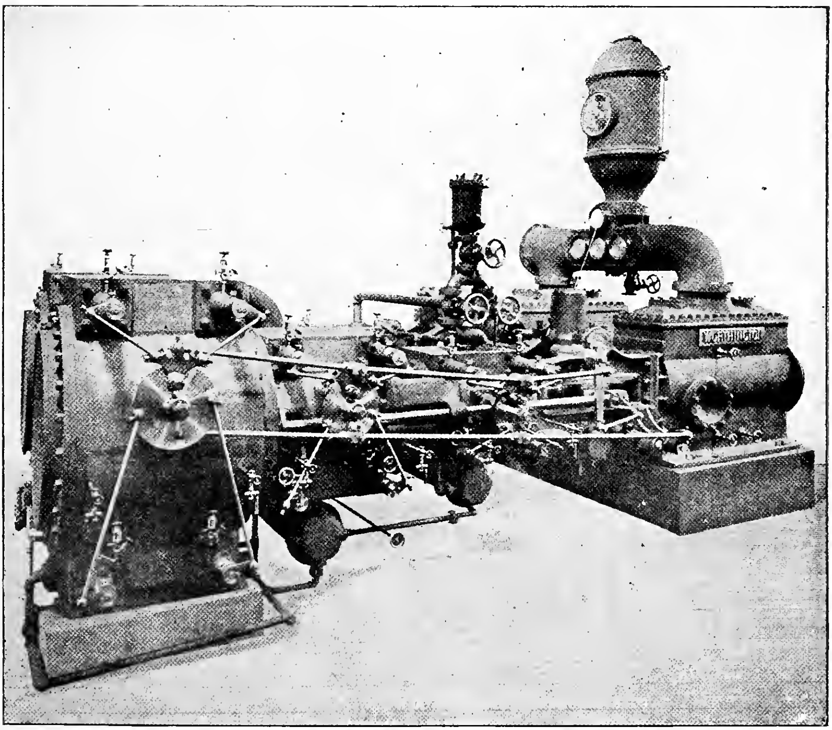
199. Basis of Computations for Duty.—It was formerly necessary in giving the duty of a pumping-engine to state whether the 100 pounds of coal was actually coal as shovelled into the furnace, or whether it was that coal less the weight of ash remaining after combustion. It was also necessary to specify the quality of coal used, because the heating capacity of different coals may vary materially. For these different reasons the statement of the duty of a pumping-engine in terms of a given weight of coal consumed involved considerable uncertainty, hence in 1891 a committee of the American Society of Mechanical Engineers, appointed for the purpose, took into consideration the best method of determining and stating the duty of a pumping-engine. The report of that committee may be found in vol. XII of the Transactions of that Society. The committee recommended that in a duty test 1,000,000 heat-units (called British Thermal Units or, as abbreviated, frequently B.T.U.) should be substituted for 100 pounds of coal. In other words, that the following should be the expression for the duty:

$$\text{Duty} = \frac{\text{foot-pounds of work done}}{\text{total number of heat-units consumed}} \times 1,000,000.$$

For some grades of coal in which 1,000,000 heat-units would be available for every 100 pounds the numerical value of the duty expressed in the new terms would be unchanged, but for other grades of coal the new expression of the duty might be considerably different.

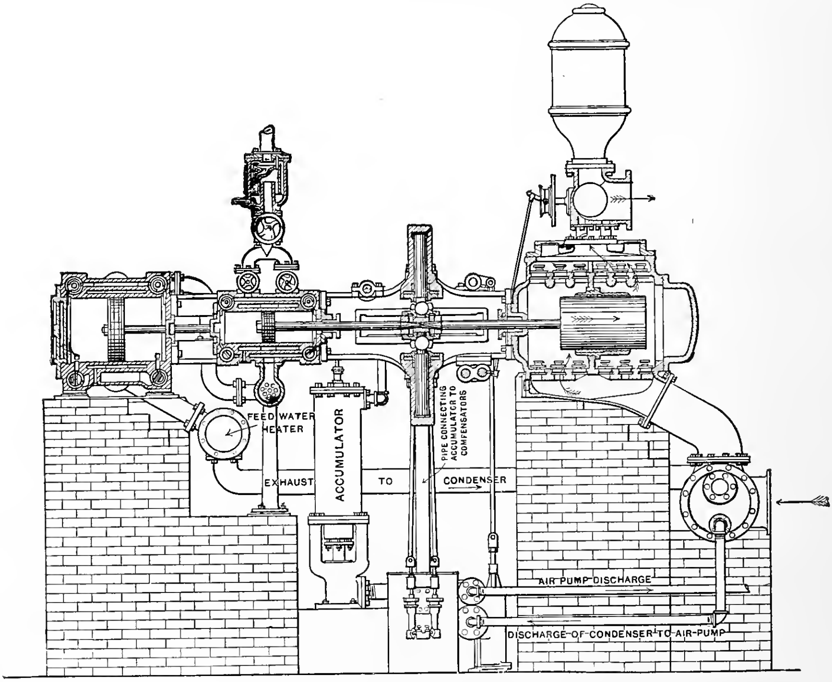
200. Heat-units and Ash in 100 Pounds of Coal, and Amount of Work Equivalent to a Heat-unit.—The following table exhibits results determined by Mr. George H. Barrus (Trans. A. S. M. E., vol. XIV. page 816), giving an approximate idea of the total number of heat-units which are made available by the combustion of 100 pounds of coal of the kinds indicated:

	Percentage of Ash.
Semibituminous:	
George's Creek Cumberland,	
1,287,400 to 1,421,700	6.1 to 8.6
Pocahontas,	
1,360,800 to 1,460,300	3.2 to 6.2
New River,	
1,385,800 to 1,392,200	3.5 to 5.7
Bituminous:	
Youghiogheny, Pa., lump,	
1,294,100	5.9
Youghiogheny, Pa., slack,	
1,166,400	10.2
Frontenac, Kan.,	
1,050,600	17.7
Cape Breton Caledonia,	
1,242,000	8.7
Anthracite:	
1,152,100 to 1,318,900	9.1 to 10.5



Worthington Pump.

Each unit or B.T.U. represents the amount of heat required to raise one pound of water at 32° Fahr. 1° Fahr., and it is equal to 778 foot-pounds of work. In other words, 778 foot-pounds of work is said to be the mechanical equivalent of one heat-unit. The amount of work, therefore, which one pound of dry steam is capable of performing at any given pressure and at the corresponding temperature may readily be found by multiplying the number of available heat-units which it contains, and which may be readily



Section of Worthington Pump.

computed if not already known, by 778, or as in a pumping-engine duty trial, knowing by observation the number of pounds of steam at a given pressure and temperature supplied through the steam-cylinders, the number of heat-units supplied in that steam is at once known or may easily be computed. Then observing or computing the total weight of water raised by the pumping-engine, as well as the total head (the dynamic head) against which the pumping-engine has worked, the total number of foot-pounds of work performed can be at once deduced. This latter quantity divided by the number of million heat-units will give the desired duty.

201. Three Methods of Estimating Duty.—At the present time it is frequently, and perhaps usually, customary to give the duty in terms of 100 pounds of coal consumed, as well as in terms of 1,000,000 heat-units. Frequently, also, the duty is expressed in terms of 1000 pounds of dry steam containing about 1,000,000 heat-units. As has sometimes been written, the duty unit is 100 for coal, 1000 for steam, and 1,000,000 for heat-units.

202. Trial Test and Duty of Allis Pumping-engine.—The following data are taken from a duty test of an Allis pumping-engine at Hackensack, N. J., in 1899 by Prof. James E. Denton. This pumping-engine was built to give a duty not less than 145,000,000 foot-pounds for each "1000 pounds of dry steam consumed by the engine, assuming the weight of water delivered to be that of the number of cubic feet displaced by the plungers on their inward stroke, i.e., to be 145,000,000 foot-pounds at a steam pressure of 175 pounds gauge." The capacity of the engine was to be 12,000,000 gallons per twenty-four hours at a piston speed not exceeding 217 feet per minute. The engine was of the vertical triple-expansion type with cylinders 25.5 inches, 47 inches, and 73 inches in diameter with a stroke of $42\frac{1}{16}$ inches, the single-acting plunger being 25.524 inches in diameter. The following data and figures illustrate the manner of computing the duty:

DUTY PER 1000 POUNDS OF DRY STEAM BY PLUNGER DISPLACEMENT.

1. Circumference of plungers, Cl........................ 80.1875 ins.
2. Length of stroke, l............................... 42.0625 ins.
3. Number of plungers (single-acting) 3
4. Aggregate displacement of plunger per revolution = $\frac{3C^2l}{4\pi}=d$ .... 64,4557.1 cu. ins.
5. Revolutions during 24 hours, N 43,337
6. Weight of one cubic foot of water, w .... 62.42 lbs.
7. Total head pumped against, H .... 266.61 ft.
8. Total feed-water per 24 hours, W .... 160,354 lbs.
9. Duty per 1000 lbs. of feed-water $=\frac{d\times w}{1728}\times\frac{H\times N\times 1000}{W}$

$$=2,331,976\times\frac{266.61\times 43,337\times 1000}{160,354}= \qquad 168,027,200 \text{ ft.-lbs.}$$

10. Percentage of moisture in steam at engine-throttle valve .... 0.3 per cent.
11. Duty per 1000 lbs. of dry steam, $\frac{168,027,200}{0.997}=$ 168,532,800 ft.-lbs.

DUTY PER MILLION HEAT-UNITS.

12. Average steam pressure at throttle above atmosphere.	173 lbs.
13. Average feed-water temperature	78°.5 Fahr.
14. Total heat in one pound of steam containing 0.3 per cent. of moisture above 32° Fahr	1,194.2 B. T. U.
15. Heat per lb. of feed-water above 32° Fahr............	46.5 "
16. Heat supplied per lb. of feed-water above 32° Fahr....	1,147.7 "
17. Duty per lb. of feed-water	168,027.2 ft.-lbs.
18. Duty per million B. T. U............................	146,403,614 "

203. Conditions Affecting Duty of Pumping-engines.—Manifestly the duty of a pumping-engine by whatever standard it may be measured will vary with the conditions under which it is made. A new engine running under the favoring circumstances of a short-time test may be expected to give a higher duty than when running under the ordinary conditions of usage one month after another. Hence it can scarcely be expected that the monthly performance, and much less the yearly performance, of an engine will show as high results as when tested for a day or two or for less time.

204. Speeds and Duties of Modern Pumping-engines.—The following table gives the piston or plunger speeds of a number of the best modern pumping-engines, and the corresponding duties, with the standards by which those duties are measured.

Engine.	Piston Speed in Feet per Minute.	Duty in Foot-pounds.	Expressed in
Ridgewood Station, Brooklyn, Worthington engine	164.0	137,953,585	1000 lbs. of dry steam
14th St. pumping-station, Chicago; built by Lake Erie Engine Works	210.54	133,445,000	Million B. T. U.
Allis engine at Hackensack, N. J.	210.65	146,403,416	" "
Snow pump at Indianapolis ...	214.6	150,100,000	" "
Leavitt pump at Chestnut Hill	....	144,499,032	" "
Nordberg at Wildwood.......	256.0	162,132,517	" "
Allis at Chestnut Hill, tested May 1, 1900..............	192.5	157,002,500	Million B. T. U.
Allis at St. Louis, tested February 26, 1900............	197.16	158,077,324	" "
Barr at Waltham, Mass......	194.28	128,865,000	1000 lbs. of dry steam
Allis at St. Paul, Minn.......	189.0	144,463,000	" " " "
Lake Erie Engine Works at Buffalo	207.7	135,403,745	Million B. T. U.

These results show that material advances have been made in pumping-engine designs within a comparatively few years.

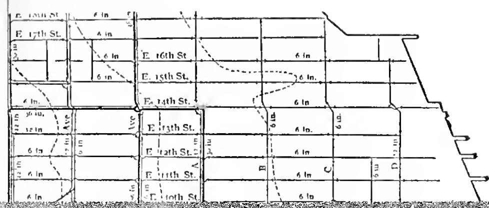
CHAPTER XIX.

205. Distributing-reservoirs and their Capacities.—The water of a public supply seldom runs from the storage-reservoir directly into the distributing system or is pumped directly into it, although such practices may in some cases be permissible for small towns or cities. Generally distributing-reservoirs are provided either in or immediately adjacent to the distributing system of pipes, meaning the water-pipes large and small which are laid through the streets of a city or town, and the service-pipes leadnig from the latter directly to the consumers.

The capacity ordinarily given to these distributing-reservoirs is not controlled by any rigid rule, but depends upon the local circumstances of each case. If they are of masonry and covered with masonry arches, as required for the reception of some filtered waters, they are made as small as practicable on account of their costs. If, on the contrary, they are open and formed of suitably constructed embankments, like the distributing-reservoirs of New York City in Central Park and at High Bridge, they are and should be of much greater capacity. The storage volume of the High Bridge reservoir amounts to 11,000,000 gallons, while that of the Central Park reservoir is 1,000,000,000 gallons. Again, the capacity of the old receiving-basin in Central Park is 200,000,000 gallons. These reservoirs act also as equalizers against the varying draft on the system during the different portions of the day and furnish all desired storage for the demands of fire-streams, which, while it lasts, may be a demand at a high rate. It may be approximately stated under ordinary circumstances that the capacity of distributing-reservoirs for a given system should equal from two or three to eight or ten days' supply. It is advantageous to approach the upper of those limits when practicable. The volume of water retained in these reservoirs acts in some cases as a needed storage, while repairs of pumping-machinery or other exigencies may temporarily stop the flow into them. The larger their capacity the more effectively will such exigencies be met.

206. System of Distributing Mains and Pipes. — Gate-houses must be placed at the distributing-reservoirs within which are found and operated the requisite gates controlling the supply into the reservoir and the outflow from it into the distributing system. The latter begins at the distributing-reservoir where there may be one or two or more large mains, usually of cast iron. These mains conduct the water into the branching system of pipes which forms a network over the entire city or town. A few lines of large pipes are laid so as to divide the total area to be supplied into convenient portions served by pipes of smaller diameter leading from the larger, so that practically every street shall carry its line or lines of piping from which every resident or user may draw the desired supply. Obviously, as a rule, the further the beginning of the distributing system is departed from in following out the ramifications of the various lines the smaller will the diameter of pipe become. The smallest cast-iron pipe of a distributing system is seldom less than 3 inches, and sometimes not less than 4 or 6 inches. There should be no dead ends in any distributing system. By a dead end is meant the end of a line of pipes, which is closed so that no water circulates through it. Whenever a branch pipe ceases it should be extended so as to connect with some other pipe in the system in order to induce circulation. The entire distributing system should therefore, in its extreme as well as central portions, constitute an interlaced system and not a series of closed ends. This is essential for the purity and potability of the water-supply. A circulation in all parts of the entire system is essential and it should be everywhere secured.

The diagram shows a portion of the distributing system of the city of New York. It will be noticed that there is a complete connection of the outlying portions, so as to make the inter-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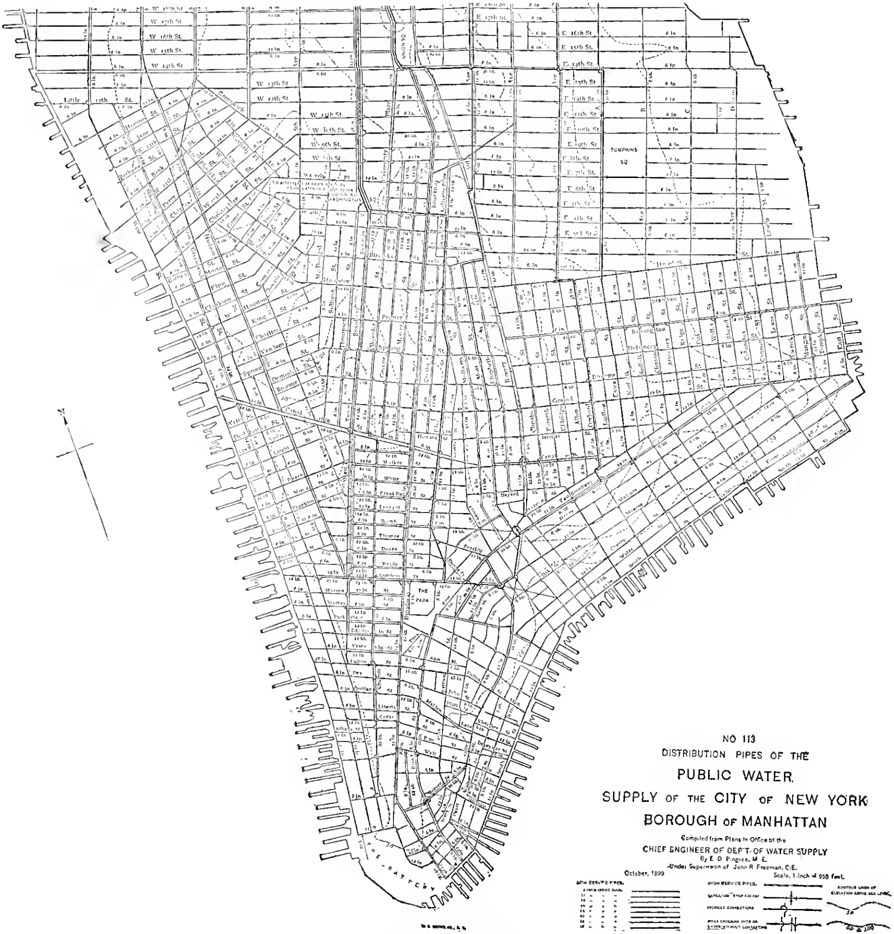


FIG. 4.—New York City Distributing System.

lacing and corresponding circulation as complete and active as possible.

207. Diameters of and Velocities in Distributing Mains and Pipes.—In laying out a distributing system it will not be possible to base the diameters at different points on close computations for velocity or discharges based upon considerations of friction or other resistances, as the conditions under which the pipes are found are too complicated to make such a method workable. Approximate estimates may be made as to the number of consumers to be supplied at a given section of a main pipe, and consequently what the diameter should be to pass the required daily supply so that the velocity may not exceed certain maximum limits known to be advisable. Such estimates may be made at a considerable number of what may be termed critical points of the system, and the diameters may be ascertained in that manner with sufficient accuracy. In this field of hydraulics a sound engineering judgment, based upon experience, is a very important element, as it is in a great many other engineering operations.

It will follow from these considerations that as a rule the larger diameters of pipe in a given distributing system will belong to the greater lengths, and it will be found that the velocities of water in the various parts of a system will seldom exceed the following limits, which, although stated with some precision, are to be regarded only as approximate:

For	4-inch	pipe...............	2 3	feet	per	second.
"	6	" "	2 3	"	"	"
"	8	" "	1 7	"	"	"
"	11	" "	1 2	"	"	"
"	12	" "	1 2	"	"	"
"	16	" "	9	"	"	"
"	20	" "	8	"	"	"
"	24	" "	7	"	"	"
"	30	" "	7	"	"	"
"	36	" "	7	"	"	"
"	48	" "	7	"	"	"
"	60	" "	7	"	"	"

208. Required Pressures in Mains and Pipes.—In designing distributing systems it is very essential so to apportion the pipes as to secure the requisite pressure at the various street services. Like many other features of a water-supply system no exact rules can be given, but it may be stated that at the street-level a pressure of at least 20 to 30 pounds should be found in resident districts, and from 30 to 35 or 40 pounds in business districts. The character and height of buildings affect these pressures to a large extent. Old pipe systems usually have many weak points, and while pressures requisite to carry water to the top of three- or four-story buildings are needed, any great excess above that would be apt to cause breaks and result in serious leakages. If the distributing system is one in which the pressure for fire-streams is to be found at the hydrants, then greater pressures than those named must be provided. In such cases the pressures in pipes at the hydrants should range from 60 to 100 pounds.

209. Fire-hydrants.—Fire-hydrants must be placed usually at street corners, if the blocks are not too long, and so distributed as to control with facility the entire district in which they are found. Unless fire-engines are used to create their own pressure, the lower the pressure at the hydrant the nearer together the hydrants must be placed. It is obvious, however, that when the pressure of the system is depended upon for fire-streams it is desirable to have the pressure comparatively high, so far as the hydrants are concerned, as under those conditions they may be placed farther apart and a less number will be required.

210. Elements of Distributing Systems.—The following table gives a number of statistics, exhibiting the elements of the distributing system of a considerable number of cities, including some pumping and meter data pertinent to the costs of pumping on the one hand and the extension of the use of meters on the other.

It contains information of no little practical value in connection with the administration of the distributing systems and the consumption of water in it. This table has been compiled by Mr. Chas. W. Sherman of the New England Water-works Association, and was published in the proceedings of that association for September, 1901. The service-pipes, varying from $\frac{1}{2}$ to 10 inches in diameter, are of cast iron, wrought iron, lead, galvanized iron, tin-lined, rubber-lined, cement-lined, enamelled and tarred, the practice varying widely not only from one city to another, but in the same city.

TABLE

Name of City or Town.	Kind of Pipe.	Size of Pipe. Ins.	Total Length in Use Miles.	Cost of Repairs per Mile.	Total Number of Hydrants in Use.
Albany, N. Y.	....	....	129.7	....	808
Atlantic City, N. J.	C.I.	4–20	47.6	....	519
Boston, Mass.	C.I.	2–48	713.4	27.09	7606
Burlington, Vt.	C.L. C.I. W.I.	4–30	38.0	4.61	213
Cambridge, Mass	....	....	....	....	968
Chelsea, Mass.	C.I.	6–16	37.8	....	253
Concord, N. H	C.I. C.L.	4–30	60.2	....	267
Fall River, Mass.	C.I.	6–24	87.3	....	954
Fitchburg, Mass.	C.I.	2–20	66.6	....	499
Holyoke, Mass	C.I. W.I.	½–30	81.6	5.14	860
Lowell, Mass.	....	....	127.8	....	1098
Lynn, Mass.	W.I. C.L. C.I.	2–20	129.4	....	952
Madison, Wis.	C.I.	4–16	34.3	....	169
Manchester, N. H.	C.L. C.I.	4–20	96.9	....	743
Metropolitan Water-works, Owned by	C.I. C.L.	6–60	69.8	....	....
Metropolitan Water-works, Tot. Sup. by	C.I. C.L. Kal.	4–60	1360.3	....	11913
Minneapolis, Minn.	C.I. Steel.	1¼–50	269.2	....	3172
New Bedford, Mass.	C.I.	4–36	92.7	24.00	738
New London, Conn	W.I. C.L. C.I.	4–24	50.5	18.71	258
Newton, Mass.	C.I.	4–20	136.6	6.43	935
Providence, R. I.	C.I.	6–36	324.6	0.56	1886
" H.P. Fire System	C.I.	12–24	5.6	....	92
Quincy, Mass	W.I. C.I. C.L.	1–36	144.7	5.50	955*
Springfield, Mass	C.I. Kal.	2–20	84.1	....	539
Woonsocket, R. I.	C.I.	4–20	45.8	3.57	548
Yonkers, N. Y	....	....	74.1	....	771
Worcester, Mass.	....	2–40	173.5	....	1763

* Public hydrants only.

XIX.

Total Number of Gates in Use.	Range of Pressure on Mains at Centre, Pounds.	Size of Service-pipe in Inches.	Total Number of Service-taps in Use.	Total Number of Meters in Use.	Total Pumpage for the Year in Gallons.	Average Static Head against which Pumps Work, Feet.
803	....	....	....	2030	....	....
....	....	½-4	4,249	3298	{ 955,726,046 148,662,947	81.7 119.5
8910	40-90	½-8	87,525	4516	....	....
618	70-85	½-6	3,350	2311	312,896,525	289
....	....	....	14,207	860	2,651,277 240	....
399	48-50	⅝-2	6,146	104	....	....
757	....	....	3,340	1010	142,772,165	....
940	80	½-2	6,943	6,544	1,388.776,336	186.2
554	{ 75 L.S. 155 H.S.	¾-8	4,432	2.427	....	....
734	80-100	⅝-4	3,610	210	....	....
1188	....	....	10,634	5,586	2,042,066.140	156.1
966	45-60	¾-4	13,504	2,571	378,782,675 1,330,784,875	....
234	....	....	2,758	2.586	306,637.454	223.8
910	....	½-6	5,513	3,667	....	....
268	....	....	134,496	10,385	15,027,410,000(*a*)	....
....	....	....	....	....	9,431,140,000(*b*)	....
....	....	....	....	....	2,015,130,000(*c*)	....
2195	....	⅝-1	20,064	5,030	6,863,135,200	....
1065	28-64	½-10	9,280	1,429	2,307 429,372	167.2
318	40-48	½-4	3,088	229	....	....
801	84	½-6	7,087	6,001	762,876,073	234
3399	64-73	½-10	21,566	17,813	3,833,243,445	171.6
					34,401,038	172.4
31	114	....	....	....	578,940,480	111.2
1889	{ 30-35 H.S. 100-120 L.S.*	1-6	9,764	3,122	....	....
1001	78-85	⅝-3	4,330	122	....	....
456	50-120	⅝-6	2,193	1,889	340,849,628	237.6
498	....	¼-8	4,968	4,852	1,323,696,099	....
2432	{ 70 L.S. 150 H.S.*	....	13,292	12,529	....	....

TABLE

Name of City or Town.	Kind of Pipe.	Size of Pipe.	Average Dynamic Head against which Pumps Work, Feet.	Duty in Foot-pounds per 100 Pounds of Coal. No Deductions.
Albany, N. Y.	....	....	....	....
Atlantic City, N. J.	C.I.	4–20	123.3 119.5	36,501,217 15,518,455
Boston, Mass.	C.I.	2–48	....	....
Burlington, Vt.	C.L. C.I. W.I.	4–30	316	....
Cambridge, Mass.	....	....	....	....
Chelsea, Mass.	C.I.	6–16	....	....
Concord, N. H.	C.I. C.L.	4–30	....	....
Fall River, Mass.	C.I.	6–24	....	....
Fitchburg, Mass.	C.I.	2–20	....	....
Holyoke, Mass.	C.I. W.I.	½–30	....	....
Lowell, Mass	....	....	163.9	93,489,048
Lynn, Mass.	W.I. C.L. C.I.	2–20	167 167	88,780,036 87,265,319
Madison, Wis.	C.I.	4–16	242.4	47,530,839
Manchester, N. H.	C.L. C.I.	4–20	....	....
Metropolitan Water-works — Owned by....	C.I. C.L	6–60	96.5	121,800,000
Metropolitan Water-works — Tot. Sup. by....	C.I. C.L. Kal.	4–60	51.8 125.6	109,380,000 80,400,000
Minneapolis, Minn.	C.I. Steel.	1½–50	....	68,016,609
New Bedford, Mass.	C.I.	4–36	192	130,336,508
New London, Conn.	W.I. C.L. C.I.	4–24	....	....
Newton, Mass.	C.I.	4–20	254	72,500,000
Providence, R. I.	C.I.	6–36	176.9 177.7 124.7	101,301,600 69,329,100 68,533,300
" H.P. Fire-system	C.I.	12–24	....	....
Quincy, Mass	C.I. Kal.	2–20	....	....
Springfield, Mass.	W.I. C.I. C.L.	1–36	....	....
Woonsocket, R. I.	C.I.	4–20	239.5	51,024,641
Yonkers, N. Y.	....	....	....	....
Worcester, Mass.	....	2–40	....	....

XIX.—*Continued.*

Cost per Million Gallons raised 1 Foot High, Figured on Pumping-station Expenses.	Cost per Million Gallons Raised 1 Foot High, Figured on Total Maintenance.	Net Cost of Works to Date.	Bonded Debt at Date.	Value of Sinking Fund at Date.	Rate of Interest. Per Cent.
....	$0.264	$916,723.59	$892,000	$100,407.01	$4\frac{1}{2}$–5
....	....	23,054,387.81	11,960,272	10,144,647.08	$3\frac{1}{2}$–6
0.08	0.366	468,039.73	248,000	64,076.40	$3\frac{1}{2}$–4
....	....	5,670,229.52	3,302,100	604,326.58	
....	....	483,335.52	300,000	50,921	4
....	....	857,440.98	650,000		
....	....	1,937,862.93	1,920,000	581,647.78	5.1
....	....	452,091.09	648,000	195,908.91	
....	....	1,244,742.23	300,000	37,403.46	4
0.0399	....	....	1,274,700	287,226.20	
0.042	0.51	2,472,821.85	1,800,300	524,027.50	$3\frac{1}{2}$–5
0.159	....	337,630.13			
......	....	1,513,012.79	900,000	159,466.83	4–6
0.0314					
0.032					
0.043					
0.033					
0.0259	0.2867	1,820,107.73	558,000	148,793.77	av. 4.44
....	....	706,978.44	410,000	....	3.5–4
0.05	0.59	2,034,808.07	2,075,000	849,115.40	av. 4.7
....	L.S.=0.0259	6,470,093.35	5,920,000	713,431.62	av. 3.7
....	H.S.=0.1134				
....	....	....	720,500	....	4
....	....	2,128,559.56	1,500,000	461,861.90	av. 5.9
0.061	0.37	390,841.78			
....	....	1,577,105.15	1,475,000	310,700	3.5–7

C.L. = cement-lined.
(*a*) = Chestnut Hill high service.
(*b*) = Chestnut Hill low service.
(*c*) = Spot Pond Pumping-station.

CHAPTER XX.

211. Sanitary Improvement of Public Water-supplies. — In the preceding consideration of a public water-supply it has been virtually assumed that the water will reach consumers in the proper sanitary condition; but this is not always the case. With great increase of population and corresponding increase of manufacturing and other industries there arise many sources of contamination, so that pure spring- or river-water for public supplies becomes less available and at the present time in this country it is rarely to be had.

The legal responsibility of parties who allow sewage, manufacturing wastes, or other contaminating matter to flow into streams is already clearly recognized, and many cities and towns are required to dispose of their sewage and other wastes in such manner as to avoid polluting streams of water flowing past sewer outfalls or manufacturing establishments; but even these restraints are not sufficient. If a stream has once been polluted it can scarcely be considered safe as a supply for potable water for public or private purposes. There are certain diseases whose bacilli are water-borne and which are conveyed by drinking-water containing them; prominent among such diseases are typhoid fever and cholera. Experience has many times shown that these bacilli or disease germs may find their way from isolated country houses as well as from the sewage of cities into water that would otherwise be potable. Besides such considerations as these it is equally well known from engineering experience that many waters of otherwise fair quality carry the remains of organic matter in one shape or another which operate prejudicially to the physical condition of those who drink such water. It is therefore becoming more and more the conviction of civil engineers and sanitarians that there are few sources of potable water so free from some degree of pollution that the supplies drawn from them do not require treatment in order to put them into good condition for drinking. It is not intended in this observation to state that there are no streams or springs from which natural waters may not be immediately used for domestic purposes without improving them by artificial means, but it may be stated even at the present time that no water of a public water-supply should be used without treatment, unless the most thorough bacteriological examinations show that its sanitary condition is eminently satisfactory.

It is the common experience of many public water-supplies in this country that during certain seasons of the year, extending through the summer and autumn months, certain low forms of vegetation flourish, causing sometimes discoloration and always offensive tastes and odors. While such waters are usually not dangerous, they certainly are not desirable and may cause the human system to become receptive in respect to pathogenic bacilli. The tendency at the present time, therefore, is to consider the improvement of any water-supply that may be contemplated for any city or town.

212. Improvement by Sedimentation.—The two broad methods of improving the water of a public supply at the present time are sedimentation and filtration, the latter generally through clean sand, although sometimes other fine granular material or porous mass is used. The operation of sedimentation is carried on when water is allowed to stand absolutely at rest or to move through a series of basins with such small velocity that the greater portion of the solid material held in suspension is given an opportunity to settle to the bottom. All water which is taken from natural sources, whether surface or underground, carries some solid matter. Some waters, like spring-water or from an underground supply, are so clear as to be very nearly free from solid matter in suspension, but, on the other hand, there are waters, like those from silt-bearing rivers, which carry large amounts. Observations upon the Mississippi River at St. Louis have shown that the suspended matter may reach as much as 1000 parts in one million, although the quantity held in suspension is usually much less than that. Similar observations have been made upon other silt-bearing streams. Such large proportions of suspended solid matter are not usually found in streams used for potable purposes, but there are few surface sources of water-supply the water from which will not be sensibly improved by sedimentation in settling-basins or reservoirs.

The process of sedimentation is usually preliminary to that of filtration. If raw water, i.e., as it comes from its natural source, is conducted directly to filtration-beds, the amount of solid matter is frequently so great that the surface of the filter would be too quickly clogged; hence it is advisable in almost every case to subject to sedimentation any water which is designed to be treated subsequently by filtration.

The degree of turbidity is usually measured by means similar to those employed in gauging discoloration from vegetable matter. One method devised by Mr. Allen Hazen, to which allusion will again be made, is that in which the depth in inches is observed at which a platinum wire 1 mm. in diameter and 1 inch long can be seen. The degree of turbidity is then represented by the reciprocal of that distance. The permissible turbidity estimated in this manner is taken by different authorities at different values running from .025 to .2. Water of this degree of turbidity appears, when seen through a glass, to be practically clear.

The rapidity with which sedimentation can be performed depends greatly upon the character and degree of comminution of the solid material. If it is coarse, comparatively speaking, it will quickly fall to the bottom; if the solid matter is clay of fine texture, it is dissipated through the water in an excessively high degree of diffusion and will remain obstinately suspended. This has been found to be the case at some points with the Ohio River water. Ordinarily sufficient sedimentation can be accomplished where the water remains at rest from twenty-four to forty-eight hours; in general, observations as to this matter, however, must be applied very cautiously. Water of the Mississippi River at St. Louis has been found to deposit nearly all of its sediment within twenty-four hours. At Cincinnati, on the other hand, the Ohio River water carries so fine a sediment that on an average not more than 75 per cent of it will be deposited in three days by unaided subsidence. Again, at Omaha the water of the Missouri River has been found to be turbid at the end of seventy-two hours. In some cases, as with the waters of the Delaware and Schuylkill at Philadelphia, a greater amount of subsidence has been found to exist at times at the end of twenty-four hours than after forty-eight hours. It is obvious that some special conditions must have produced such results that would not ordinarily occur in connection with the operation of sedimentation.

213. Sedimentation Aided by Chemicals.—In cases where simple unaided subsidence proceeds too slowly it can be accelerated by the introduction of suitable chemicals. At Cincinnati, for instance, it was found advantageous to introduce into the water before flowing into the settling-basins a small amount of alum or sulphate of alumina, depending upon the degree of turbidity, the average being about 1.6 grains per gallon, rising to perhaps 4 grains in floods. By these means a few hours of aided sedimentation would produce more subsidence than could be obtained in several days without the chemicals. A similar recommendation has been made for the purpose of improving the water-supply for the city of Washington, D. C., from the Potomac River. In other cases between 5 and 6 grains of lime per gallon have produced effective results.

214. Amount of Solid Matter Removed by Sedimentation.—Under adverse conditions, or with sediment which remains obstinately suspended, not more than 25 to 50 per cent of the solid material will be removed by sedimentation, but when the process is working satisfactorily, sometimes by the aid of chemicals acting as coagulants, 90 to 99 per cent even of the solid material may be removed. The operation of sedimentation has another beneficial effect in that the solid matter when being deposited carries down with it large numbers of bacteria, which, in some cases, have been observed to be 80 or 90 per cent of the total contents of the water. In other words, the subsidence of the solid matter clears the water of a large portion of the bacteria.

215. Two Methods of Operating Sedimentation-basins.—Sedimentation is carried on in two ways, one being the "fill-and-draw" method and the other the "continuous" method. In the former method a basin or reservoir is first filled with water and then allowed to stand while the subsidence goes on for perhaps twenty-four hours. The clear water is then drawn off, after which the reservoir is again filled. In the continuous method, on the other hand, water is allowed to flow into a single reservoir or series of reservoirs through which it passes at an extremely low velocity, so that its contents will not entirely change within perhaps twenty-four hours or more. In this method the clear water is continuously discharging at a comparatively low rate, the velocity in the reservoir being so small that the solid matter may be deposited as in the fill-and-draw method. Both of these methods are used, and both are effective. The choice will be dependent upon local conditions. In the continuous method the solid matter is largely deposited nearer the point of entrance into the reservoir, but more generally over the bottom in the fill-and-draw method. The velocity of flow in the reservoirs of the continuous method generally ranges between 0.5 inch and 2.5 inches per minute. Occasionally the velocity may be slightly less than the least of these values, and sometimes one or two inches more than the maximum value.

216. Sizes and Construction of Settling-basins.—The sizes of the settling-basins will obviously depend to a considerable extent upon the daily consumption of water. There is no general rule to be followed, but the capacity of storage volume of those actually in use run from less than 1 to possibly 14 or 15 days' supply. Under ordinary circumstances their volumes may usually be taken from 5 to 6 or 8 days' supply. Their shape should be such as to allow the greatest economy in the construction of embankments and bottoms. They may generally be made rectangular. Their depths is also a matter, to some extent, of constructive economy. The depth of water will usually be found between about 10 and 16 feet, it being supposed that possibly 2 or 3 feet of depth will be required for the collection of sediment. These basins must be water-tight. The bottom surfaces may be covered with concrete 6 to 9 inches thick, with water-tight firm puddle 12 to 18 inches thick underneath, resting on firm compacted earth. The inner embankment surfaces or slopes may be paved with 10- or 12-inch riprap resting on about 18 inches of broken stone over a layer of puddle of equal thickness with the bottom and continuous with it. Occasionally the bottom and sides may be simply puddled with clay and lined with brick or riprap pavement, laid on gravel, or broken stone. It is only necessary that the sides and bottoms shall be tight and of such degree of hardness and continuity as to admit of thorough cleaning.

The bottoms of sedimentation-basins may advantageously not be made level. In order to facilitate cleaning away the solid matter settling on them, a valley or depression may be formed along the centre line to which the two portions of the bottom slope. A grade in this channel or central valley of 1 in 500 with slopes on either side of 1 in 200 or 1 in 300 will be effective in the disposition of the solid matter. At the lowest end of the central valley there should be suitable gates through which the accumulated sediment can be moved out of the basin. This sedimentary matter will in many cases be soft mud, but its movement will always be facilitated by the use of suitable streams of water. The frequency of cleaning will depend upon the amount of sediment carried by the water and upon its accumulation in the basin. Whenever its depth ranges from 1 to 2 or 3 feet it is removed.

Complete control of the entrance of the water to and its exit from the basin must evidently be secured by suitable gates or valves and other appliances required for the satisfactory operation of the basin. In some cases the cost of sedimentation-reservoirs with concrete bottoms and sides has risen as high as $9000 per million gallons of capacity; but where the cheaper lining has been used, as in the case of reservoirs at Philadelphia, the range has been from about $3300 to about $4300.

217. Two Methods of Filtration.—After the process of sedimentation is completed there will necessarily always be found the remains of organic matter and certain other polluting material which should be removed before the water is allowed to enter the distributing system. This removal is accomplished usually by filtration through clean sand, but occasionally through porous material, such as concrete slabs, porcelain, or other similar material. The latter processes are not much used at the present time, and they will not be further considered.

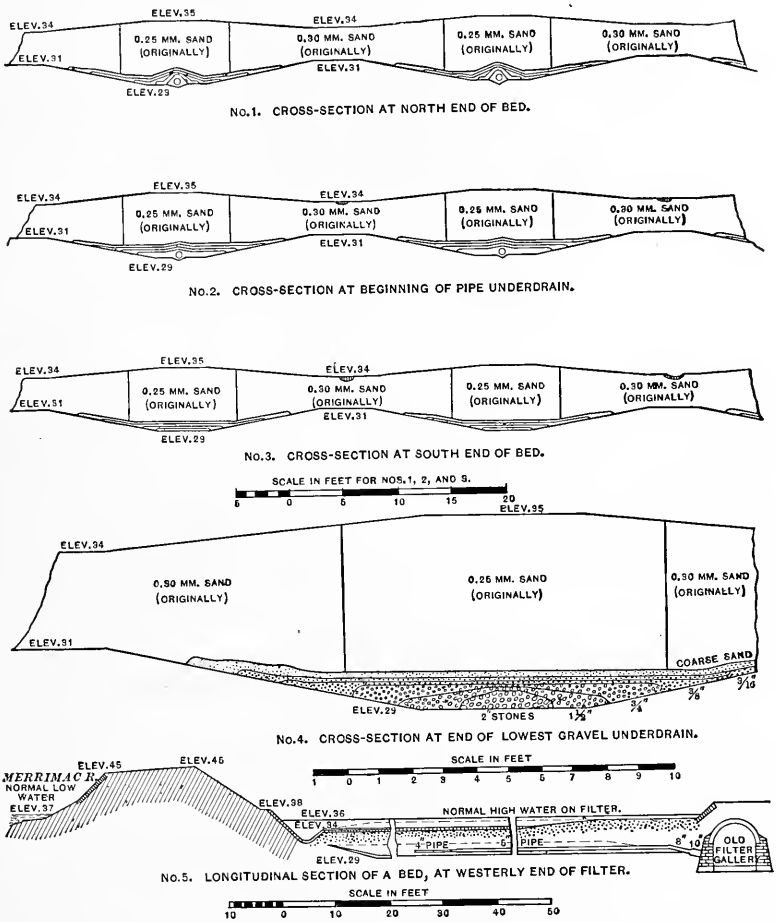
The filtration of water through sand is carried on by two distinct methods, one called slow sand filtration and the other rapid sand filtration. In the first method the water is simply allowed to filter slowly through beds of sand from 2 to 3 or 5 feet thick and suitably arranged for the purpose. In the second method special appliances and conditions are employed in such manner as to cause the water to flow through the sand at a much more rapid rate. The method of slow sand filtration will first receive attention.

218. Conditions Necessary for Reduction of Organic Matter.—The most objectionable class of polluting materials includes organic matter which from one source or another finds its way into natural waters. Such material has originally constituted or formed a part of living organisms and chemically consists of varying proportions of carbon, oxygen, hydrogen, and nitrogen. As found in public water-supplies it is usually in some stage of decomposition. The chemical operations taking place in these decompositions are more or less complicated, but in a general way it may be said that the first step is the oxidizing of the carbon which may produce either carbon monoxide or carbon dioxide and a combination of nitrogen with hydrogen as ammonia. When the conditions are favorable, i.e., when free oxygen is present, the ammonia may be oxidized by it, thus producing nitric acid and water. If, as is generally the case, suitable other substances, as alkalis, are present, the nitric acid combines with them, forming nitrates more or less soluble and essentially innocuous. It is therefore seen that the complete result is a chemical change from the original organic matter, offensive and possibly dangerously polluting, to gaseous and solid matter, the former escaping from the water and the latter either passing off unobjectionably in a soluble state or precipitating to the bottom as inert mineral matter. In order that these processes may be completely effective, two or three conditions are necessary, i.e., sunlight, free oxygen, and certain species of that minute and low class of organisms known as bacteria, the nature and conditions of existence of which have been scientifically known and studied within a period extending scarcely farther back than ten or fifteen years. The precise nature of their operations and their relations to the presence of the necessary oxygen, or just the parts which they play in the process of decomposition, are not completely known, although much progress has been made in their determination. It is positively known that their presence and that of uncombined oxygen are essential. Certain species of these bacteria will live and work only in the presence of sunlight and oxygen; these are known as aerobic bacteria. Other species, forming a class known as anaerobic bacteria, live and effect their operations in the absence of sunlight and oxygen in that offensive mode of decomposition which takes place in cesspools and other closed receptacles for sewage and waste matter. They play an essential part in what promises to be one of the most valuable methods of sewage-disposal in which the septic tank is a main feature.

219. Slow Filtration through Sand—Intermittent Filtration.— In the slow sand-filtration method of purifying the water of a water-supply the aerobic bacteria only act. In order that their operations may be completed, free oxygen and sunlight are essential requisites, and the first of these is found in every natural water which can be considered potable. Any water which does not contain sufficient free oxygen for this purpose is to be regarded with suspicion, and generally cannot be considered suitable for domestic purposes. The amount of uncombined oxygen contained in any potable natural water is greatly variable and changes much with the period of exposure in a quiet state, as well as with pressure and temperature. In the river Seine it has averaged nearly 11 parts in a million throughout the year, being lowest in July and August and highest in December and January. It has been found in the experimental work of the Massachusetts State Board of Health that free or dissolved oxygen in potable water may vary from 8.1 parts at 80° Fahr. to 14.7 parts by weight at 32° Fahr. in 1,000,000 at atmospheric pressure.

In some cases where liability to dangerous contamination exists it may be advisable to increase the available supply of oxygen in the water by using a slow sand filter intermittently, as has been done at Lawrence, Mass. Instead of permitting a continuous flow of water through the sand, that flow is allowed for a period of 6 to 12 hours only, after which the filter rests and is drained for perhaps an equal period. During this intermis-

one is intermittent. In this manner the oxygen of the air finds its way into the sand voids of each drained filter in turn and thus becomes available in the presence of suitable species of bacteria



TYPICAL SECTIONS OF UNIT BEDS IN LAWRENCE CITY FILTER.
APRIL, 1901.
COPIED FROM PLAN FURNISHED BY A. D. MARBLE, CITY ENGINEER.

for reducing the organic matter in the water next passing through the filter. Intermittent filters operated in this manner are not much used, but the most prominent instance is that at Lawrence, Mass. At that place the water after being filtered is pumped to a higher elevation for use in the distribution system. The pumps have been run nineteen hours out of the twenty-four, and the water is shut off from the filters five hours before the pumps stop. The gate admitting water to the filter is open one hour before they start. Nine hours of each day the filter does not receive water, and rests absolutely about four hours.

220. Removal of Bacteria in the Filter. — The grains of the sand at and near the surface of a slow sand filter, within a short time after its operation is begun, acquire a gelatinous coating, densest at the surface and decreasing rapidly as the mass of sand is entered. This gelatinous coating of the grains is organic in character and probably largely made up of numerous colonies of bacteria whose presence is necessary for the reduction of the organic matter. It is necessary to distinguish between these species of bacteria and those which are pathogenic and characteristic of such diseases as typhoid fever, cholera, and others that are water-borne. Every potable surface-water and possibly all rain-water carry bacteria which are not pathogenic and which apparently accumulate in dense masses at and near the surface of the slow sand filter. As the water finds its way through the sand it loses its organic matter and its bacteria, both those of a pathogenic and non-pathogenic character. Potable water, therefore, is purified and rendered innocuous by the removal in the filter of all its bacteria, including both the harmless and dangerous.

221. Preliminary Treatment — Sizes of Sand Grains.—In designing filtration-works consideration must be given to the character of water involved. There are waters which when standing in open reservoirs exposed to the sunlight will develop disagreeable tastes and odors, and it may be necessary to give them preliminary treatment especially for the removal of such objectionable constituents.

The character and coarseness of the sand employed are both elements affecting its efficiency as a filtering material. It should not be calcareous, for then masses of it may be cemented together and injure or partially destroy the working capacity. Again, if it is too coarse and approaches the size of gravel, water may run freely through it without experiencing any purification. Much labor has been expended, especially by the State Board of Health of Massachusetts, in investigating the characteristics of sand and the sizes of grains best adapted to filter purposes. In that work it has become necessary to classify sands according to degrees of fineness or coarseness. The diameter of a grain of sand in the system of classification employed means the cube root of the product of the greatest and least diameters of a grain multiplied by a third diameter at right angles to the greatest and least. The "effective" size of any given mass of sand means the greatest diameter of the finest 10 per cent of the total mass. There is also a term called the "uniformity coefficient." The uniformity coefficient is the quotient arising from dividing the greatest diameter of the finest 60 per cent of the mass by the greatest diameter of the finest 10 per cent of the same mass. These are arbitrary terms which have been reached by experience as convenient for use in classifying sands. Evidently absolute uniformity in size will be indicated by a uniformity coefficient of 1, and the greater the variety in size the greater will be the uniformity coefficient. Sands taken from different vicinities and sometimes even from the same bed will exhibit a great range in size of grain.

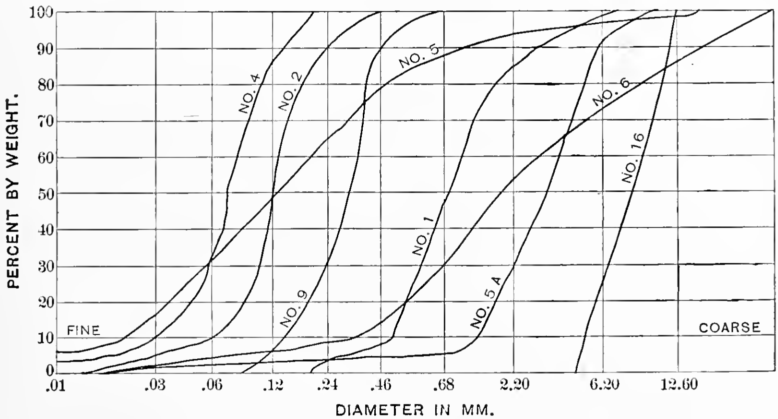


FIG. 5.—Sizes of Grain or Fineness of Sand.

Fig. 5 represents the actual variety of size of grain as found in eight lots of sand among others examined in the laboratory of the Massachusetts State Board of Health. The vertical scale shows the per cent by weight of portions having the maximum grains less in diameter than shown on the horizontal line. The more slope, like No. 5 or 6, the greater is the variety in size of grain. Those lines more nearly vertical belong to sands more nearly uniform in size of grain.

222. Most Effective Sizes of Sand Grains.—Investigations by the Massachusetts State Board of Health indicate that a sand whose effective diameter of grain is .2 mm. (.008 inch) is perhaps the most efficient in removing organic matter and bacteria from natural potable waters. At the same time wide experience with the operation of actual filters seems to indicate that no particular advantage attaches to any special size of grain, so long as it is not too fine to permit the desired rate of filtration or so coarse as to allow the water to flow through it too freely. Experiments have shown that effective sizes of sand from .14 to .38 mm. in diameter possess practically the same efficiency in a slow sand filter. The action of the filter is apparently a partial straining out of both organic material and bacteria, but chiefly the reduction of organic matter in the manner already described and probably the destruction to a large extent of the bacteria, especially those of a pathogenic nature, although at the present time it is impossible to state the precise extent of either mode of action.

223. Air and Water Capacities.—Another important physical feature of filter-sands, especially in connection with intermittent filtration, is the amount of voids between the grains. When the intermittent filter is allowed to drain, so that the only water remaining in it is that held between the grains by capillary attraction, generally at the bottom of the filter unless the sand is very fine, the volume of the water which remains in the voids is called the water capacity of the sand. The remaining volume between the grains is called the air capacity of the same sand. It is evident that the air capacity added to the water capacity will make the total voids between the sand grains.

Fig. 6 shows the amount of air and water capacities of the same sands whose sizes of grains are exhibited in Fig. 5. The depth of the sand is supposed to be 60 inches, as shown on the vertical line at the left of the diagram, while the percentages of the total volume representing the amounts of voids is shown on the horizontal line at the bottom of the diagram. Both air and water capacities for each sand are shown by the various numbered lines partially vertical and partially inclined. It will be observed that the fine sands No. 2 and No. 4 have large water capacities, the water capacity being shown by

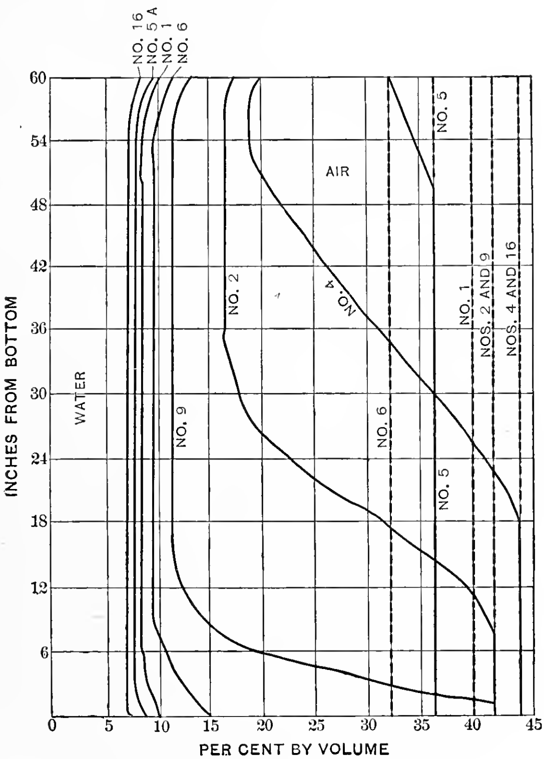


Fig. 6.

that part of the diagram lying below and to the left of each line. It will be noticed that No. 5 sand is made up of approximately equal portions of fine and coarse grains, the former largely filling the voids between the latter. This mixture, as shown by the No. 5 line, gives a very high water capacity and a correspondingly low air capacity. Obviously a sand with a high water capacity has a correspondingly low air capacity, and in general would not be a very good sand for an intermittent filter, since it is the purpose of the latter to secure in the voids