CHAPTER 5

Removal of Suspended Solids

The removal of suspended solids from any industry's waste plays an important part in its overall waste treatment program for the following reasons:

1. Elimination of a major portion of the contaminant (often as high as 20–30%)
2. Segregation of one type of contaminant so that it can be further treated more easily and economically
3. Removal of this type of constituent so that the remaining contaminants are more homogeneous and likewise can be treated more efficiently—usually chemically or biologically
4. When their removal is the sole method of waste treatment, it reduces the unsightliness or visibility from the public viewers and even prevents damage to the habitats of riverbeds, which are not generally visible to the receiving water user

Sedimentation Theory

Although sedimentation is a method of treatment used in almost all domestic-sewage treatment plants, it should be considered for industrial waste treatment only when the industrial waste is combined with domestic sewage or contains a high percentage of "settleable" suspended solids, such as those found in cannery, paper, sand and gravel, coal-washery, and certain other wastes. The efficiency of sedimentation tanks depends, in general, on the following factors:

- Detention period
- Wastewater characteristics
- Tank depth
- Floor surface area and overflow rate
- Operation (cleanliness)
- Temperature
- Particle size
- Inlet and outlet design

- Velocity of particles
- Density of particles
- Container-wall effect
- Number of basins (baffles)
- Sludge removal
- Pretreatment (grit removal)
- Flow fluctuations
- Wind velocity

Although settling tanks have been used for other purposes, such as grease flotation, equalization, and biochemical oxygen demand (BOD) reduction, they are primarily used for removing settleable suspended matter. Theoretically, a suspended particle in a wastewater solution will continue to settle at a fixed velocity relative to the solution, as long as the particle remains discrete; when it coalesces with other particles, its size, shape, and resulting density will change, as will its settling velocity. Coagulation, or self-flocculation, of particles causes an increase in velocity. In liquid wastes containing high percentages of suspended solids, greater reductions in the suspended solids will occur primarily because of increased flocculation. The fixed settling velocity will also be altered by changes in the temperature and density of the liquid solvent through which the particle is moving. Rising layers of warmer liquid can cause eddying and a disturbance in the settling of particles; an increased density in the lower layers of liquid can deter the particle from settling to the bottom. These factors can interfere with settling to such an extent that particles may be carried out of the tank with the effluent.

Tank depth is also important. The deeper the tank (all other factors being equal), the better the chance of preventing the deposited solids from being re-suspended—for example, by sudden scouring due to turbulence caused by unequal flow distribution or by exposure to wind or temperature effects—and thus being carried out with the effluent. This is especially important when sludge is stored in sedimentation basins for lengthy periods before pumping. If the solids are continuously removed from the bottom of settling tanks as soon as they land, shallower tanks can be built.

Surface area is another factor affecting tank efficiency, and engineers agree that floor area must be adequate to receive all the particles to be removed from the wastewater. However, many state health departments, when establishing acceptable dimensions for settling basins, do so on the basis of standard detention periods. In certain designs, this method may not provide adequate floor area and complete settling is not achieved.

Figure 5.1 illustrates the effect of doubling the floor area and halving the depth of a settling basin, with volume and detention time remaining constant. Theoretically, the basin in Figure 5.1B will remove twice as many discrete particles as the basin in Figure 5.1A. Therefore, the engineer should strive to design settling basins that are as shallow as possible and contain ample floor area. However, tanks less than 6 feet deep have been found impractical from an operational standpoint, because they are subject to upsetting by scouring or velocity of currents. The floor area is increased most satisfactorily by extending the length of the basin.

Because the percentage of particles reaching the bottom of the settling basin also depends on the rate of waste flow, an expression correlating horizontal flow with the floor or surface area has been devised. It is commonly referred to as the *overflow rate*

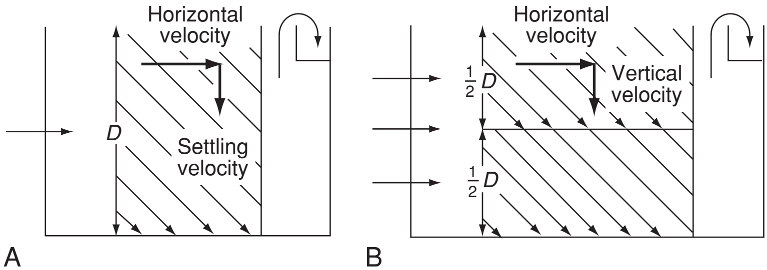

FIGURE 5.1. Effect of (**A**) doubling the floor area and (**B**) halving the depth of a settling basin.

and is expressed as gallons per square foot per day (g/ft^2/day). Typical overflow rates vary from 200 to 800 g/ft^2/day for primary sedimentation basins and from 1,000 to 3,000 g/ft^2/day for final tanks, because particles in the final tanks usually settle more rapidly than those in primary basins. Exceptions include grit particles, which settle faster than the average particle in primary basins, and activated sludge floc, which tends to slow down the settling rate in secondary basins. Because of these discrepancies, both primary and secondary settling basins are often designed for the same overflow rates. Lower overflow rates for domestic-type wastes generally result in the removal of more suspended solids and BOD, as shown in Figure 5.2 (Great Lakes–Upper Mississippi River Board of State Sanitary Engineers 1960). For further details on theories of sedimentation, the reader is referred to Eckenfelder (1966).

Unfortunately, actual settling velocities may vary from theoretical formulations. Turbulence and flocculation are the main causes of variation. Another factor is that velocities do not remain constant throughout a cross-sectional area of a tank. The settling velocity of discrete particles of diameter *d* in a quiescent viscous fluid is given by

$$V = 4/3 \bullet gd/C_d\ (p_s - 1/p),$$

where C_d is the drag coefficient between the fluid and the particle, g is the acceleration due to gravity, and p_s and p are the densities of the particle and the fluid. The drag coefficient does not remain constant but varies with the Reynolds number, R, which equals pdV/μ. The correlation between C_d and R has been plotted in various textbooks, but a trial-and-error procedure is still required to obtain V.

Turbulence in sedimentation basins has both a positive and a negative effect on the settling velocity of a particle. It causes eddies that carry some particles down and some up (as shown in Figure 5.1), so it both helps flocculation and hinders sedimentation. Settling or rising velocities can be unequal, depending on the local circumstances causing the turbulence, such as increased horizontal velocity of water at the inlet.

Other factors that induce eddying include wind, unequal distribution of flow, changes in temperature, and changes in density of the liquid at various depths. Eddying generally decreases the settling velocity and efficiency of operation, while flocculation generally increases the overall total of solids removed. The influence of flocculation is illustrated in Figure 5.3, where θ is the angle of vertical settling of the average particle.

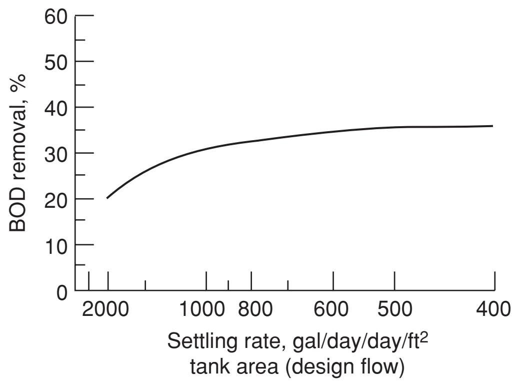

FIGURE 5.2. Effect of overflow rate on BOD removal.

Because shallow tanks appear to induce more flocculation, and because of other reasons (such as reaching the bottom sooner), they are preferred over deep tanks, provided that scouring of settled particles is prevented. The average settling velocities of particles in industrial wastes vary appreciably (Figure 5.4).

The percentage of suspended solids removed depends on the tank design, which in turn depends on the demands of the particular situation. Design engineers have begun to use either circular or square tanks instead of the conventional rectangular basins for reasons of space or economics. Circular tanks require less form work, materials, and land space than rectangular basins for large flows and for any size of tank. However, they are less efficient, because of: (1) reduced length of effective settling zone; and (2) short-circuiting (wastewater leaving the tank before theoretical detention time) (Figure 5.5). The efficiency of circular tanks has been increased somewhat by the introduction of peripheral feed with center draw-off. This system eliminates turbulence at the inlet.

The relative percentages of total transverse distance occupied by the inlet zones of circular and rectangular tanks are shown in Figure 5.6. Because the inlet zone of a circular tank occupies such a large portion of the horizontal particle path, special care

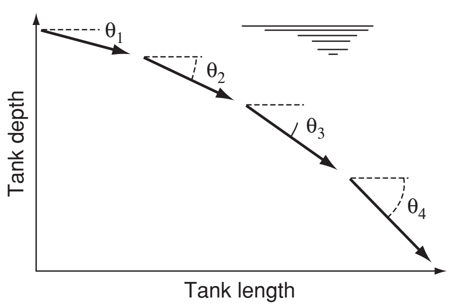

FIGURE 5.3. Flocculation increases settling rate.

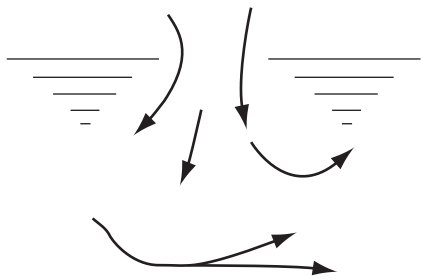

FIGURE 5.4. Effect of turbulence on particle path.

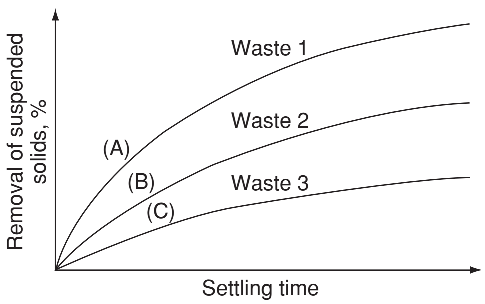

FIGURE 5.5. (A) Fast and good settling characteristics typical of heavy suspended solids. (B) Medium and normal settling characteristics typical of homogeneous mixture of solids. (C) Slow and poor settling characteristics typical of highly colloidal and finely divided solids.

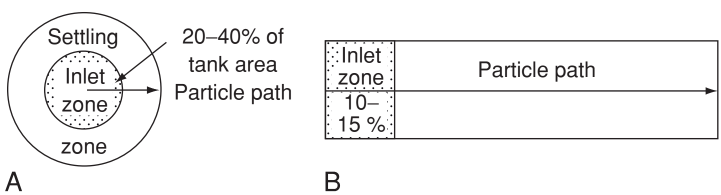

FIGURE 5.6. Inlet zone of a circular tank (A) occupies 20–40% of tank area. Inlet zone of a rectangular tank (B) occupies only 10–15% of tank area.

must be used in designing inlet and outlet devices. The slightest disturbance in flow conditions will tend to disrupt the operation of a circular tank, but with long, narrow, rectangular tanks, the design of the inlet and outlet zones becomes less important.

"Short-circuiting" means that effective sedimentation is not taking place in the entire volume of the settling tank; that is, a given entering volume of waste is hindered from spreading uniformly throughout the tank in a quiescent manner, so it reaches the effluent weir before the theoretical detention time has been used. This is essentially true in all tanks, regardless of shape, but it seems to occur most readily in circular and square tanks, as illustrated in Figure 5.7. To avoid short-circuiting, some state regulatory agencies specify a minimum distance between the inlet and exit of the tank. It has also been demonstrated graphically by Camp (1953) (Figure 5.8) that different shapes of sedimentation tanks cause different degrees of short-circuiting. Villemonte et al. (1966) showed that hydraulic efficiencies, predicted by basin dispersion curves, are related directly to the basin performance, measured by suspended-solids reduction.

In Figure 5.8, the higher peaks occurring over shorter ranges of t/T indicate the absence of short-circuiting. Curve A is a theoretical one for an ideal instantaneous dispersion of a slug with entire tank contents. (Short-circuiting approximates this.) Curve B is for a circular tank and indicates that some suspended contaminant reaches the outlet after about 15% of the detention period, and the greatest concentration of matter reaches the outlet after about 50% of the detention period. Curve C shows the situation in a wide rectangular tank, which approximates a square one. Curve D refers to a long, narrow rectangular tank and indicates that no contaminant reaches the end of the tank until after 50% of the detention period and most reaches the outlet after about 80% of the detention period. Curve E is the dispersion curve of a round-the-end, long, baffled rectangular chamber, with great length compared to width and depth. This type of tank gives a theoretical maximum contaminant content in the effluent after 100% of the detention period, but little or none before this time. The reader can readily appreciate from a study of Figure 5.8 the importance of proper design of sedimentation tanks. Preference should be given, wherever possible, to long rectangular tanks with proper baffling.

A major objective of sedimentation is to produce sludge with the highest possible solids concentration. As will be seen in Chapter 9, the volume and weight of sludge requiring final disposal is a major factor in waste treatment. A relatively new piece of equipment to achieve this objective is the Clarithickener, which combines sludge separation in circular settling tanks and thickening by means of slowly rotating picket-fence arms. Other methods of decreasing short-circuiting include effective inlet and outlet

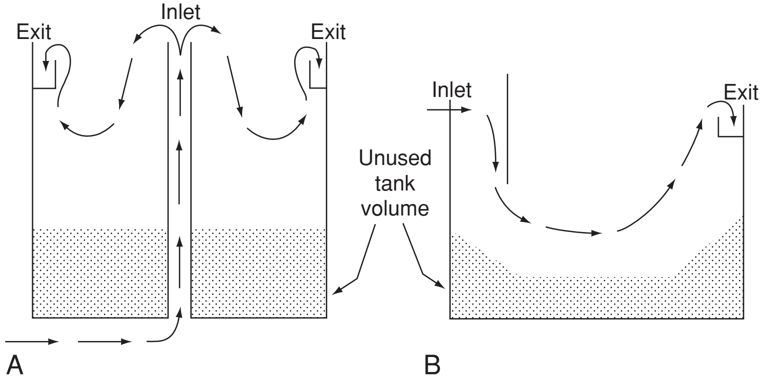

FIGURE 5.7. (**A**) Circulator tank. (**B**) Square tank.

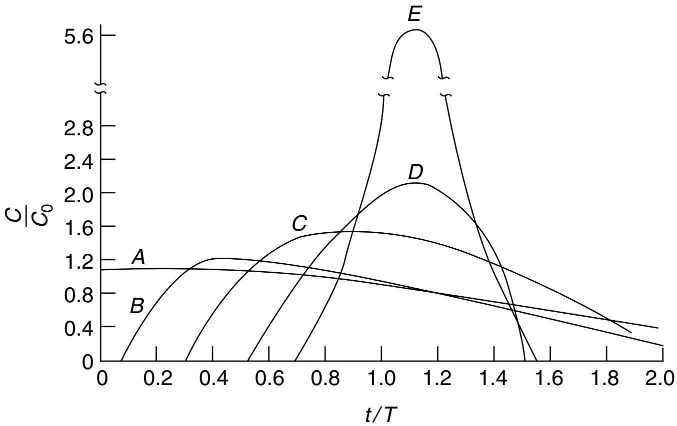

FIGURE 5.8. Typical dispersion curves for various tanks (see text for explanation). The vertical axis shows the ratio of the actual concentration of contaminant (*C*) to the concentration of contaminant mixed with the entire tank volume (C_o); the horizontal axis shows the ratio of the actual time (*t*) that a concentration takes to reach the end of the tank to (*T*), the total detention period (vol/rate) (adapted from Camp 1953.)

design, properly located baffling, inboard weirs, and modification of existing sedimentation tanks to obtain better flow distribution.

Although the differences between domestic sewage and industrial wastes are often quite significant, some general statements made for domestic sewage hold true for all wastes. Normally, with detention periods of 2 hours, primary sedimentation basins remove 50–70% of the suspended solids in the influent. Data collected from wastewater treatment plant superintendents (Bramer and Hoak 1966) are presented in Tables 5.1 and 5.2 to show design criteria and efficiencies of removal for rectangular and circular tanks.

In an unpublished study by Nemerow and McWeeny in 1972, the settling basin was separated into two zones by placing a series of vertical baffles perpendicular to the flow, with the top of the baffles below the surface of the sewage. The waste flows across the tops of the baffles following the path of least resistance, while the particles settle through the baffles into the sludge collection zone. The baffles dampen out the turbulence caused by sludge removal along the bottom of the basin. A removal efficiency of 85% of suspended solids at 691 gpd/ft^2 of suspended solids was obtained, a 20% increase over the then-current design expectation. A removal efficiency of 65% of suspended solids was obtained at a loading rate of 4,600 gallons/ft^2 with a baffle spacing of 0.25 feet.

Design of Sedimentation Process Units

Sedimentation processes are very effective in removing suspended solids in industrial wastewater. Clarifiers, either rectangular or circular, are most commonly used in

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TABLE 5.1
Rectangular Primary Settling-Tank Data[a]

Plant Location	*No. of Tanks*	*Length, ft*	*Width, ft*	*Depth, ft*	*Length Width*	*Length Depth*	*Flow, mgd*	*Detention, hr*	*Over-Flow, gpd/ft²*	*Weir Rate, gpd/ft*	*Raw Suspended Solids, mg/liter*	*Removal Suspended Solids, %*	*Raw BOD, mg/ liter*	*Removal BOD, %*
Hartford, Conn.	8	100	68	8.8	1.5	11.4	24.30	3.53	450	56,800	173	61	240	42
Detroit, Mich.	8	270	117	13	2.3	20.8	418.00	1.41	1,650	408,000	184	44	153	39
Racine, Wis.	4	140	40	10.5	3.5	13.3	17.03	2.48	760	106,500	149	67	133	48
New York City, Bowery Bay	3	124	50	12	2.5	10.3	41.00	0.98	2,210	284,000	152	39	169	22
New York City, Tallmans Island	3	124	50	11.6	2.5	10.7	31.00	1.25	1,670	215,000	137	55	128	39
Fort Wayne, Ind.	3	100	33	13	3.3	7.7	18.70	1.25	1,890	94,500	409	61	231	34
Rochester, N.Y.	2	37	12	8	3.1	4.6	0.81	1.56	914	41,000	233	21	260	21
Marshalltown, Iowa	3	80	16	8	5.0	10.0	1.22	1.51	950	13,550	436	58	414	42
Kenosha, Wis.	4	132	32	10.4	4.1	12.7	12.77	2.49	755	100,000	138	48	102	48
Jackson, Mich.	3	67.3	31	10	2.2	6.7	0.17	1.22	1,470	118,000	193	16.1	134	22
Hammond, Ind.	6	120	16	13.25	7.5	9.0	20.70	1.32	1,800	24,000	273	30	206	25
New York City, 26th Ward	4	162	67	12	2.4	13.5	41.00	2.16	930	35,500	139	31	127	28
New York City, Hunts Point	4	168	108.9	12	1.5	14.0	95.00	1.70	1,300	97,000	140	48	113	30
Abington, Pa.	2	50	14	10	3.6	5.0	1.24	2.02	855	44,400	237	39	198	29
Portsmouth, Va.	4	100	15.25	10	6.5	10.0	7.36	1.49	1,200	46,000	153	63	185	45
Canton, Ohio	3	124	32	10.6	3.9	11.7	17.00	1.33	1,430	214,000	577	40	253	33
Niles, Mich.	6	75	14	9	5.4	8.3	2.30	1.86	362	27,200	250	69.2	106	57
Dallas, Tex.	2	180	50	12	3.6	15.0	19.40	2.00	1,080	24,000	358	66	256	41

Richmond, Ind.	4	95	16	14.5	5.9	6.5	6.10	2.64	990	25,000	159	40	133	23
Lansing, Mich.	16	87.5	16	10	5.5	8.7	16.45	2.45	735	23,700	445	76	201	68
Winsted, Conn.	2	65	12	9	5.5	7.2	0.50	5.00	320	20,800	130	75	170	51
Waterbury, Conn.	3	212.5	33	10	6.4	21.2	13.94	2.71	660	14,500	144	54	166	33
Oklahoma City, Okla.	3	85	33	10	2.5	8.5	5.19	2.91	619	20,400	242	50	228	31
Tampa, Fla.	4	170	40	13	4.2	13.1	12.30	5.12	455	17,300	215	69	183	37
Roanoke, Va.	2	120	32	10.5	3.8	11.4	7.76	1.87	1,010	120,000	230	67	190	51
Blackstone Valley, R.I.	2	230	68	10.8	3.4	21.1	12.21	4.97	390	62,000	212	62	333	12
East Hartford, Conn.	2	125	32	7.5	3.9	16.7	1.50	7.18	187	12,500	212	54	242	50
Milford, Conn.	2	55	16	9.75	3.5	5.1	9.70	4.40	400	21,800	150	79	130	72
Springfield, Mass.	4	115	50	14.5	2.3	7.9	17.5	3.36	761		160	49	145	26
Orrville, Ohio	2	43.8	16	10.4	2.7	4.2	0.73	3.65	515		342	64	415	18
New Haven, Conn.	3	145	31	11.5	4.7	12.6	14.7	1.90	1,090		176	49		
Cleveland, Ohio (Easterly)	8	115	50	15	2.3	7.7	97.7	1.27	2,120		240	37	149	35

[a]Data from plant superintendents. See Federation of Sewage and Industrial Wastes association (1959).

TABLE 5.2
Circular Primary Tanks: Long-Term Performance Data[a]

Location	Data Period		Average Flow, mgd	No. of Tanks	Diameter ft	Sidewater Depth, ft	Detention, hr	Overflow, gpd/ft^2	Suspended Solids			BOD			Sludge	
	Years	No.							Raw, mg/liter	Effluent, mg/liter	Removal, %	Raw, mg/liter	Effluent, mg/liter	Removal, %	Solids, %	Volatile matter, %
Washington, D.C.	1944–45	2	136.3	12	106	14	1.88	1,350	163	83	49	173	120	30.5	8.05	67.5
Winnipeg, Man.	1943–44	2	22.8	2	115	12	1.98	1,100	348	159	55	310	231	25.5	9.0	70.5
Battle Creek, Mich.	1938–42	5	4.92	2	80	10	3.66	490	282	85	70	264	174	34.1	5.5	82.5
Buffalo, N.Y.	1939–41	3	135	4	160	15	1.6	1,690	209	114	46	138	107	22.5	5.8	59
Albuquerque, N. Mex.	1939–46	7	5	1	80	12.2	2.21	995	254	91	61	282	150	44.5	3.9	81
Yakima, Wash.	1942	1	9.5	4	90	9	4.32	373	110	23	74	175	92	50	7.0	74.4
Appleton, Wis.	1938–45	7	4.8	2	70	10	2.90	623	276	63	77	284	141	50	5.6	58
Baltimore, Md.	1939–44	4	89.5	3	170	12	1.64	1,360	214	83	61	281	204	27.5	3.9	82.7
Springfield, Ohio	1937–40	4	14.8	2	90	10	1.55	1,160	166	63	62	90	43	52		
Mansfield, Ohio	1944–45	2	3	1	65	12	2.38	905	208	87	58	227	139	38.8	4.2	76
Cedar Rapids, Iowa	1936–44	9	4.21	1	70	11.5	1.95	1,060	354	132	63	383	291	24	5.5	81.2
Austin, Tex.	1944–45	2	5.64	1	75	12	1.69	1,275	263	95	64	285	152	46.3	4.0	83
Denver, Colo.	1939–43	5	46	4	140	9.7	2.34	750	187	44	77	212	108	49	5.4	76
Ypsilanti, Mich.	1943–45	3	1.66	2	40	9	2.5	660	226	87	62	141	95	33	8.2	71.4
Monroe, Mich.	1938–46	8	4.3	2	85	7.5	3.55	378	329	75	77	135	73	46	5.2	67.7

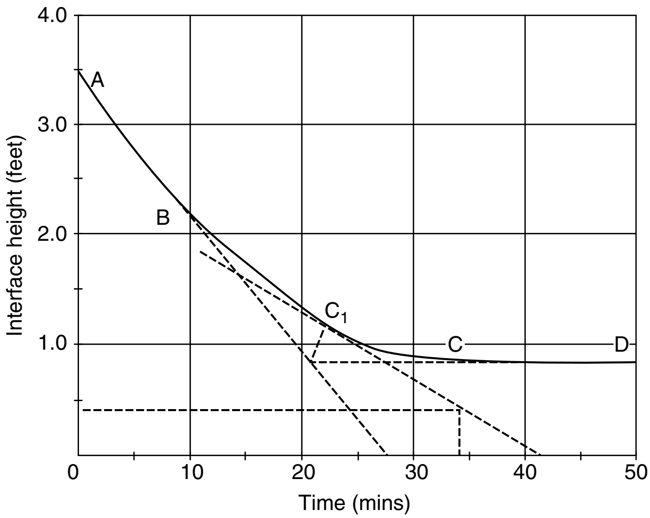
[a]Data from plant superintendents and/or annual reports. See Federation of Sewage and Industrial Wastes Association (1959).

the application of sedimentation in wastewater treatment facilities. The design of the clarifiers is based on several factors, as follows:

- Influent total suspended solids (TSS) concentration
- Effluent TSS concentration
- Surface loading
- Detention time
- Sludge generation

Clarification is used as a process to remove suspended solids at different stages of industrial wastewater treatment. It is often used in the primary treatment stage to remove TSS or colloidal solids before treatment for removal of dissolved inorganic or organic materials. A typical example of this application is in the treatment of metal-finishing industry wastewater, in which the suspended solids are removed by primary clarification before other physicochemical processes are used to remove the dissolved heavy metals. Sedimentation is also commonly used in the secondary treatment stage, usually after biological treatment. An example of this application is the treatment of pulp and paper-mill wastewater in which primary clarification is followed by biological treatment, and then the biological solids are removed by secondary clarification. In this case, the clarifier is used not only to remove the TSS, but also to act as a thickener for the sludge generated. The design of the clarifier is based on different considerations depending on the stage of the treatment in which clarification is used.

Another consideration in the design of sedimentation processes is the characteristics of the suspended solids. In some cases, the suspended solids could be discrete particles, as in the case of grit, sand, or suspended metal scales or particles. These types of solids settle easily following the principles of discrete settling (Figure 5.9). In other



$$V_s = \frac{3.5}{27 \quad 60} = 0.0022 \text{ ft/sec}$$

FIGURE 5.9. Graphical analysis of settling test results.

cases, the TSS could be composed of floc-type particles, and the settling characteristics of these suspended solids are different from those of discrete-type solids (Figure 5.9). Examples of the floc-type particles are biological flocs or chemically coagulated and flocculated particles. Because of the different settling characteristics of the suspended solids, it is important that batch-settling tests be conducted using settling columns before designing the sedimentation unit processes. In the settling test (Figure 5.9), the height of the interface between the clear supernatant liquid and the layer of suspended solids is noted with time as settling occurs in the column. (The data are plotted as shown in Figure 5.9.) The settling of the solids takes place in essentially two phases. The initial rate of settling (AB), known as *hindered settling,* is used to compute the area required for clarification. The second phase of settling (CD) represents the thickening of the sludge. A graphical method of combination of the rates of settling in the AB and CD portions of the curve is used to compute the area required for thickening. The larger of the two areas for clarification and thickening is used for sizing the clarifier:

$$V_s = Q/A_c$$

or

$$A_c = Q/V_s,$$

where

V_s = settling velocity in the hindered settling zone,
Q = hydraulic flow,
A_c = surface area required for clarification, and
V_s is computed as the slope of the line AB.
The area required for thickening is computed from the following equation:

$$A_c = Qt_u/H_o,$$

where

A_t = surface area required for thickening to desired solids concentration in sludge,
Q = hydraulic flow into the clarifier,
H_o = initial interface height of the settling column, and
t_u = time required to reach desired solids concentration in sludge.

t_u is computed by the following steps: (1) draw tangents to each of the portions AB and CD of the curve; (2) draw the bisector of the angle formed by the intersection of the two tangents (C_1 represents the critical concentration in the transition between the hindered and compression settling phases); (3) draw a tangent at C_1; and (4) draw a line parallel to the time axis at the interface height (H_u) corresponding to the desired solids concentration in the sludge (C_u). The time-scale intercept of tangent with the sludge concentration line is the required time t_u. H_u is computed as follows:

$$H_u = C_o H_o / C_u,$$

where
C_o = solids concentration in the influent,
C_u = desired solids concentration in the sludge, and
H_u = interface height at desired solids concentration in sludge.

Example

The results of a batch-settling column test for an industrial wastewater is given below:

Time (min)	*Interface Height (ft)*
0	3.5
5	2.8
10	2.2
15	1.5
20	1.2
25	0.9
30	0.7
35	0.6
40	0.5
45	0.5

Using the test data, determine the size of the clarifier. Flow = 0.8 mgd, influent solids concentration = 2,000 mg/liter, and sludge solids concentration = 1.5%.

Solution
The data from the settling test are plotted as shown in Figure 5.9. From the figure, V_s is computed as follows:

$$V_s = 3.5/27 \times 60 = 0.0022 \text{ ft/sec}$$

Area required for clarification:

$$\begin{aligned} A_c &= Q/V_s \\ &= (0.8 \times 1.547 \text{ ft}^3\text{/sec}) / (0.0022 \text{ ft/sec}) \\ &= 563 \text{ ft}^2 \end{aligned}$$

H_u is computed as follows:

$$H_u = C_oH_o/C_u$$
$$C_o = 2{,}000 \text{ mg/liter}$$
$$= 2{,}000/16{,}020 = 0.125 \text{ lb/ft}^3$$
$$C_u = (1.5 \times 10{,}000) / (16{,}020) = 0.94 \text{ lb/ft}^3$$
$$H_u = C_oH_o/C_u$$
$$= (0.125 \times 3.5) / (0.94) = 0.47 \text{ ft}$$

From the figure, t_u = 33 min for H_u = 0.47 ft.

Area required for thickening:

$$A_t = Ot_u/H_o$$
$$= (0.8 \times 1.547 \times 33 \times 60) / (3.5)$$
$$= 700 \text{ ft}^2.$$

Therefore, the size of the clarifier selected is 700 ft^2.

$$1{:}w = 4{:}1$$

Flotation

"Flotation" is the process of converting suspended substances and some colloidal, emulsified, and dissolved substances to floating matter (Hess et al. 1953). The term *flotation* includes both violently agitated froth flotation, as used in the separation of ores in the mining industry, and quiescent flotation, which is now becoming popular as an efficient method for the removal of most suspensions from wastewaters.

Small and difficult-to-settle particles in suspension can be flocculated and buoyed to the liquid surface by the lifting power of the many minute air bubbles that attach themselves to the suspended particles. Floated agglomerated sludge can be readily and continuously removed from the surface of the liquid by skimming. These skimmings are usually collected as a concentrated sludge and normally drain quite readily. A convenient practice is to detain the sludge float in a receiving tank for a few hours before draining the subnatant liquor from the bottom. The solids content of the float can be more than doubled by this concentration method; water is actually squeezed out of the float while the particles compact. Such a sludge float is usually quite stable and free from odors. Because the flotation process brings partially reduced chemical compounds into contact with oxygen in the form of tiny air bubbles, satisfaction of any immediate oxygen demand of the wastewater is thereby aided.

Typical vacuum flotation units first aerate the waste with air diffusers or mechanical beaters. Aeration periods are brief, some as short as 30 seconds, and require only about 0.025–0.05 ft^3 of air per gallon of wastewater. A brief de-aeration period is then provided at atmospheric pressure to remove large bubbles. The waste, at this point nearly saturated with dissolved air, passes to an evacuation tank that is enclosed and maintained under a vacuum of about 9 inches of mercury. This vacuum gives rise to bubbles, which cause flotation.

Pressure flotation differs from vacuum flotation in that air is injected into the waste under pressure, and bubbles of air are then formed when the waste is exposed to atmospheric pressure. Wastes are normally pressurized to about 30–40 $lb/in.^2$ and retained at this pressure for approximately 1 minute. Some coagulant aids (alum and/or silica) and a small volume of air can be bled into the system at the suction end of the pump, where wastewater enters the tank. Passage through the pump usually suffices to provide good mixing of the chemicals and air with the waste. When released to the atmosphere in the flotation tank, the tiny rising bubbles trap suspended, colloidal, and (some) emulsified particles. The floated sludge is usually continuously skimmed and removed from the tank by sludge pumps.

Vrablik (1960) makes a distinction between two methods of flotation: dissolved air and dispersed air. Dispersed-air flotation generates gas bubbles by the mechanical shear of propellers, diffusion of gas through porous media, or by homogenizing a gas and liquid stream. Dissolved-air flotation generates gas bubbles by precipitation from a solution supersaturated with the gas. These bubbles are much smaller than dispersed-air bubbles, generally not exceeding 80 microns[1] in diameter, while dispersed-air bubbles often reach 1,000 microns in diameter.

To understand the theory of dissolved-air flotation, the student must investigate the gas, liquid, and solid phases, as they are brought into intimate contact with each other. Henry's Law indicates the relationship between the solubility of gas (in this case, dissolved air) and the total pressure:

$$C = kp,$$

where C is the concentration of gas in solution, k is the Henry's Law constant, and p is the absolute pressure above the solution at equilibrium.

By attachment to, or inclusion in, a suspended-solids structure or liquid phase, the bulk density of the paired system may be less than the density of the parent system, causing the agglomeration to be floated to the top. The gas bubbles, therefore, render a buoyancy to the original suspended particle in accordance with Archimedes' principle: The resultant pressure of a fluid on an immersed body acts vertically upward through the center of gravity of the displaced fluid and is equal to the weight of the fluid displaced. The resultant upward force exerted by the fluid on the body is called *buoyancy,* and this force is responsible for the floating of solids, which were originally somewhat heavier than the surrounding fluid.

[1] 1 micron = 0.0001 cm = 0.0000394 in.; 1 in. = 2.54 cm.

Because we are usually dealing with large volumes of water in waste treatment, detention time in flotation chambers becomes a critical factor. Detention time, in turn, is dependent primarily on the rate of rise of air bubbles in the water. This can best be expressed by Stokes' Law, which holds true for particles with a diameter of less than 130 microns:

$$V = kD^2,$$

where V is the rate of bubble rise (ft/min), k is Stokes' conversion factor (this includes all the factors that affect the rise or fall of bubbles, such as density or viscosity of the liquid, excluding the density of the bubble), and D is the diameter of the air bubble. The Stokes relationship is shown quantitatively in Figure 5.10.

Typical results obtained from samples of several industrial wastes (Hess et al. 1953) treated by dissolved-air flotation show suspended solids and BOD reductions of 69.0–97.5 and 60.0–91.8%, respectively (Table 5.3).

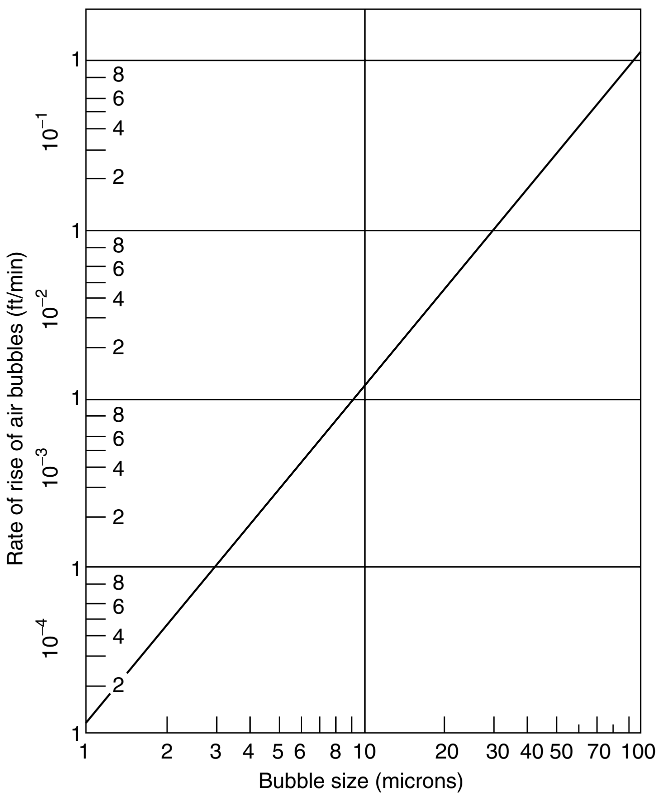


FIGURE 5.10. Rate of rise of air bubbles in tap water (calculated by means of Stoke's law) as a function of bubble size (after Vrablik 1960).

TABLE 5.3
Typical Efficiencies of Dissolved-Gas Flotation Treatment of Wastes

Waste Source	*Suspended Solids in Influent, ppm*	*Reduction Obtained, %*	*BOD in Influent, ppm*	*Reduction Obtained, %*
Petroleum production	441	95.0		
Railroad maintenance	500	95.0		
Meatpacking	1,400	85.6	1,225	67.3
Paper manufacturing	1,180	97.5	210	62.6
Vegetable-oil processing	890	94.8	3,048	91.6
Fruit-and-vegetable canning	1,350	80.0	790	60.0
Soap manufacture	392	91.5	309	91.6
Cesspool pumpings	6,448	96.2	3,399	87.0
Primary sewage treatment	252	69.0	325	49.2
Glue manufacture	542	94.3	1,822	91.8

Adapted from Quigley and Hoffman (1966).

Because almost twice as much air can be dissolved in water, all other factors being equal, at 0˚C than at 30˚C, the temperature of wastewater is a significant factor in the effectiveness of the flotation process. This relationship is shown in Figure 5.11.

Generally, air bubbles are negatively charged, the anions collecting mainly on the gas side of the interface, while the cations spread themselves out thinly on the water side of the interface. Because suspended particles or colloids may have a significant electrical charge, either attraction or repulsion will occur between these and air bubbles.

Vrablik (1960) made an extensive study of the three processes by which flotation may be caused: (1) adhesion of a gas bubble to a suspended liquor or solid phase; (2) the trapping of gas bubbles in a floc structure as the gas bubble rises; (3) the absorption of a gas bubble in a floc structure as the floc structure is formed. These three phenomena are illustrated in Figure 5.12. An illustration of pressure flotation is shown in Figure 5.13.

Finally, the engineer should be aware of both the advantages and the disadvantages of flotation as a waste-treatment process (Federation of Sewage and Industrial Wastes Association 1959). The advantages are as follows:

1. Grease and light solids rising to the top and grit and heavy solids settling to the bottom are all removed in one unit.
2. High overflow rates and short detention periods mean smaller tank sizes, resulting in decreased space requirements and possible savings in construction costs.
3. Odor nuisances are minimized because of the short detention periods, as well as in pressure and aeration-type units, because of the presence of dissolved oxygen in the effluent.
4. Thicker scum and sludge are obtained, in many cases, from a flotation unit than from gravity settling and skimming.

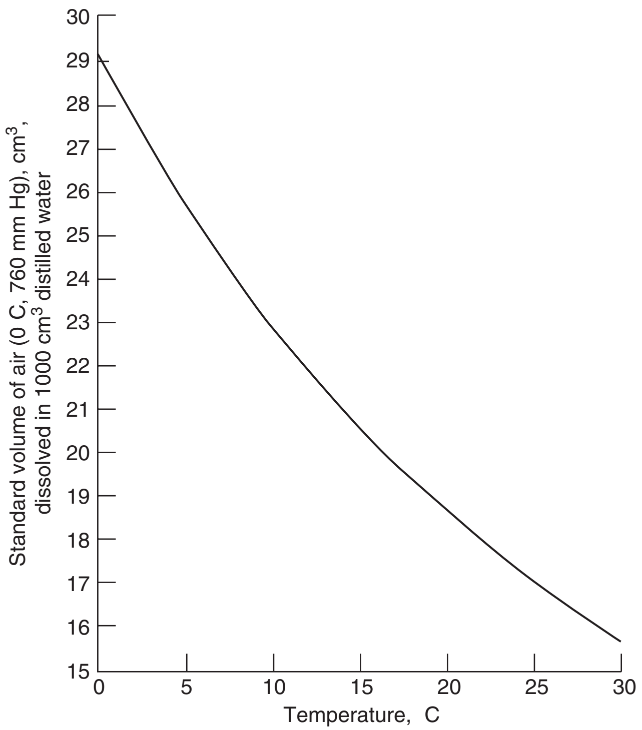


FIGURE 5.11. Solubility of air in distilled water at various temperatures (from *Handbook of Chemistry and Physics,* 1955).

The disadvantages are as follows:

1. The additional equipment required results in higher operating costs.
2. Flotation units generally do not provide treatment as effective as gravity-settling units, although efficiency varies with the waste.
3. The pressure type has high power requirements, which increases operating cost.
4. The vacuum type requires a relatively expensive airtight structure capable of withstanding a pressure of 9 inches of mercury; any leakage to the atmosphere will adversely affect performance.
5. More skilled maintenance is required for a flotation unit than for a gravity-settling unit.

Quigley and Hoffman (1966) deserve credit for daring to refer to flocculation and dissolved-air flotation as "secondary treatment" when it follows sedimentation. They describe an effective dissolved-air flotation system for treating oil-refinery wastes. By recycling treated effluent and using lime as a coagulant, they were able to obtain oil removals of 68–96%.

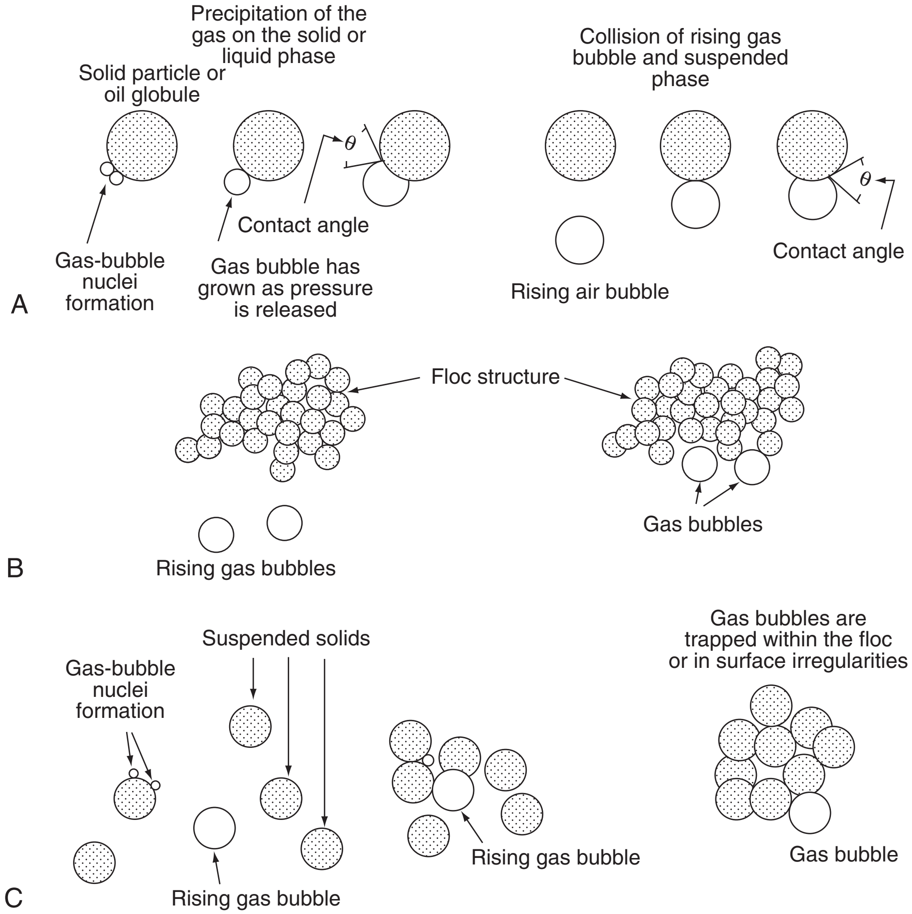


FIGURE 5.12. Methods of dissolved-air flotation. (**A**) Adhesion of a gas bubble to a suspended liquid or solid phase. (**B**) The trapping of gas bubbles in a floc structure as the gas bubbles rise. (**C**) The absorption and adsorption of gas bubbles in a floc structure as the floc structure is formed (adapted from Vrablik 1960).

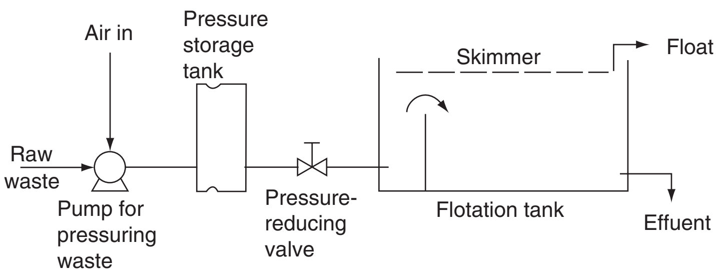


FIGURE 5.13. Schematic drawing of pressure flotation system.

Screening

Screening of industrial wastes is generally practiced on wastes containing larger suspended solids of variable sizes, such as from canneries, pulp and paper mills, or poultry processing plants. It is an economical and effective means of rapid separation of these larger suspended solids from the remaining waste material. In many cases, screening alone will reduce the suspended solids to a low enough concentration to be acceptable for discharge into a municipal sewer or a nearby stream. Often, considerable BOD is also removed by the screening process, the percentage removed varying almost directly with the size of the screen and the amount of BOD associated with the "screenable" solids. Screens are available in sizes ranging from coarse (10 or 20 mesh) to fine (120–320 mesh).

The North and Sweco screens are two major types used in industry today. The former are generally rotary, self-cleaning, gravity-type units (Figure 5.14). The latter are mostly circular, overhead-fed, vibratory units (Figure 5.15).

The rotary, gravity-type, waste-disposal screens are manufactured in several sizes to handle almost any volume of waste liquid. In general, they vary from 3 to 5 feet in diameter and from 4 to 12 feet in length and weigh between 1 and 5 tons. These screens separate solid and liquid constituents from waste materials at a location where they gravitationally flow or can be pumped into the screened cylinder. The machine's large drum rotates at 4 rpm. The lift paddles within the drum pick up the solid material from the water and deposit it into a stationary perforated hopper within the cylinder. The hopper holds a spiral screw conveyor that moves the solids to the

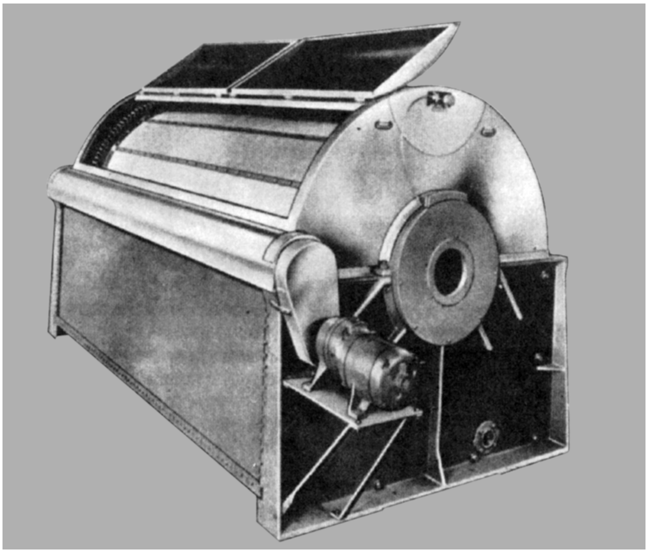


FIGURE 5.14. North water filter (photograph courtesy Green Bay Foundry and Machine Works, Green Bay, Wisconsin). Used with permission from John Wiley and Sons.

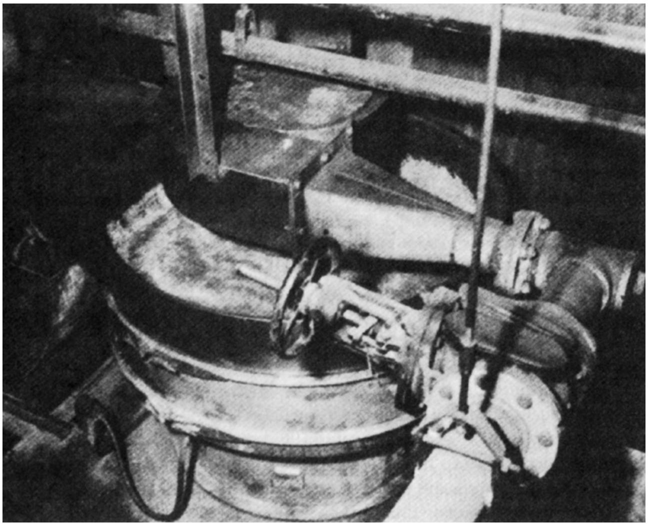


FIGURE 5.15. The 48-inch-diameter Sweco separator shown is screening lint from wastewater at the Eastern Overall Company, in Baltimore, Maryland. The wastewater is fed onto the 60-mesh market-grade screen at a rate of 300 gpm. The screened wastewater is discharged to the sewer (photograph courtesy Sweco, Inc., Los Angeles, California). Used with permission from John Wiley and Sons.

rear end of the machine and out through the discharge spout. In the process, it compresses the wastes and squeezes out more liquid, which drains through the perforated hopper back into the cylinder. The water in the cylinder drains through the wire mesh and collects in a steel or wooden tank, which is part of the machine. The fine wire mesh is at all times kept free from clogging by a continuous spray pipe with jet nozzles, located above the rotating cylinder. Such scenes have been used successfully in treating wastes from meatpacking, canning, grain-washing, tanning, malting, woolen, and seafood plants.

The circular vibratory screens have been quite effective in screening wastes from food-packing processes such as meat and poultry packing or fruit and vegetable canning. Vibration is designed usually to remove solids at the periphery of the screen, although Swallow (1965) reported the use of a new center-discharge separator.

Micro-straining, a particular screening device, was first introduced by Dr. P. L. Boucher (1965) in England in 1945 for water clarification, and there were about 70 water-treatment plants in the United States using this process. It involves the use of high-speed, continuously backwashed, rotating drum filters working in open gravity-flow conditions (see cutaway picture in Figure 5.16). The principal filtering fabrics employed have apertures of 35 or 25 microns and are fitted on the drum periphery. Head loss is between 4 and 6 inches. Results in London, England, showed that micro-straining removes most of the suspended solids remaining after biological treatment (Table 5.4).

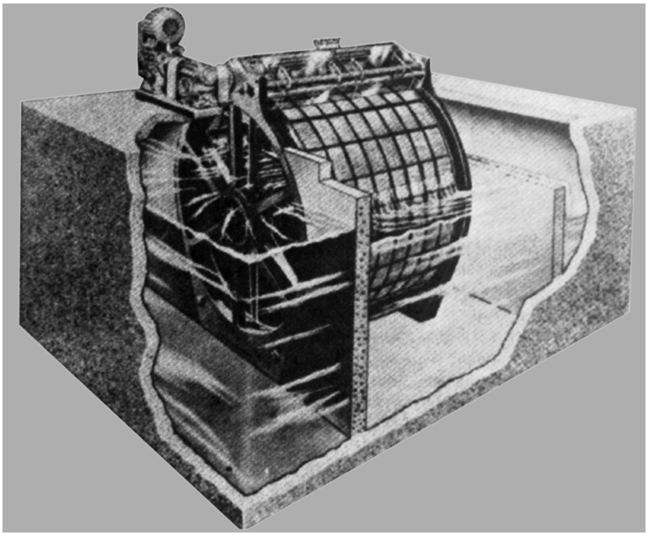


FIGURE 5.16. Cutaway view of a 7½-foot-diameter microstrainer (photograph courtesy Crane Company, King of Prussia, Pennsylvania). Used with permission from John Wiley and Sons.

The Bauer Company manufactures a perforated plate screen (referred to as a Hydrasieve), which is installed at a slight angle to the vertical. Wastewater is passed down the screen from the top, with water going through the screen and solids collecting at the bottom. The efficiency of removal depends primarily on the size of the screen opening and the wastewater application rate.

Example of Twentieth-Century Practice of Suspended Solids Reduction

Johnson and Lindley (1982) showed that a hydroclone—a cone type of settling clarifier—could be used to remove efficiently and economically suspended fish particles. The overflow is discharged as effluent, and underflow is collected and stored for reuse. Effluents—the overflow—were able to meet Environmental Protection Agency (EPA) standards for seafood processing. Although the overflow is clean enough for discharge, the underflow may need further processing for by-product recovery operation. Thus, they used a rather common type of treatment to attain the objective of suspended-solids reduction.

Suspended solids may also be an asset for the industrial waste engineer. Your author used the high suspended solids content of the Moench Tannery wastewater to form a nucleus for the aerating mixed liquor during biological treatment (Nemerow et al. 1978). In this way, separate suspended solids removal was unnecessary and biological treatment to remove colloidal and dissolved contaminants was enhanced simultaneously.

TABLE 5.4
Results Obtained on Humus Tank Effluent at Eastern Sewage Works, London, England, December 30, 1966–January 13, 1967

	Effluent from			
Characteristic	*Humus Tank*	*Micro-Strainer*	*Ozonizer*	*Sand Filter*
Suspended solids	51[a]	19	15	10
Total solids	931			928
BOD	21	13	11	9
COD	78	54	44	39
Permanganate value	16	10	6	5
Organic carbon		23	19	10
Surface-active matter				
Anionic (as Manoxol OT)	1.4	1.4	0.6	0.6
Nonionic (as Lissapol NX)	0.37		0.07	0.07
Ammonia (as N)	7.1	7.5	7.4	7.6
Nitrite (as N)	0.4	0.4	0.02	0.01
Oxidized nitrogen (as N)	26	26	26	27
Total phosphorus (as P)	8.2			7.4
Orthophosphate (as P)	6.6			7.0
Total hardness (as $CaCO_3$)				468
Chloride				98
Sulfate	212			213
Color (Hazen units)	36		4	7
Turbidity (ATU)	66		27	13
Total phenol	3.4			0.9
Temperature (˚C)	8.1	8.0	7.9	7.7
Dissolved oxygen (% saturation)	52	52	99	94
Conductivity (μmho/cm^3)	1,173	1,175	1,170	1,150
Langlier index	–0.08			+0.12
pH	7.4	7.4	7.4	7.5
Pesticides (μg/l)				
α BHC		0.025	0.007	
γ BHC		0.035	0.030	
Aldrin		0.004	0.000	
Dieldrin		0.193	0.032	
pp DDT		0.031	0.030	

[a]All results are given in milligrams per liter unless otherwise specified.
Adapted from Diaper (1968).

Review Questions

1. What are three major methods of removing suspended solids?
2. When would you use sedimentation for removal of suspended solids?
3. When should you use flotation for removal of suspended solids?

4. Would you ever use both sedimentation and flotation together?
5. Why and when would you use screening for suspended solids removal?
6. What are the most important factors affecting industrial wastewater sedimentation?
7. In dissolved-air flotation, what is the apparent anomaly that exists because of the size of the air bubble?
8. What are the three methods by which suspended matter can be removed by dissolved-air flotation with chemical coagulant addition?
9. What are the two major types of screening devices mentioned in this chapter? What is a third type of screening device type not pictured in the chapter? What are the major advantages of each type?

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