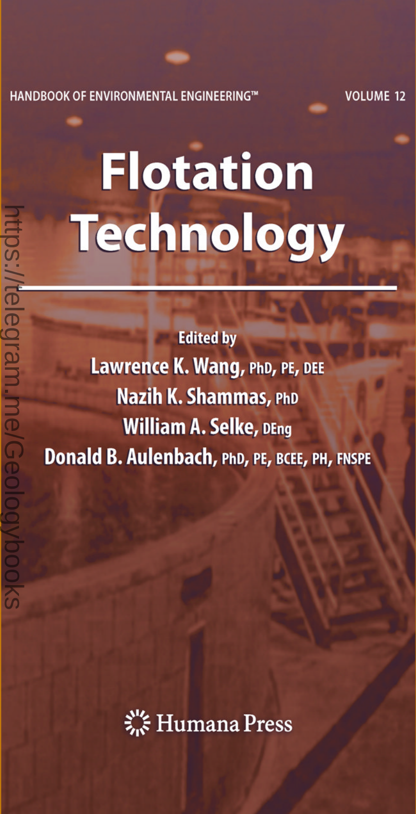

HANDBOOK OF ENVIRONMENTAL ENGINEERING™ VOLUME 12

Flotation Technology

Edited by

Lawrence K. Wang, PhD, PE, DEE

Nazih K. Shammas, PhD

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Humana Press

Flotation Technology

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Dedications

The Editors of the Handbook of Environmental Engineering series dedicate this volume and all other volumes to Thomas L. Lanigan (1938–2006), the founder and President of Humana Press, who encouraged and vigorously supported the editors and many contributors around the world to embark on this ambitious, life-long handbook project started in 1978 for the sole purpose of protecting our environment, in turn, benefiting our entire mankind.

The Editors also dedicate this volume, *Flotation Technology*, to Milos Krofta (1912–2002), who was the founder and President of the Lenox Institute of Water Technology (LIWT), Krofta Engineering Corporation (KEC) and other Krofta Companies. Under Dr. Krofta's leadership, the LIWT-KEC trained hundreds of flotation engineers and disseminated the flotation technologies to the entire world.

Preface

The past 30 years have seen the emergence of a growing desire worldwide that positive actions be taken to restore and protect the environment from the degrading effects of all forms of pollution – air, water, soil, and noise. Since pollution is a direct or indirect consequence of waste, the seemingly idealistic demand for “zero discharge” can be construed as an unrealistic demand for zero waste. However, as long as waste continues to exist, we can only attempt to abate the subsequent pollution by converting it to a less noxious form. Three major questions usually arise when a particular type of pollution has been identified: (1) How serious is the pollution? (2) Is the technology to abate it available? and (3) Do the costs of abatement justify the degree of abatement achieved? This book is one of the volumes of the *Handbook of Environmental Engineering* series. The principal intention of this series is to help readers formulate answers to the last two questions above.

The traditional approach of applying tried-and-true solutions to specific pollution problems has been a major contributing factor to the success of environmental engineering and has accounted in large measure for the establishment of a “methodology of pollution control.” However, the realization of the ever-increasing complexity and interrelated nature of current environmental problems renders it imperative that intelligent planning of pollution abatement systems be undertaken. Prerequisite to such planning is an understanding of the performance, potential, and limitations of the various methods of pollution abatement available for environmental scientists and engineers. In this series of handbooks, we will review at a tutorial level a broad spectrum of engineering systems (processes, operations, and methods) currently being utilized, or of potential utility, for pollution abatement. We believe that the unified interdisciplinary approach presented in these handbooks is a logical step in the evolution of environmental engineering.

Treatment of the various engineering systems presented will show how an engineering formulation of the subject flows naturally from the fundamental principles and theories of chemistry, microbiology, physics, and mathematics. This emphasis on fundamental science recognizes that engineering practice has, in recent years, become more firmly based on scientific principles rather than on its earlier dependency on empirical accumulation of facts. It is not intended, though, to neglect empiricism where such data lead quickly to the most economic design; certain engineering systems are not readily amenable to fundamental scientific analysis, and in these instances we have resorted to less science in favor of more art and empiricism.

Since an environmental engineer must understand science within the context of application, we first present the development of the scientific basis of a particular subject, followed by the exposition of pertinent design concepts and operations, and detailed explanations of their applications to environmental quality control or remediation. Throughout the series, methods of practical design and calculation are illustrated by numerical examples. These examples clearly demonstrate how organized, analytical reasoning leads to the most direct and clear solutions. Wherever possible, pertinent cost data have been provided.

Our treatment of pollution-abatement engineering is offered in the belief that the trained engineer should more firmly understand fundamental principles, be more aware of the similarities and/or differences among many of the engineering systems, and exhibit greater flexibility and originality in the definition and innovative solution of environmental pollution problems. In short, the environmental engineer should by conviction and practice be more readily adaptable to change and progress.

Coverage of the unusually broad field of environmental engineering has demanded an expertise that could only be provided through multiple authorships. Each author (or group of authors) was permitted to employ, within reasonable limits, the customary personal style in organizing and presenting a particular subject area; consequently, it has been difficult to treat all subject material in a homogeneous manner. Moreover, owing to limitations of space, some of the favored topics of the authors could not be treated in great detail, and many less important topics had to be merely mentioned or commented on briefly. All authors have provided an excellent list of references at the end of each chapter for the benefit of the interested readers. As each chapter is meant to be self-contained, some mild repetition among the various texts was unavoidable. In each case, all omissions or repetitions are the responsibilities of the editors and not the individual authors. With the current trend toward metrication, the question of using a consistent system of units has been a problem. Wherever possible, the authors have used the British system (FPS) along with the metric equivalent (MKS, CGS, or SIU) or vice versa. The editors sincerely hope that this redundancy of the usage of units will prove to be useful rather than being disruptive to the readers.

The goals of the *Handbook of Environmental Engineering* series are: (1) to cover entire environmental fields, including air and noise pollution control, solid waste processing and resource recovery, physicochemical treatment processes, biological treatment processes, biosolids management, water resources, natural control processes, radioactive waste disposal, and thermal pollution control; and (2) to employ a multimedia approach to environmental pollution control since air, water, soil, and energy are all interrelated.

This book, Vol. 12, *Flotation Technology*, has been designed to serve as a basic flotation textbook as well as a comprehensive reference book. We hope and expect it will prove of equal high value to advanced undergraduate and graduate students, to designers of water and wastewater treatment systems, and to scientists and researchers. The editors welcome comments from readers in all of these categories. It is our hope that the book will not only provide information on flotation technology, but will also serve as a basis for advanced study or specialized investigation of the theory and practice of various flotation systems.

This book covers topics on principles of air flotation technology, gas dissolution, release and bubble formation, separation of oil from wastewater, fundamentals of wastewater flotation, electroflotation, electrocoagulation–flotation, treatment of paper mill whitewater, recycling and recovery of raw materials, ozone–oxygen oxidation flotation, wastewater renovation by flotation, flotation–filtration system for wastewater reuse, algae removal by flotation, completely closed water systems in paper mills, lake restoration using DAF, Jiminy Peak, Hancock-Massachusetts wastewater treatment plant, Pittsfield-Massachusetts water treatment system, pretreatment of meat processing waste, treatment of seafood processing wastewater, and laboratory simulation of air flotation processes.

The editors are pleased to acknowledge the encouragement and support received from their colleagues and the publisher during the conceptual stages of this endeavor. We wish to thank the contributing authors for their time and effort, and for having patiently borne our reviews and numerous queries and comments. We are very grateful to our respective families for their patience and understanding during some rather trying times.

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Principles of Air Flotation Technology

Nazih K. Shammas and Gary F. Bennett

CONTENTS

Abstract Air flotation, in all its variations, is an efficient way to separate light particulates and oils from wastewater. Particulates that adhere to an air bubble, either by adsorption or absorption, can be floated from the liquid phase. Polymers may be added to improve the attachment of the particle to the bubble. Agglomerization of colloids into floc particles with the aid of chemicals will aid in their removal. Some soluble materials can be precipitated with chemicals, allowing their removal. If the wastewater is chemically pretreated to break the oil emulsion, air flotation units are capable of removing most of the emulsified oil in addition to the free oil. This chapter covers the theory and practice of air flotation and the various flotation processes including electroflotation, dissolved air flotation (DAF), induced air flotation (IAF), and nozzle air flotation (NAF).

Key Words Particulate separation • air flotation • electroflotation • DAF • IAF • NAF • performance • costs.

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1. INTRODUCTION

Today, municipalities as well as industries must treat their wastewaters to comply with limits imposed by the U.S. Environmental Protection Agency (USEPA) before discharge into any waterway. These limits are designed to protect public health, prevent the spread of waterborne diseases, maintain stream and lake water quality, and even assure aesthetics. The standards represent a level of control achievable by the Best Available Technology (BAT) for removal of pollutants (1). In addition, industries must comply with sewer regulations that limit the concentration of pollutants such as oils and heavy metals that may be discharged to them. Numerous air flotation system adaptations are available to achieve adequate wastewater treatment. These are described in this chapter.

If a facility discharges wastewater or stormwater to the land surface or to waters of the state, this discharge may be subject to federal, state, or local regulations governing surface water quality. Additionally, if the facility discharges directly to an aquifer, to the land surface, or to the vadose zone in such a manner that the pollutant will reach an aquifer, then the state's aquifer protection permit regulations may also apply.

Air flotation has been used for many years in the beneficiation of ores. Its first application in the wastewater-treatment field was in the flotation of suspended solids (SS), fibers, and other low-density solids (2, 3). Flotation also is used for the thickening of activated sludge (4) and flocculated chemical sludges. More recently, air flotation has been applied to the removal of oils and greases from wastewater because it is a practical, reliable, and efficient treatment process (5–8).

Air flotation is widely used to treat wastes from a wide variety of sources: paper making, refineries, ship's bilge and ballast waste, deinking operations, metal plating, meat processing, laundries, iron and steel plants, soap manufacturing, chemical processing and manufacturing plants, barrel and drum cleaning, washrack and equipment maintenance, glass plants, soybean processing, mill waste, and aluminum forming.

The process of flotation consists of four basic steps (9, 10):

1. Bubble generation in the wastewater
2. Contact between the gas bubble and the particle or oil droplet suspended in the water
3. Attachment of the particle or oil droplet to the gas bubble
4. Rise of the air/solids combination to the surface where the floated material are skimmed off

Flotation utilizes the differential density between the bubbles to which the small solid particles and oil droplets become attached, and the water, to effect separation. Since the agglomerates have a lower density than the medium in which they are immersed, they rise to the surface where they are removed.

There are essentially five different types of flotation systems, their classification being based on the method of bubble formation:

1. *Dissolved air*. The gas is released from a supersaturated solution as a result of the reduction of pressure (11–14).
2. *Induced (dispersed) air*. The gas and liquid are mechanically mixed to induce bubble formation in the liquid (15, 16).

3. *Froth*. The gas is directly injected into the fluid by means of a sparger (17, 18).
4. *Electrolytic*. The bubbles are generated by electrolysis of the water (19–22).
5. *Vacuum*. The air is released from a saturated solution by a negative pressure (23).

Only the first four are utilized industrially to any extent for wastewater treatment.

The two major commercial types of gas flotation systems currently used industrially are (1) dispersed or induced gas (normally air) flotation (IAF) in which air bubbles are introduced into the waste stream mechanically using high-speed impellers, or by a venturi nozzle, in which bubbles are formed at the throat of the nozzle, and (2) dissolved gas (air) flotation (DAF) in which air is dissolved in the wastewater under pressure and comes out of solution when the pressure is released. As a result of this pressurization–depressurization, very small gas bubbles are formed and rise to the surface with oil and SS attached.

Froth flotation is not commercially utilized because high concentrations of surfactants are needed to enhance the separation. It is also very difficult to separate the surfactant from the water.

The older process of vacuum flotation is described by Rohlich (23) in the following stepwise manner:

1. Preaeration to saturate the wastewater at atmospheric pressure
2. Release of large bubbles
3. Application of vacuum to the wastewater

Depending on the vacuum applied, the air bubbles have sizes approximating those in DAF systems; however, the desorption process may require more energy than conventional DAF.

Even within a plant, industrial wastewaters fluctuate in quality and quantity with time depending on the process and production cycle. Most water treatment processes are sensitive to changes in flow rate, contaminant concentration, pH, and temperature. The fluctuations in these parameters can be reduced by equalization (24), which may be the single most important pretreatment feature in a wastewater-treatment facility (25).

Adams et al. (26) have demonstrated the need for smoothing out the variations in flow and concentration as well as the need for removal of free oil. Installing an equalization tank reduced fluctuations in loading and allowed operation at a constant polymer dosage.

2. THEORY OF FLOTATION

Separation of particles by flotation adheres to the same laws as sedimentation but in a "reverse field of force." The governing equation in air flotation separation, as in all gravity-controlled processes, is Stoke's Law (at least in laminar flow), which is used to compute the rise rate of bubble flocs, agglomerates, and bubble-oil aggregation (2, 11):

$$V_t = \frac{gD^2(\rho_a - \rho_o)}{18\mu}, \tag{1}$$

where V_t is the terminal rise velocity of the agglomerate, cm/s; g is the gravitational constant, 980 cm/s^2; D is the effective diameter of the agglomerate, cm; ρ_a is the density of the

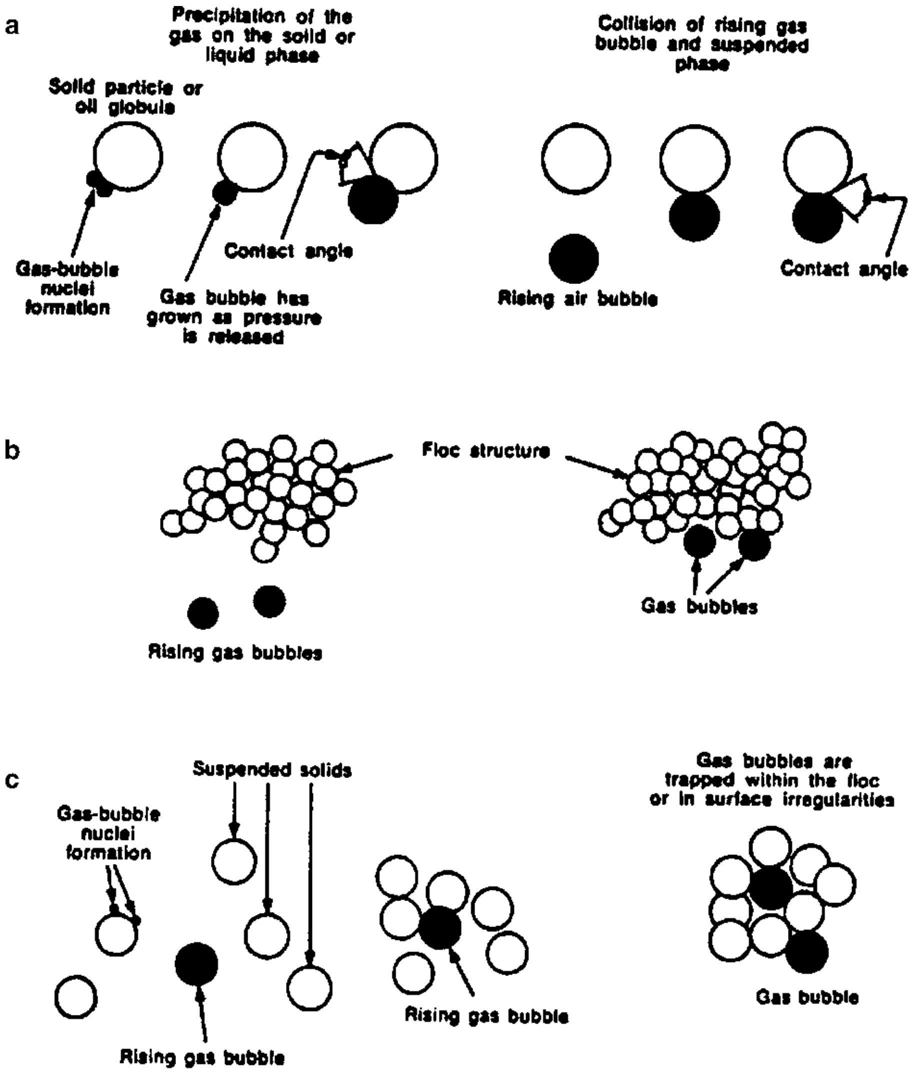

Fig. 1.1. Mechanisms of bubble/droplet formation and adhesion in dissolved air flotation.

agglomerate, g/cm^3; ρ_o is the density of the aqueous phase, g/cm^3; and μ is the viscosity of the aqueous phase, cp.

The key to an increase in rise rate of bubble/solid or bubble/oil agglomerates over the rise in unaerated systems is a reduction in the effective density of the oil (or solid) particle (or agglomerate) that is accomplished by the attachment or encapsulation of an air bubble onto or into flocs, bubbles, or solid particles (Fig. 1.1). The process follows these steps (11):

1. Introduction of gas bubbles into the wastewater
2. Collision between the gas bubble and suspended matter (suspended particulates as well as oil droplets)

3. Attachment of fine bubbles to the surface of the suspended matter
4. Collision between gas-attached suspended particles with the formation of agglomerates
5. Entrapment of more gas bubbles in the agglomerates
6. Upward rise of floc structures in a sweeping action, which is termed "sweep flocculation"

Key design variables in the system controlling efficiency of removal are (2, 9, 11, 27) as follows:

1. Gas input rate and volume of gas entrained per unit volume of liquid
2. Bubble-size distribution and degree of dispersion
3. Surface properties of the suspended matter
4. Hydraulic design of the flotation chamber
5. Concentration and type of dissolved materials
6. Concentration and type of suspended matter and oils
7. Chemicals added
8. Temperature
9. Residence time
10. Recycle ratio
11. pH

However, there is still much that is unknown about parameters and rate-controlling mechanisms (28). Roberts et al. (29) concluded that the performance of DAF systems (in the concentration of suspended solids) cannot be reliably predicted from conventional design parameters based on hydraulic loadings, solids loadings, and amount of air available. It is recommended to test the actual wastewater to be treated on a pilot-scale before embarking on the design of a full-scale DAF unit (2, 9, 11).

2.1. Gas Solubility

The key to DAF is the dissolution of air (or other suitable gas) under pressure and the reduction of this pressure to form bubbles. The amount of gas going into solution generally obeys Henry's Law:

$$p = kC, \tag{2}$$

where p is the partial pressure of the gas, C is the concentration of the gas dissolved in the solution, and k is the Henry's Law constant.

Thus, the amount of gas dissolved in solution and consequently the amount of gas released upon reduction of the pressure are both direct functions of the initial air pressure.

The solubility of gases is also a function of temperature and dissolved solids concentration (Tables 1.1 and 1.2). The solubility of air in distilled water, for example, is reduced 45% as the temperature is raised from 0 to 30°C. Also, the solubility of oxygen decreases 19% as its salinity increases from 0 to 20,000 mg/L. Following pressurization, the water proceeds from the saturator, through the pressure-reducing valve, into the flotation basin; there the bubbles will first nucleate on any available low-energy sites on solid particles. If no sites are available, bubbles will nucleate homogeneously in the liquid phase (29). The bubbles will then grow until their growth is diffusion limited (30).

Table 1.1
Volume and weight of air dissolved in water per 1,000 gal at 30 psi

AT 30 psig: $Sg\left[f\,\frac{P+14.7}{14.7}\right]$													
Temperature		Sg at 1 atm		$f = 100\%$		$f = 90\%$		$f = 80\%$		$f = 70\%$		$f = 60\%$	
°C	°F	lb	Ft^3	lb	ft^3	lb	ft^3	lb	ft^3	lb	ft^3	lb	ft^3
0	32	0.311	3.86	0.95	11.7	0.85	10.6	0.76	9.5	0.66	8.2	0.57	7.1
10	50	0.245	3.15	0.75	9.6	0.67	8.6	0.60	7.7	0.52	6.7	0.45	5.8
20	68	0.203	2.70	0.61	8.2	0.56	7.4	0.50	6.6	0.43	5.8	0.37	4.9
30	86	0.175	2.40	0.53	7.3	0.48	6.6	0.43	5.9	0.37	5.1	0.32	4.4
40	104	0.155	2.20	0.47	6.7	0.43	6.0	0.38	5.4	0.33	4.7	0.28	4.0
50	122	0.142	2.09	0.43	6.4	0.39	5.7	0.35	5.1	0.30	4.5	0.26	3.8
60	140	0.133	2.01	0.40	6.1	0.36	6.6	0.32	4.9	0.28	4.3	0.24	3.7
70	158	0.128	2.00	0.39	6.1	0.35	5.5	0.31	4.9	0.27	4.3	0.23	3.7
80	176	0.125	2.01	0.38	6.1	0.34	5.5	0.30	4.9	0.27	4.3	0.23	3.7
90	194	0.124	2.05	0.38	6.2	0.34	5.6	0.30	5.0	0.26	4.4	0.23	3.8
100	212	0.125	2.13	0.38	6.5	0.34	5.8	0.30	5.2	0.27	4.5	0.23	3.9
$\left[f\,\frac{(30+14.7)}{14.7}\right]$				3.04		2.74		2.44		2.13		1.83	

Table 1.2
Volume and weight of air dissolved in water per 1,000 gal at 65 psi

AT 65 psig: $Sg\left[f\,\frac{P+14.7}{14.7}\right]$													
Temperature		Sg at 1 atm		$f = 100\%$		$f = 90\%$		$f = 80\%$		$f = 70\%$		$f = 60\%$	
°C	°F	lb	ft^3	lb	ft^3	lb	ft^3	lb	ft^3	lb	ft^3	lb	ft^3
0	32	0.311	3.86	1.69	20.9	1.52	18.8	1.35	16.8	1.18	14.7	1.01	12.6
10	50	0.245	3.15	1.33	17.1	1.20	15.4	1.06	13.7	0.93	12.0	0.80	10.3
20	68	0.203	2.70	1.10	14.6	0.99	13.2	0.88	11.7	0.77	10.3	0.66	8.8
30	86	0.175	2.40	0.95	13.0	0.86	11.7	0.76	10.4	0.67	9.1	0.57	7.8
40	104	0.155	2.20	0.84	11.9	0.76	10.7	0.67	9.5	0.59	8.4	0.51	7.2
50	122	0.142	2.09	0.77	11.3	0.69	10.2	0.62	9.1	0.54	7.9	0.46	6.8
60	140	0.133	2.01	0.72	10.9	0.65	9.8	0.58	8.7	0.51	7.6	0.43	6.6
70	158	0.128	2.00	0.70	10.8	0.63	9.8	0.56	8.7	0.49	7.6	0.42	6.5
80	176	0.125	2.01	0.68	10.9	0.61	9.8	0.54	8.7	0.48	7.6	0.41	6.6
90	194	0.124	2.05	0.67	11.1	0.60	10.0	0.54	8.9	0.47	7.8	0.40	6.7
100	212	0.125	2.13	0.68	11.6	0.61	10.4	0.54	9.3	0.48	8.1	0.41	6.9
$\left[f\,\frac{(65+14.7)}{14.7}\right]$				5.42		4.88		4.34		3.80		3.26	

The amount of gas that will theoretically be released from solution when the pressure is reduced to 1 atm is given by the following equation:

$$S = S_g\left(\frac{P}{14.7} + 1\right), \tag{3}$$

where S is the gas released at atmospheric pressure (mg/L), S_g is the gas saturation at atmospheric pressure (mg/L), and P is the gauge pressure of pressurization (psig).

Bratby and Marais (31) have demonstrated that, in agreement with diffusion theory, most, but not all, of the dissolved air will precipitate out in the flotation tank.

Since dissolution systems are not 100% efficient, one must modify the above equation by including f, a "fractional system dissolving-efficiency factor."

$$S = S_g\left(\frac{fP}{14.7} + 1\right). \tag{4}$$

The amount of air dissolved at various efficiencies is also shown in Tables 1.11 and 1.12.

Obviously, one of the key parameters in the foregoing equation is "*f*", the efficiency of saturation. Bratby and Marais (31) have developed useful methods to determine the mass of air dissolved under pressure. Their technique volumetrically measures the amount of air coming out of the pressurized solution when exposed to atmospheric pressure. They then use this method to test components of the saturating system and determine the following important parameters:

1. The type of valve through which the pressurized saturated feed is released, flow rate (i.e., turbulence) through the valve, turbulence in the flotation chamber (i.e., downstream of the value), mixing of dilution water with the precipitating, saturated feed, and concentration of the particulate nuclei (mass of air precipitation)/(unit volume of saturation feed).
2. The most efficient saturation system involves spraying water over a proprietary packing medium (i.e., Raschig rings); this system is much more efficient than sparging air into the liquid or injecting it into the suction side of centrifugal pumps.
3. Air dissolution at lower pressures is markedly less efficient than at higher pressures due to the reduced driving force for absorptive mass transfer.

Franzen et al. (32) note that in the treatment of refinery wastewater, 50 psi in the saturator provides more dissolved air and does a better job of removing oil and SS than 30 psi air. The quantity of air released is dependent, according to Gardner (33), on the degree of mixing at the given point of pressure reduction and on the degree of saturation. For conventional designs of pressure vessels, up to 50% air saturation can be achieved, but if mechanical mixing or a packing is utilized, the saturation can be increased to 90%.

Air normally has been the gas of choice (as the precursor to bubble formation), but CO_2, N_2, and CH_4 and their combinations have been tried (Table 1.3). Conway et al. (34) found that by using gases of higher aqueous solubility, they could improve the operation of an existing DAF system and produce thicker floats through a decrease in the recycle flow rate. The solubilities of different gases are given in Table 1.4 and Fig. 1.2.

Table 1.3
Reports of the utilization of gases other than air in DAF systems

Author	Gas	Wastewater
Conway et al. (34)	Combusted digester gas and oxygen-activated sludge off-gas	Solids flotation
Ellis and Fischer (35)	CH_4	Oil field
Sport (36)	N_2	Oil field
Travers and Lovett (37)	CO_2	Abbatoir
Sato et al. (38)	N_2	Emulsified oil in lab

Table 1.4
Solubility of various gases in water at 24°C

Gas	Solubility	
	By weight (mg/L·atm)	By volume (mL/L·atm)
N_2	17.8	15.5
O_2	40.1	30.8
CO_2	1,493	831
Combusted digester gas (84% N_2, 4% O_2, 12% CO_2)	22.3	18.6
Oxygen-activated sludge off-gas (20% N_2, 50% O_2, 30% CO_2)	466	265.8

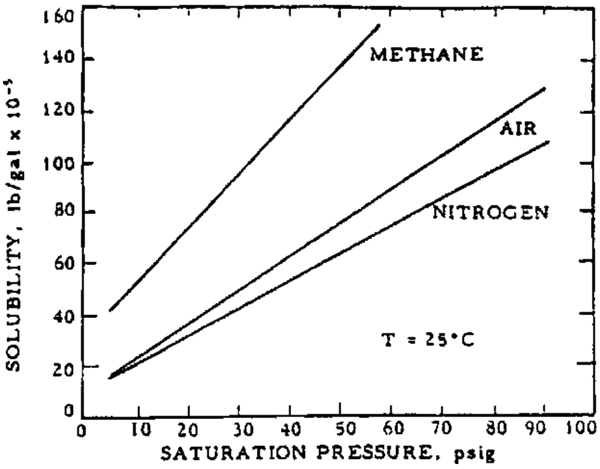

Fig. 1.2. Solubility of gases in water as a function of pressure.

The pertinent design equation for calculating the ratio of gas to SS or oil (34) is

$$\frac{G}{S} = \frac{\mathrm{RC_s}\, f(P/101.3)}{S_o Q - S_e R}, \tag{5}$$

where G is the gas concentration, mg/L; S is the SS (oil) concentration, mg/L; R is the pressurized liquid flow rate, L/d; C_s is the gas saturation concentration at atmospheric pressure, mg/L; f is the saturation efficiency; P is the saturation pressure, gauge kN/m^2 (psig × 6.89); S_o is the SS (or oil) in wastewater, mg/L; Q is the raw wastewater flow rate, L/d; and S_e is the SS (oil) in the pressurized liquid stream, mg/L.

2.2. *Bubble Size*

The most important dependent variable in air flotation systems is bubble size. Vrablik (39) produced the bubble-size distribution data found in Fig. 1.3. The bubble sizes reported by Vrablik ranged from approximately 45 to 115 μm with mean diameters of 75–85 μm at 20 and 50 psi saturation pressures, respectively. Vrablik also noted that the largest bubble that will rise in viscous (laminar) flow in water is 130 μm, a diameter that is much smaller than the approximate 1,000-μm diameter bubbles generated in induced air flotation.

The number and sizes of air bubbles formed in a given volume of water are a function of both the physical system and the chemical content of the wastewater. Concerning the latter, surface tension and dissolved solids concentration are extremely important parameters. Katz (40) reported that as surface tension decreases, smaller bubbles in larger numbers are formed. On the other hand, Shannon and Buisson (41), experimenting with a DAF system at elevated temperatures (50 and 80°C), found there was considerable change in bubble size with pressure. They obtained an average bubble size of 66 μm at 30.5 psi and 42 μm at 40 psi.

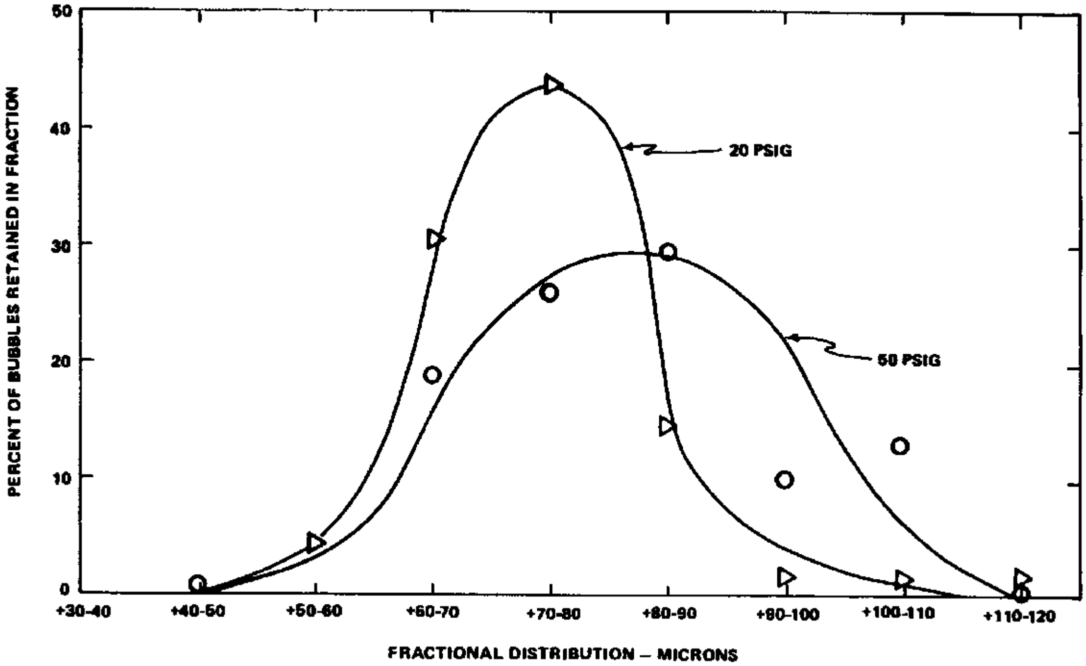

Fig. 1.3. Size distribution of air bubbles released into a flotation chamber in laboratory flotation tests.

Air is released from solution as a stream of small bubbles within a relatively narrow size range of 30–120 µm with a rising velocity that obeys Stoke's Law (33). The bubbles have a flotation effect only to the extent to which they adhere to the particles and droplets. This condition generally means that the bubble diameters are less than the diameters of the material or floc in suspension.

Ramirez (42) measured bubble-size distribution for systems in which the bubbles were generated: (1) by electrolysis, (2) by dispersed air, and finally, (3) by DAF. The data for bubble sizes are given in Fig. 1.4 and Table 1.5.

Degremont (43) has also produced a table of bubble sizes (Table 1.6); Degremont's data cover much of the same range that Ramirez's did, and their bubble sizes are of the same order of magnitude as found in other references. Since Degremont's table was in the design section of their book on wastewater treatment, they reported energy consumption and retention times (this latter topic receives more attention later in this chapter).

Travers and Lovett (37) measured bubble sizes in both CO_2 and air-saturated DAF systems at 30 psi pressure. Bubble sizes, 10 s after release, were five times larger when CO_2 was used compared with air – and consequently rose much faster, creating turbulent conditions in the flotation chamber.

Two other researchers working with nitrogen found bubble sizes in the 80-µm range. Sato et al. (38) determined an average bubble size of 82 µm, while Schmidt and Morfopoulos (44) found bubbles in the 48-µm range, with the bubble size depending on the degree of supersaturation.

Bubble formation is a science in itself. The paper by Schmidt and Morfopoulos (44) described a theoretical and experimental study of bubble formation. They reported that

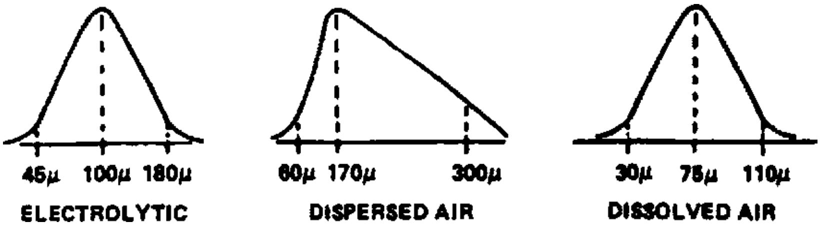

Fig. 1.4. Bubble-size distribution measured in three different aeration systems.

Table 1.5
Comparison of bubble size utilized in three different flotation processes

Parameter	Generation process		
	Electrolytic	Dispersed air	Dissolved air
Average bubble diameter at 60 dyn/cm (mm)	100	170	75
Bubble rise rate in ft/min (cm/s)	1 (0.5)	3 (1.5)	0.2 (0.1)
Number of bubles/cm^3	10^6	0.2×10^4	3.6×10^6
Bubble surface area (cm^2/cm^3)	454	293	800

Table 1.6
Comparison of the various flotation processes

Flotation process	Size of bubbles (µm)	Energy consumption		Retention time (min)	Principal applications
		Watts per volume treated (m^3/h)	Watts per volume treated (gal/min)		
Blown air	100–500	20–30	4.5–6.8	2–5	Grease
Mechanical	100–1,000	100–200	22.5–45	2–16	“Roughing” of polymer and latex or elastomer suspensions
Dissolved air with 20% recirculation	40–70	45–60	10.2–13.6	20–30	Hydrocarbons solvents, fibers, fine suspension and flocculated particles
Electrical	50–70	150–300	34–68		Same applications as those of dissolved air flotation in the case of hot saline water

supersaturated solutions of gases in liquids are very stable and that external agitation is needed to form bubbles. They developed a model to show that viable bubble nuclei are formed in the centers of free liquid eddies, that there is a critical velocity of the gas–liquid solution below which viable bubble nuclei cannot be formed, and that the number of nuclei increases with solution velocity and decreases with viscosity, nozzle size, and surface tension.

2.3. Rise Rate

In air flotation systems, one is normally treating large volumes of water. Hence, detention time in the air flotation chamber becomes a very important process variable. Retention time (as shown in Table 1.6), in turn, is primarily dependent on the rate of rise of air bubbles in the liquid; the rise rate, in turn, can be calculated using Stoke’s Law (the equation that governs bubble motion in flotation). The results of the calculation are shown graphically in Fig. 1.5 and also in Table 1.7.

Beychock (45) has compared the design value computed rise rates for flotation systems to those used in coagulation/sedimentation to show the significance of the former in allowing smaller units to be used (Table 1.8).

Hydraulic loading is also a common design parameter. If one looks carefully at the units used (gal/min/ft^2) and converts them to a common basis (ft^3/ft^2/min), by canceling one obtains units of ft/min, which is equivalent to the velocity expression reported as the rise rate. The above values are much less than the computed velocities of free bubbles (Table 1.7). What has happened, of course, is the bubbles are markedly slowed by their inclusion in the floc and interference (collision) with each other in rising.

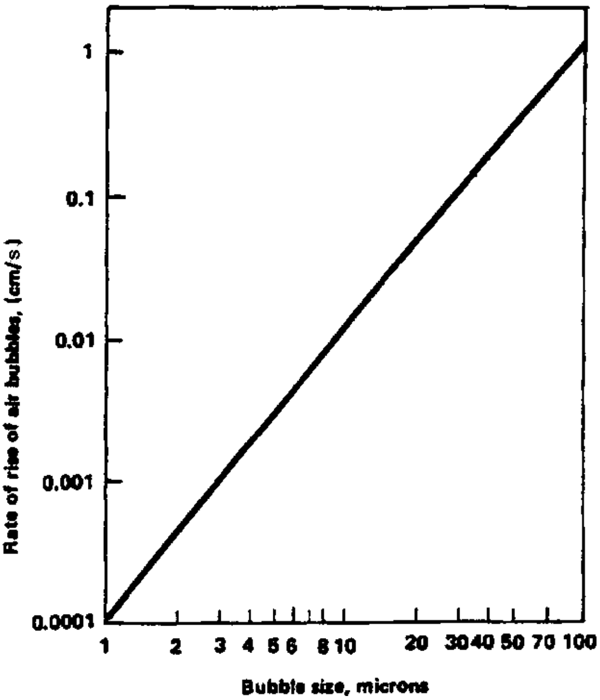

Fig. 1.5. Rise rate of air bubbles in tap water.

Table 1.7
Bubble rise velocity as a function of size

Bubble diameter (mm)	Upward vertical rise rate	
	(cm/s)	(ft/min)
0.2	1	2
1	15	30
10	25	50
50	55	110

Table 1.8
Comparison of retention time and settling/rise rates in sedimentation and air flotation systems

Parameter	Settling rate: coagulation/ sedimentation	Rise rate: flotation
Retention time based on influent flow (h)	2–3	0.5
Rise rate		
gal/min/ft^2	0.5–1.0	2.0
ft/min	0.07–0.13	0.27

Ramirez (42) noted that the actual rise rate of bubbles greater in size than 150 μm is considerably faster than predicted by Stoke's Law (Fig. 1.5) since they assume an elliptical shape, thus offering less resistance to flow than the theory predicted. He also found that when the pressure was higher, the microbubbles were larger.

Degremont (43) extended the curve shown in Fig. 1.5 to illustrate the rise rates of much larger-size bubbles, which obviously are faster. Their plot (Fig. 1.6) illustrates the rise rate for bubbles ranging from 100 to 50,000 μm.

For the air flotation of activated sludge (0.91% solids), Katz and Geinopolos (46) reported rise rates ranging from 0.3 ft/min to as high as 1.8 ft/min as the amount of air was increased approximately threefold. Eckenfelder and O'Connor (47) reported initial vertical rise rates for domestic wastewater activated sludge ranging from 0.17 to 0.42 ft/min as the dissolved air content in the wastewater was increased fourfold (0.015–0.06 lb of air/lb of solids).

The initial rise rate was observed to vary with the character of the waste being treated. Activated sludge from pulp and paper waste oxidation had an initial rise rate of 0.75–0.83 ft/min as the air-to-solids ratio was increased from 0.15 to 0.25 lb of air/lb of solids.

Woodward and coworkers (48, 49) have reported two rise-rate measurements for oil and grease separators for poultry-processing wastewater treatment (Table 1.9). Their values are

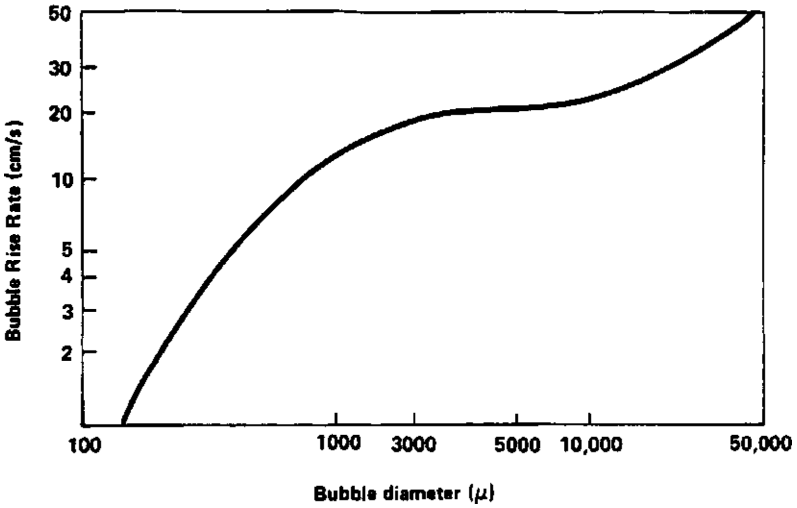

Fig. 1.6. Rise rate of larger bubbles.

Table 1.9
Values for the rise rate in selected treatment processes

Author	Rise rate (ft/min)	Wastewater	Flotation system
Woodward et al. (48)	2.6	Poultry processing	DAF/R
Woodward et al. (49)	1.8	Poultry processing	DAF/R
Katz and Geinopolos (46)	0.3–1.8	Activated sludge	–
Eckenfelder and O'Connor (33)	0.17–0.42	Activated sludge	–

larger than for a solids removal system and consistent with those found for smaller-sized bubbles.

Shammas and DeWitt (50) have reported that modern high rate DAF clarifiers advanced to such an extent that they could overshadow the conventional settling clarifiers for water and wastewater treatment. DAF units are now designed for only 3 min of retention time and with a hydraulic surface loading rate (SLR) of up to 5 gal/min/ft^2 (210 L/min/m^2).

Wang et al. (2) reported the following interesting comparison between a DAF unit and a conventional settler:

1. DAF floor space requirement is only 15% of the settler.
2. DAF volume requirement is only 5% of the settler.
3. The degree of clarification of both clarifiers is the same with the same flocculating chemical addition.
4. The operational cost of the DAF clarifier is slightly higher than that of the settler, but this is offset by the considerably lower installation cost and its financing.
5. DAF clarifiers are mainly prefabricated in stainless steel for erection cost reduction, corrosion control, better construction flexibility and possible future changes, contrary to in situ constructed heavy concrete sedimentation tanks.

2.4. *Air/Solids Ratio*

A parameter governing the rise rate of bubble-particle agglomerates in solid-particle DAF systems is the air–solids ratio, which is defined as the mass of air precipitating (coming out of solution as the pressure on the aerated stream is reduced) per unit mass of wastewater solids. In systems containing oil, the term “solids” can be replaced by “oil and grease” or “suspended solids plus oil and grease,” a term defined by Steiner (51). According to Eckenfelder (52) and Krofta and Wang (11), the most important parameter in designing air flotation systems is the air/solids ratio. If less than the optimum amount of air is employed in the air flotation system, the efficiency of solids (or oil) removal is reduced. If too much air is used, power is wasted in compressing excess air. Hence, in designing air flotation systems, one tries to optimize this important variable.

Regardless of how the gas bubbles and the dispersed phase interact, the result of this interaction is a net reduction in the specific gravity of the dispersed phase (air/particle agglomerate) and a corresponding increase in rise velocity. Rise velocity (rate) is usually expressed in the form of Stoke’s Law, Eq. (1).

Equation (1) indicates that as more air bubbles are incorporated into the aggregate, the aggregate’s net density decreases, and its rise velocity increases.

The air/solids-plus-oil ratio is easily computed for dissolved air systems using the following equation:

$$\frac{A}{S} = \frac{C_{\mathrm{s}}}{X_{\mathrm{f}}}(fP_{\mathrm{a}} - 1), \tag{6}$$

where A/S is the air/solids plus oil, mg/mg; C_{s} is the air solubility at 1.0 atm pressure and operating temperature, mg/L; X_{f} is the concentration of SS plus oil in the feed, mg/L; P_{a} is the absolute saturation pressure, atm absolute; f is the fraction (or efficiency) of air actually

Table 1.10
Air/solids ratios in various industrial wastewater-treatment systems

Author	Air/solids ratio	Wastewater system	Influent suspended solids concentration (mg/L)
Beisinger et al. (53)	0.026	Poultry processing	900
	0.020	Poultry processing	1,300
	0.020	Beef packing	2,000
	0.007	Beef packing	5,000
	0.07	Soybean oil	200
	0.7	Refinery	50
Steiner (51)	0.02–0.12	Refinery	50 (oil)[a]
Reed and Woodward (54)	0.12[a]	Poultry processing	43–273
Abo-El Ela and Nawar (55)	0.008[b]	Soap factory	1,100 (oil)
Zimmerman and Jacquez (56)	0.006	Poultry processing	250 (SS) 4,000 (O & G)
McIntyre (57)	0.02	Parts manufacturing	–
Moursy and El-Ela (58)	0.001	Refinery	56
Average	0.08 (or 0.03 if one very high value is not included)		

[a] Pilot-plant scale.
[b] Optimum value.

dissolved at the elevated pressure in the saturation chamber (typically f is 0.8); and 1 is the air left in solution at atmospheric pressure.

In recycle pressurization systems, all of the air is imparted to the recycle stream and the suspended contaminants are in the raw-waste stream; thus the equation must be modified as follows:

$$\frac{A}{S} = \frac{RC_{\mathrm{s}}}{QX_{\mathrm{f}}}(fP_{\mathrm{a}} - 1) \tag{7}$$

where R is the flow rate of recycle stream, gpm and Q is the flow rate of raw wastewater, gpm.

Examples of air/solids ratios utilized in industrial (and some laboratory) studies are found in Table 1.10.

2.5. *Laboratory Bench-Scale Testing*

In most of the laboratory test work reported in the literature, researchers (59) have used batch DAF units (Fig. 1.7) that normally consist of two cylinders: a pressurizing vessel and a flotation vessel. In using this unit, a researcher fills the pressure vessel with wastewater, adds any chemicals being tested, pressurizes the contents, shakes for 1 min, allows the mixture to stand for 3 min, and finally releases contents to the flotation chamber (for detailed procedure see Krofta and Wang (11), Adams et al. (60) and AAPSE (61)). If a recycle system is to be simulated, then part of the liquid is saturated and released into the rest of the liquid in the saturated vessel (11, 62).

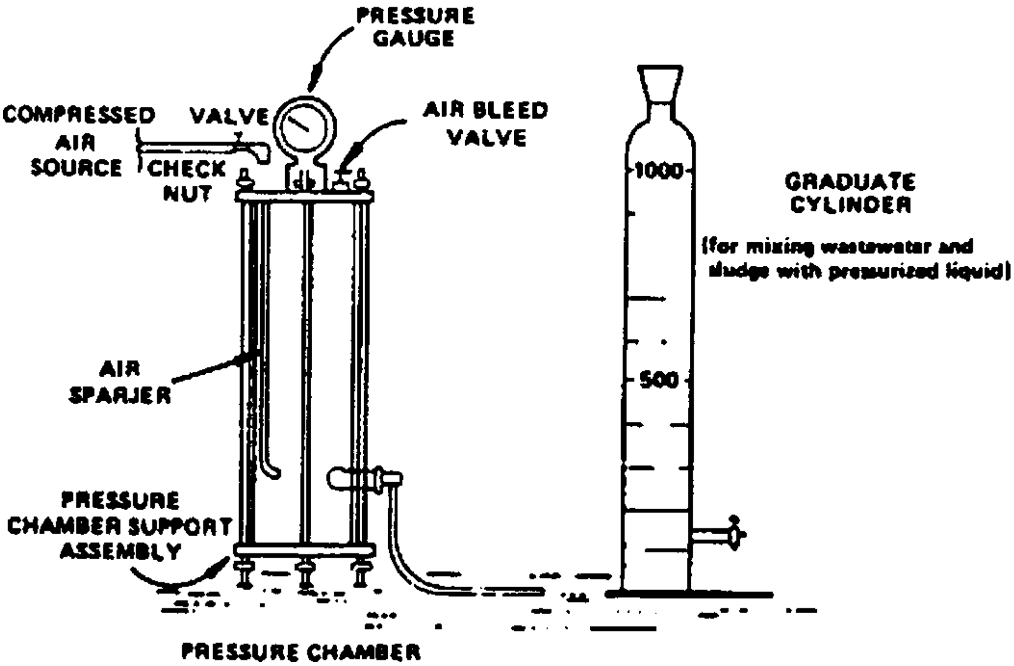

Fig. 1.7. DAF laboratory unit.

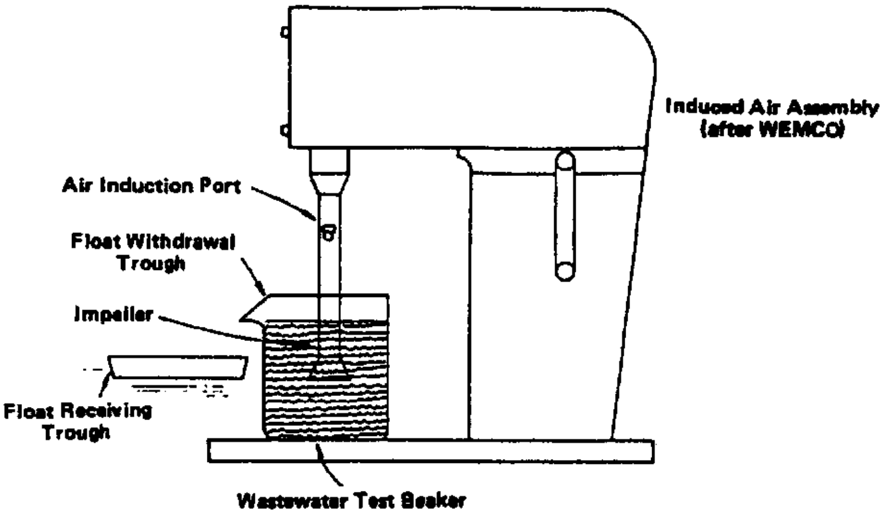

Fig. 1.8. Bench-scale IAF unit.

WEMCO (an equipment manufacturer) utilized bench-scale units of both IAF and nozzle air flotation systems. Descriptions of these test units and their use in laboratory studies are found in the masters' theses of Steiner (51), Ching (63), and Nipper (64). The IAF model is shown in Fig. 1.8.

3. ELECTROFLOTATION AND ELECTROCOAGULATION

Quite early in the history of electrochemical technology, Hillis (65) wrote that researchers in the wastewater field felt that the passage of a direct current through a solution might be useful in effluent treatment because of the resultant reactions at the anode and cathode. Some of these early ideas resulted in the development of actual processes, and several plants were built in the late 1800s.

Electrochemical flotation was rediscovered, according to Backhurst and Matis (66) in the 1960s in the USSR for the flotation of minerals. Matis (67) noted that in 1980 there were 20 electroflotation (EF) plants treating industrial effluents in the UK, while Roth and Ferguson (68) reported on an aviation-terminal treatment system in the United States.

When an effluent is introduced between two electrodes and energy is applied to the electrode (generally as a low voltage), an electric field is built up between the cathode and the anode by the conductivity of the liquid. Without the addition of chemicals, a preliminary coagulation occurs within the suspension that seeks to group the positive and negative particles together. Furthermore, upon the electrolysis of water, hydrogen, and oxygen are released in an electrically excited condition as a swarm of small, uniform bubbles that rise, producing a blanket effect. The bubble swarm carries SS and oil globules to the surface where a floating sludge layer forms and is mechanically removed.

Therefore, in the diffusion layer of the anode, free atomic oxygen is produced and then carried by convection into the suspension where it immediately combines with and oxidizes organic and inorganic materials in the suspension. In a similar manner, there is also a production of hydrogen bubbles with concomitant reduction of some contaminants in the solution (67).

Prime variables in EF that affect current density, bubble size and numbers, etc. are as follows:

1. pH
2. Type of electrolyte (NaCl, HCl, NaOH)
3. Current density
4. Retention time

Chambers and Cottrell (69) noted that there are several reasons why EF is an attractive process:

1. The electrode grids can be arranged to provide good coverage of the surface of the tank so uniform mixing between the effluent and gas bubbles is achieved.
2. A large number of very small bubbles are formed with minimum turbulence.
3. The electric field gradient between the electrode and flocculated solid can be controlled.
4. Gas production and residence time are easily controlled.

A claimed advantage for the EF system is that there is no turbulence due to sudden pressure releases and therefore no shearing of fragile flocs. Another advantage of this process over others is that bubble-generation efficiency is independent of wastewater temperature.

The treatment unit, according to Chambers and Cottrell (69), is usually a rectangular tank with a pair of electrode grids near the bottom. The cathode is mounted above the anode. When a direct current flows between the electrodes, oxygen bubbles form at the anode and hydrogen bubbles at the cathode. These bubbles rise to the surface carrying the oil and SS.

Gardner (33) found for a 20-min retention, a potential difference of 10 V at a current density of 100 A/m^2 was generally sufficient to clarify wastewaters with an initial SS particle concentration of up to 10,000 mg/L. Degremont (43) reported that at those current levels, gas production was 50–60 $L/h/m^2$ (0.16–0.20 $ft^3/h/ft^2$). The design flow rate (43) in these systems was approximately 4,000 $L/h/m^2$ (13 $ft^3/h/ft^2$).

Bubble size and numbers of bubbles are of key importance. Ramirez (42) compared dispersed, dissolved, and EF treatment. Data showed (Table 1.5) that the relative size was 110 μm for dispersed air systems, 75 μm for dissolved air systems, and 100 μm for EF systems, with density (numbers, million per cubic centimeter), of 0.2, 3.2, and 1.0, respectively. DAF thus provides the largest number of smaller bubbles and hence has the largest surface area for oil and grease and particulate removal.

Minimizing electrode fouling is the key to success and cost-effective, continuous, trouble-free operation of EF systems. The electrodes are cleaned from time to time by reversing the current. With some types of electrodes that is not possible, so a conditioning agent is added to the effluent prior to treatment to prevent deposition of carbonates on the electrode.

Ramirez (70) gives expected operational results for a New Hampshire tannery wastewater treated by dispersed air flotation/electrocoagulation. He achieved a reduction in the BOD from 500–700 to 190 mg/L, the TSS from 600–900 to 90 mg/L, and oil and grease from 200–300 to 16 mg/L (92–95% removal).

Roth and Ferguson (68) reported on the results of EF treatment at an aircraft maintenance facility. Chemical additives included lime (to pH approximately 8.5), alum (200 mg/L), and anionic polymer (1.5 mg/L). Using 6–9 V, 15–25 A/m^3 (described as low energy usage), and a retention time of 20–30 min reduced the oil and grease more than 99% from 60 to 0.3 mg/L, with a concomitant reduction of metals, achieving effluent concentrations of 0.8 mg/L Ni, 0.5 mg/L total Cr, and 0.07 mg/L Al.

Another application of electrolytic cells is in the electrocoagulation of oily wastewater prior to air flotation. The process described by Weintraub et al. (71–74) and shown in Fig. 1.9 is as follows: oily emulsion wastewater from which free oil has been removed enters the electrocoagulation cell where it permeates uniformly through a rectangular caged anode fitted with iron or steel machinery turnings and chips; the wastewater then flows through a perforated sheet-metal cathode; DC voltage is applied to the electrodes, dissolving the ferrous iron at the anode and forming hydrogen and hydrogen ions at the cathode. A few hundred mg/L of salt may be added to increase ionic conductivity and prevent passivation of the iron electrode.

Ramirez (70) has experimented with the commercial Lectro Clear system to treat rendering wastewater. The system used a combination of electrocoagulation (95) at 12.5 V and 1,500 A and EF (75) at 12.8 V and 400 A. The retention time was 25 min (70). Chemicals added included 1,200 mg/L H_2S0_4 (to pH 4.5), 100 mg/L alum, and 6 mg/L of an anionic polyelectrolyte. DAF was used to dewater the skimmings. Operational results included reduction of the oil and grease from 810 to 19 mg/L (98% removal); major amounts of SS were also removed (3,500–95 mg/L).

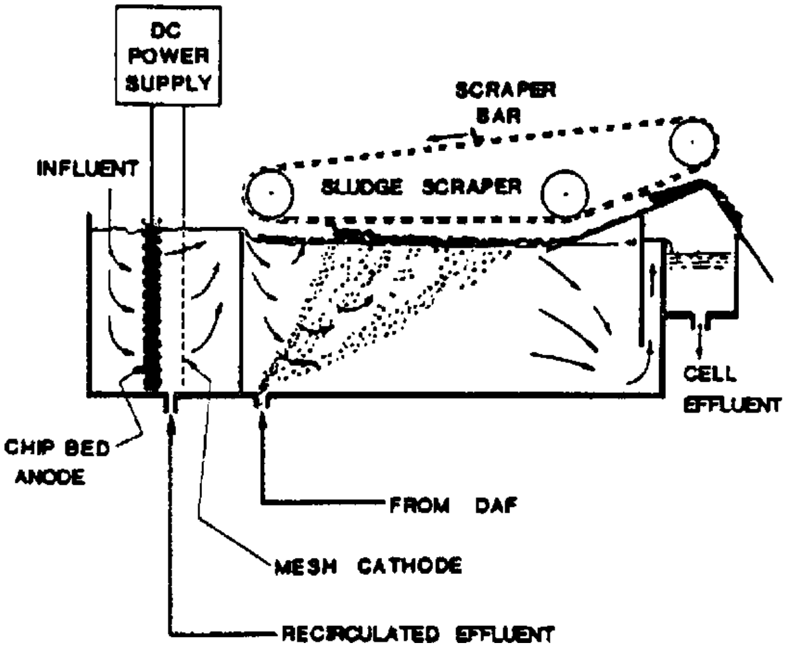

Fig. 1.9. Schematic diagram of the electrolytic cell.

Chambers and Cottrell (69) reported on the treatment of carrier-truck washings effluent in the UK. A flow of 230 m^3/d was treated in a $1.8 \times 1.2 \times 5$-m deep tank at a rate of 11.4 m^3/h; the retention time was approximately 1 h. Alum at a concentration of 60 mg/L was added. In two experiments, the ether extractables were reduced approximately 75% and the SS were reduced approximately 50%. Power requirement was approximately 0.4 kwh/m^3.

Developed in Sweden, the DAF technique called microflotation combines the benefits of advanced chemical flocculation with a novel and simple method for the production of bubbles. The equipment is very similar to the deep-shaft aeration process (76) in which the wastewater flows down one cell of a deep two-celled tank and under a baffle that divides the tank into two parts; this baffle reaches almost to the bottom of the tank. Near the bottom of the tank, air is released into the liquid. Air dissolves in the wastewater under the pressure of the hydrostatic head. Undissolved air rises against the downward flowing water and dissolves; dissolution of the air continues as the water flows under the baffle and up the second of the two shafts. Rising water on the other side of the baffle is saturated with air, but is free of undissolved bubbles. However, as the hydrostatic pressure decreases and the water rises, dissolved air is released as microscopic bubbles that attach themselves to the solids. Nineteen full-scale plants are reported to exist in Sweden with numerous others under construction in the world treating textile, steel-mill, and pulp and paper effluent. All, however, are used for solids but not oil removal (69). More applications of EF can be found in the literature (19–22).

4. DISSOLVED AIR FLOTATION

4.1. *Process Description*

In the DAF process (Fig. 1.10), very fine gas bubbles are generated by reducing the pressure on a stream of the wastewater that has been exposed to air at pressures greater than atmospheric; the solubility of oxygen in water at two different pressures (30 and 65 psi) is shown in Tables 1.1 and 1.2. When the pressure is reduced, as the liquid flows through a pressure-reducing valve into the flotation basin, small bubbles nucleate from the supersaturated solution, attach to, and become entrapped by oil and solid particles and rise to the surface where they are removed. Although air is the most common gas used in this process, methane, nitrogen, and carbon dioxide have been used (also see Table 1.3).

Two methods exist for generating air bubbles in the DAF process:

1. Air is dissolved in the liquid wastewater under pressure (30–85 psi). The pressurized stream is passed through a pressure-relief valve to be discharged near the bottom of a flotation tank where the total pressure equals the ambient air pressure plus the hydrostatic head. Here small bubbles nucleate and rise to the surface carrying the contaminants with them.
2. The wastewater is aerated until it is saturated with air at atmospheric pressure. Subsequent application of vacuum (about 9 in Hg) yields bubbles (described above as vacuum desorption). As stated previously, this process is no longer used.

A DAF system (Fig. 1.10) consists of the following units (77–79):

1. Pressurizing pump
2. Air-injection system

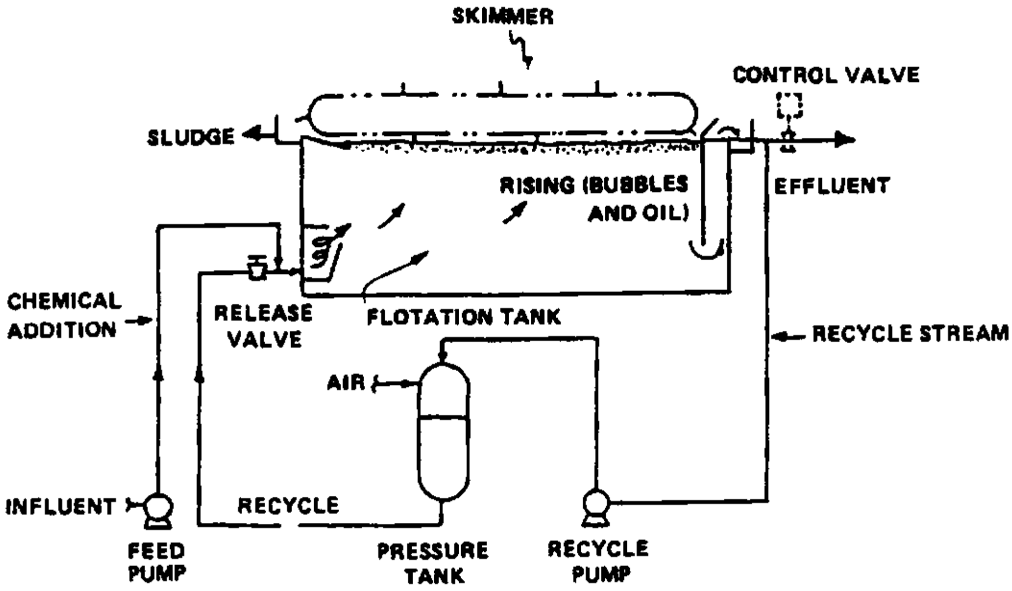

Fig. 1.10. Schematic diagram of DAF system.

3. Saturation vessel
4. Load (pressure) regulator (also called the pressure-relief valve)
5. Flotation vessel (including the influent distributor)
6. Chemical addition system

An added feature in most systems is the addition of chemicals to break emulsions or promote floc formation.

4.2. Pressurization

There are three liquid flow schemes (2, 11) that can be used in the pressurization sequence (Fig. 1.11):

1. *Full flow*. In the full-flow system, all of the incoming raw wastewater is pressurized and saturated with air. This modus operandi results in the most air being dissolved and (compared with the other two methods) yields the maximum probability of good particle–bubble contact, but it also results in a larger saturation system and subjects potentially coagulated flocs to the shearing action of the pump and pressure-reduction process.
2. *Split flow*. In the split-flow sequence, part of the incoming wastewater is diverted through the pressurization aeration system. Reduced pumping costs, better capacity of the system to handle flow fluctuations, and reduced breakup of the flocs are among the major advantages of this system. A disadvantage common to split flow and full-stream pressurization systems is shearing of flocs or emulsification of oil when the influent stream is subjected to pressure reduction. The amount of air dissolved, at comparable pressure, is less than in full-stream pressurization because of the lower flow rate.
3. *Recirculation*. In the recirculation mode of operation, 20–50% of the treated wastewater is returned to the pressurization system, thus avoiding disruption of flocs or demulsification of the oil in the untreated influent. Larger flotation basins, however, have to be used if the hydraulic loading rate (based on the influent flow rate) is not to be changed, because the recirculation flow is now added to the full-stream flow.

Each mode of operation has distinct advantages and disadvantages that must be evaluated for each individual situation. A few of the more general are described below (80).

1. *Full-Stream Pressurization*
   Advantages:
   (a) Provides maximum gas solution at any given pressure. At comparable pressures, more gas dissolves in solution than in split-stream or recycle pressurization because the entire stream is pressurized.
   (b) For the same plant throughput, a smaller flotation chamber is required than for recycle pressurization.
   (c) Because of the increased dissolved gas content, the maximum number of bubbles may be formed so that the probability for contact with the dispersed phase is increased.
   Disadvantages:
   (a) The total solids content must be pumped, increasing abrasive wear and operation and maintenance costs.
   (b) Oil in the influent stream tends to become further emulsified by the shear forces of pumping, increasing the difficulty of separation.

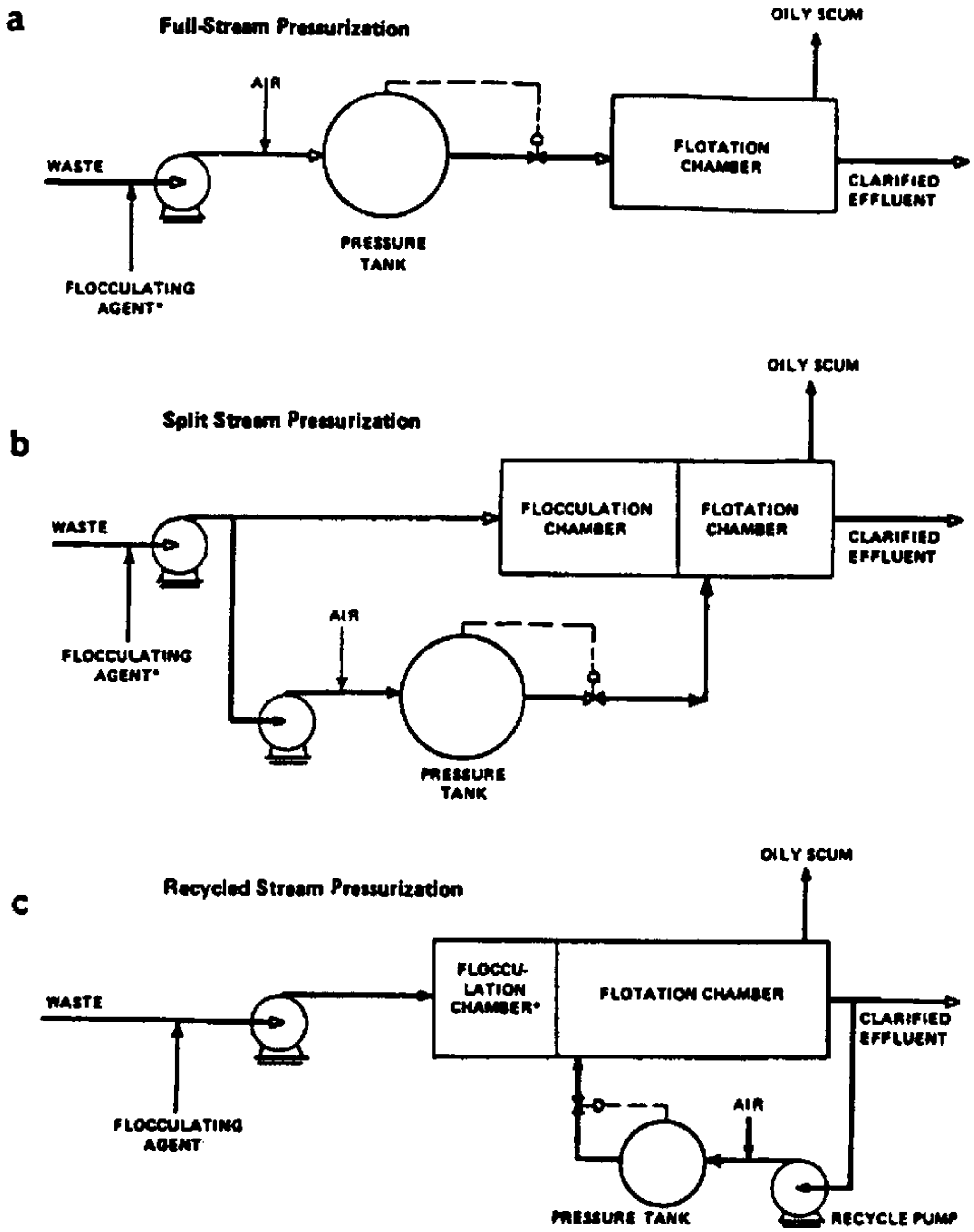

Fig. 1.11. Flow diagram of DAF pressurization systems.

2. *Split-Stream Pressurization*
   Advantages:
   (a) Requires a smaller pressurizing pump than full-stream pressurization and hence results in a reduction in operating and maintenance costs.
   (b) The flotation chamber is the same size as for full-stream pressurization but smaller than for recycle operation.
   (c) Simpler pump controls than in full-stream operation are required to accommodate a fluctuating flow. The pump may be operated at a constant rate and the fluctuations in flow remain in the unpressurized portion. However, as the flow increases, the air-to-solids ratio decreases, which may adversely affect performance.
   (d) When coagulating chemicals are used, the unpressurized stream may act as a flocculation chamber.
   Disadvantages:
   (a) At comparable pressures, a smaller volume of gas is dissolved than in full-stream pressurization.
   (b) A certain amount of abrasive solids still must be pumped.
   (c) Some oil in the influent stream still will be emulsified as a result of the shear forces in the pumping process.
3. *Recycle Pressurization*
   Advantages:
   (a) A smaller pressurizing pump is required than in full-stream pressurization so that capital and operating costs are reduced.
   (b) The system requires simple pump controls for variable flow.
   (c) Emulsion formation due to shear is minimized.
   (d) Abrasive solids need not be pumped since they are largely separated in the flotation chamber prior to pressurization.
   (e) Flocs formed in the system are not subjected to the shearing forces of the pressurizing pump.
   Disadvantages:
   (a) To maintain hydraulic loadings (gal/min/ft^2 of flotation area) comparable to those in full- and split-stream operation, it is necessary to enlarge the flotation chamber.
   (b) Another potential disadvantage of recycle operation is in the process of thickening of activated sludge by DAF. Maximum solids removal is obtained at recycle rates from 20 to 50% of the total flow. Explanation for this phenomenon is that the greater turbulence produced by the increased hydraulic loading offsets improved rise rates resulting from diluted solids feed and increased air content.

One of the early workers, Rohlich, concluded in his 1954 study (23) of various modes of pressurization of refinery wastewater that the recycle system was best. That conclusion has not changed with time.

4.3. Controls

Automated control of the recycle pressurization system can provide optimum performance (Fig. 1.12). Ettelt (81) described such a system that includes interface-level and air-input controls.

Sufficient air is needed to achieve saturation of the pressurized stream without excess air leaving undissolved in the effluent stream from the pressurization tank. The bubbles

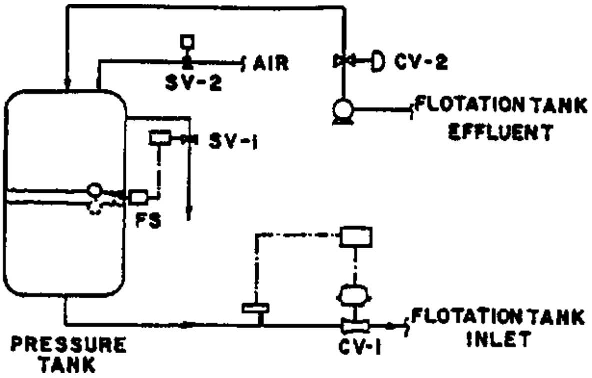

Fig. 1.12. Automatic control of a pressurization system.

produced by undissolved air not only would be too large for efficient removal of oil droplets but also would cause disturbing turbulence in the flotation tank. Too high an interface level in the pressurization vessel impairs the dissolution efficiency of air into the liquid; too low an interface level induces bubble carry-over in the discharge of the pressurization tank.

4.4. *Tank Shape*

Air flotation tanks come in two basic shapes: (1) circular and (2) rectangular. From the authors' review of the literature and manufactures' brochures, the former appears to be more popular. Krofta (11) (equipment manufacturer) agrees that the circular design should be selected as a first choice.

Advantages of circular design include:

1. Economical circular construction
2. Low velocities maintained throughout the active flotation zone
3. Pivoted arm skimmer reduces maintenance and lubrication requirements
4. Bottom scrapers can be added at little added cost
5. Top, centrally mounted drive shaft eliminates sprockets, chains, and underwater bearings

Advantages of rectangular clarifier include:

1. Conservation of space in congested areas
2. Most standard sizes can be shipped set up, thus minimizing field erection
3. Hopper bottom eliminates the need for bottom scraper

De Renzo (82) found the more uniform the distribution of the water and microbubbles, the shallower the flotation unit can be. Generally, the depth of effective flotation units is between 4 and 9 ft. The basic shape can be round, square, or rectangular. Beychock (45) suggests tank depths of 6–8 ft be employed.

4.5. *Air Supply*

Another equipment variation is the way in which air is supplied to the system. Variations include:

1. Pressurizing the saturator tank with air supplied by a plant compressed line
2. Introducing air at the throat of a venturi into a pumped stream of fluid
3. Injecting air into the flowing fluid either before or after the pressurizing pump

4.6. *Chemical Usage*

Most, if not all, air flotation systems employ chemical addition. Early in the application of air flotation systems, the importance of chemicals for emulsion breaking and floc formation was recognized.

Biesinger et al. (53) tested the efficiency of a recycle DAF system on beef-packing-plant wastewater with and without the use of chemicals. Without chemicals, 73% of the influent oil and grease (initial concentration 300 mg/L) was removed, whereas with the addition of 10 mg/L alum, the removal increased to 86%.

Hart (83) and Pearson (84) also experimented with chemical additives on a rather dilute refinery wastewater. Without chemicals, 65% of oil was removed (from 18 reduced to 6 mg/L); with chemicals, 79% removal was achieved (11 down to 2 mg/L). There were concomitant removals of SS, BOD, and COD (Table 1.11). Using an IAF system, McIntyre also found that chemicals enhanced oil removal slightly, increasing the removal from 93 to 96% (Table 1.11). Pearson (84) experimented with the effects of the addition of inorganic chemicals, specifically alum, on oil removal. The use of alum plus a polyelectrolyte increased the oil removal from 40 to 90% (Fig. 1.13). Weight for weight, the aluminum ions were more efficient than ferric ions; they gave optimum removals at 35 mg/L as opposed to 60 mg/L with iron. In addition, the effluent produced by aluminum ions contained one half the oil present in the ferric-treated waste, i.e., 10 vs. 20 mg/L oil.

4.7. *Ionic Strength*

The ionic strength of solvents can also have an effect. Sato et al. (38) found that in general, oil removal was improved at higher ionic strengths and higher cation valences.

Table 1.11 Comparison of the treatment efficiency of refinery wastewater with and without chemicals

Treatment process	Removals (%)			
	Oil	SS	COD	BOD
DAF				
Without chemicals	65	55	30	33
With 2 mg/L polyelectrolyte	79	75	42	40
IAF				
Without chemicals	93			
With chemicals	96			

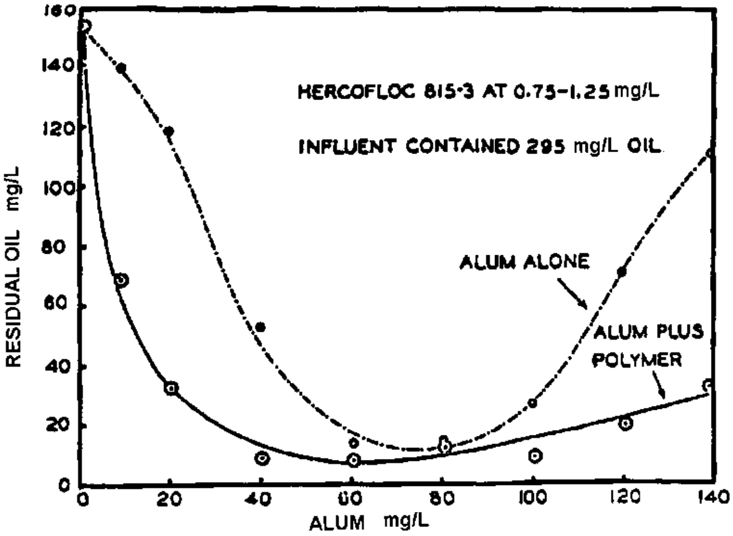

Fig. 1.13. Effect of alum and polyelectrolytes on oil removal.

4.8. Design Variables

One can find a plethora of differing, recommended design values in the literature. The first general compilation published by Beychock (45) is found in Table 1.12. He is quite specific for most of his parameters. In 1981, Adams et al. (60) published (Table 1.13) a similar, although not quite so complete, list of design values using ranges that generally encompassed the values suggested by Beychock (45).

The above recommended design ranges have been repackaged and combined with other suggestions from the literature. The same type of information is shown in Table 1.14 with the recommended numerical design values provided by Wang et al. (2), Adams et al. (60), De Renzo (82), and the API (85) under a set of different headings (from Beychock): air pressure, retention time, hydraulic loading, and air requirements.

The recommended design values can thus be compared with those actually used. Data for air pressures actually employed in operating DAF systems are reported in Table 1.15. Air pressures utilized ranged from 40 to 85 psi with a computed average of 56 psi. There are no reports of pressure at the lower end of the scale being used, but the recommended design values at the high end were exceeded (62).

4.9. Retention Time

In reference to loading, most authors report their data in terms of hydraulic loading (gal/min/ft^2). This term can easily be related to retention time if the proper data are available, but few authors give the necessary physical measurements to make the calculations. Recommendations of Table 1.14 note that retention time in the flotation tank should be between 10 and 60 min. Retention times are considerably less in IAF systems. The importance of surface

Table 1.12
Design basis for a recycle pressurization air flotation unit

Parameter	Variable
Air pressure	35–55 psi
Saturation retention time	2 min (based on recycle flow)
Air requirements	0.25–0.50 SCF/min/100 gal total flow
Flotation tank retention time	15–20 min (based on raw plus recycle flow)
Recycle rate	50% of raw influent feed rate
Hydraulic loading rate	3.0 gal/min/ft^2 (based on raw plus recycle flow)
Ph	7.5–8.5
Chemicals	25 mg/L alum (based on raw plus recycle flow)
Flotation tank depth	6–8 ft

SCF = standard cubic feet.

Table 1.13
Recommended design variables and ranges for DAF systems

Parameter	Variable
Flotation tank retention time	20–40 min
Air pressure	40–60 psi
Hydraulic loading	1–4 gal/min/ft^2 (including recycle)
Recycle ratio	10–60%

Table 1.14
Recommended design parameter ranges for DAF

Air pressure in saturation tank (psi)		
Adams et al. (60)	40–60	
DeRenzo (82)	25–70	
Beychock (45)	35–55	
Wang et al. (2)	25–75	
Retention time (min)	Flotation tank	Pressurization tank
DeRenzo (82)	20–60	0.5–3.0
Beychock (45)	15–20	2
API (85)	10–40	1–2
Wang et al. (2)	3–5	0.17
Hydraulic loading (gal/min/ft^2)		
Adams et al. (60)		1–4
Beychock (45)		3–0
API (85)		2–2.5
Wang et al. (2)		3.5–5
Air requirement (SCF/100 gal)		
Beychock (45)		0.25–5.0
API (85)		0.5–1.0

SCF = standard cubic feet.

Table 1.15
Air pressure used in industrial DAF systems

Author	Wastewater	Saturation pressure (psi)
McIntyre (57)	Automotive	70
Quigley and Hoffman (86)	Refinery	40–50
Hart (87)	Refinery	40
Zimmerman and Jacquez (56)	Poultry processing	40
Adams et al. (26)	Edible oil	45
Barker et al. (88)	Steel industry	50
Churchill and Tacchi (89)	Metal working	50
Franzen et al. (32)	Refinery	50
Churchill and Tacchi (88)	Refinery	60
Woodward et al. (48, 49)	Poultry processing	80
Oblinger et al. (72)	Metal working	85
	Average	56

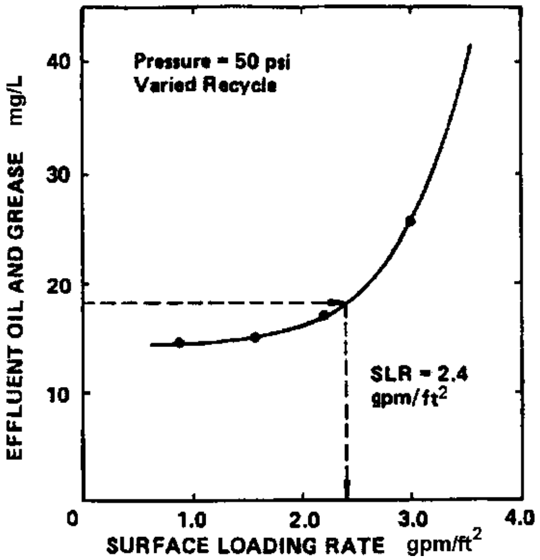

Fig. 1.14. Effect of surface loading rate on effluent quality.

loading was demonstrated by Adams et al. (60), who plotted the degree of removal against surface loading (Fig. 1.14). The curve breaks sharply upward (i.e., the quality of the effluent decreases markedly) as the SLR exceeds 2.5 gal/min/ft^2.

Retention time does take on considerable importance in batch studies. Moursy and El-Ela (58) reported that optimally the residence time was 7 min based on maximization of COD removal, while Pearson (108) found 4 min was the optimum for removal and electrolytic desalting of wastewater in a batch DAF (Fig. 1.15). Wang et al. (2) and Shammas and DeWitt (50) recommended 3–5 min for optimal design.

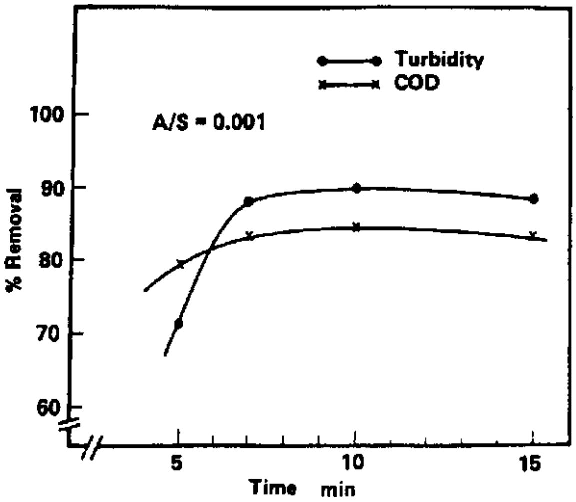

Fig. 1.15. Effect of retention time on refinery wastewater treatment in a batch DAF study.

Their results showed that some hydrocarbons were completely removed; others were removed with efficiencies between 79 (n-C_{13}) and 98% (n-C_{12}). They attributed the differences in removal to the differences in solubility and molecular weights of the hydrocarbons, especially as the water solubility of the compounds decreased, the degree of removal increased.

5. INDUCED AIR FLOTATION

5.1. Process Description

Induced gas (air) flotation (IAF) has been used for many years in the mining industry for ore beneficiation, but in industrial wastewater treatment the use of the IAF process really began around 1970 (115). In 1971, Bassett (90) described the historical development and industrial operating experiences for the earlier models which used mechanical mixing impellers. For this separation process, bubbles are generated and discharged into the liquid by high-speed rotating impellers, by diffusers, or by homogenization of a gas/liquid stream.

Degner and Winter (91) have stated that, in general, DAF can be characterized as a relatively quiescent, high-retention-time process, using relatively small quantities of gas (first dissolved, then later desorbed) in contrast to IAF which is a low-retention-time process, less quiescent, using a relatively large volume of gas.

The fundamental difference between the two air flotation processes is the mechanism by which air bubbles are introduced into the liquid (3, 15, 80):

1. In the DAF system, air is first dissolved under pressure and then allowed to nucleate as relatively small bubbles at atmospheric pressure. In the standard IAF system, high-speed rotating impellers induce much larger amounts of air into the suspension producing bubbles an order of magnitude larger (about 1,000 μm in diameter) than DAF bubbles.

2. The kinetics of IAF is very rapid, resulting in a relatively short retention time (5 min or less) with a concomitant reduction in equipment size, Degner (92).
3. Commercial wastewater-treatment units utilizing the IAF principle are generally multicell in design, thus avoiding short-circuiting while allowing more than one chance for contaminant removal. If, for example, there are four cells, each with a 60% average removal efficiency, the total removal is 97.5%.
4. In DAF, chemicals are added to flocculate the oil and SS so bubbles can attach to and/or become entrapped in the floc to float it to the surface. In induced air flotation, chemicals are added to cause the oil and SS to engulf the air bubble and be floated to the surface.
5. In DAF systems, chemicals are usually added and mixed with the wastewater in a vessel that precedes the DAF equipment. In IAF systems, the chemicals are put into the wastewater just before the first flotation cell, with the turbulent conditions in this cell providing the needed energy for mixing.

The hydraulic regime (Fig. 1.16) existing in the IAF cell has been described by Degner (92): "The dispersed (induced) air flotation cell consists of two fluid flow paths (gas and liquid) together with three distinct regions, each of which is important to achieving good wastewater contaminant removal performance. If the flotation cell is to ingest air naturally, i.e., the air is not supplied to the cell via an external compressor, the air (or gas) will enter the liquid in the upper, rather than the lower region of the flotation vessel (Path A). Concurrently, the liquid is circulated from the lower region of the vessel (Path B) meeting and mixing intimately with the air ingested through the upper portion of the vessel in the two phase fluid mixing

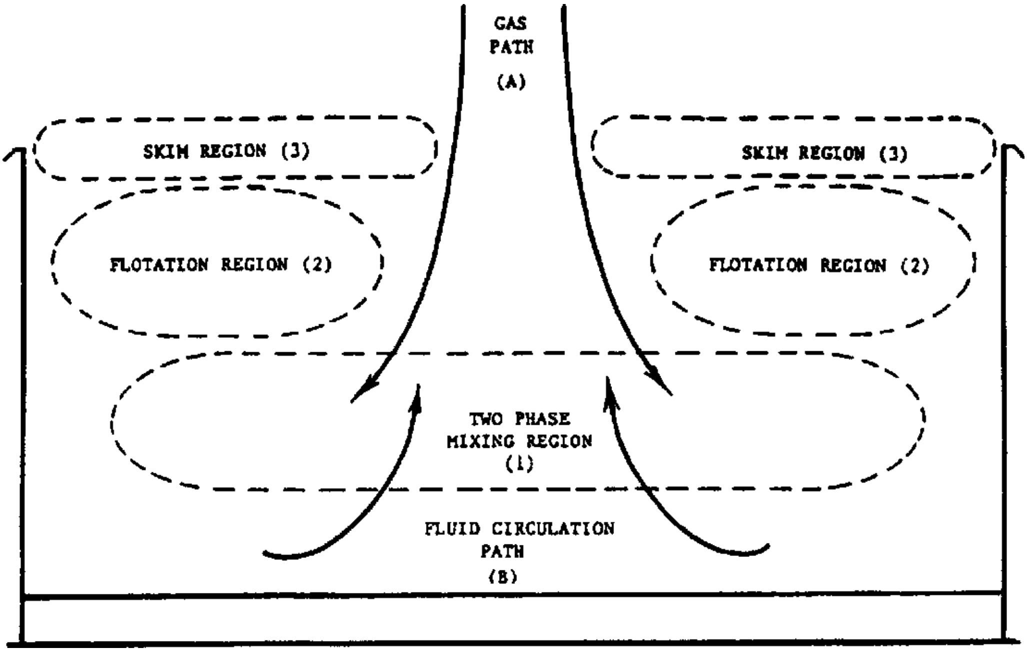

Fig. 1.16. Hydraulic characteristics of an IAF cell.

region ***(Region 1)***". In addition to the two phase mixing region, Degner (92) described two more zones:

> ***The flotation zone (Region 2).*** This region is generally above the mixing region through which the contaminant-laden gas bubbles can rise (as in froth) without excessive physical disturbance which could cause the contaminant to break away from the gas bubble and return to the original waste liquid stream.
>
> ***The skim zone (Region 3)***. In this zone one tries to provide a surface flow pattern that is sufficient to sweep the contaminant-laden froth, produced as a result of bubble collapse, continuously from the vessel, with minimum mechanical disturbance.

5.2. *Design*

The literature describing IAF systems, their design and operation is less prevalent than for DAF systems, due in part to IAF being a much more recent innovation. Churchill and Tacchi (89) have described the factors affecting flotation performance of both DAF and IAF systems (Table 1.16). For IAF systems, the key design variables are the rotor speed and submergence, eductor type, and liquid residence time. The commercial IAF units are shown in Figs. 1.17 and 1.18. Figure 1.17 depicts a single cell, while Fig. 1.18 combines four of the units shown in Fig. 1.17 into a multicell treatment system.

5.3. *Performance Data*

Puget et al.'s work (93) "aimed to study the performance of three different IAF units (flotation column, flotation tank and centrifugal flotation in a hydrocyclone) for the treatment of a synthetic dairy effluent. Under continuous operation, it was possible to achieve removal efficiencies of milky material in suspension up to 90%, both for the flotation column and the flotation tank units. Using the centrifugal flotation unit in a hydrocyclone, it was possible to decrease up to 45% of all suspended material in the effluent, with a clarified flow rate approximately three times greater than those found for the previous flotation units. In the centrifugal flotation unit, better results were obtained for air flow rate–feed flow rate ratios (Q_{air}/Q_L) greater than 0.15, and for underflow–overflow ratios (Q_u/Q_o) lower than 1.0."

Table 1.16
Factors affecting flotation performance

	DAF	IAF
Gas	Type Pressure Temperature Recycle (%)	Type Eductor Rotor speed Rotor submergence
Influent	Characteristic Concentration Fluctuation	Characteristic Concentration Fluctuation
Loading	Hydraulic Mass	Hydraulic Mass
Chemical conditioning	Type of additive concentration	Type of additive concentration

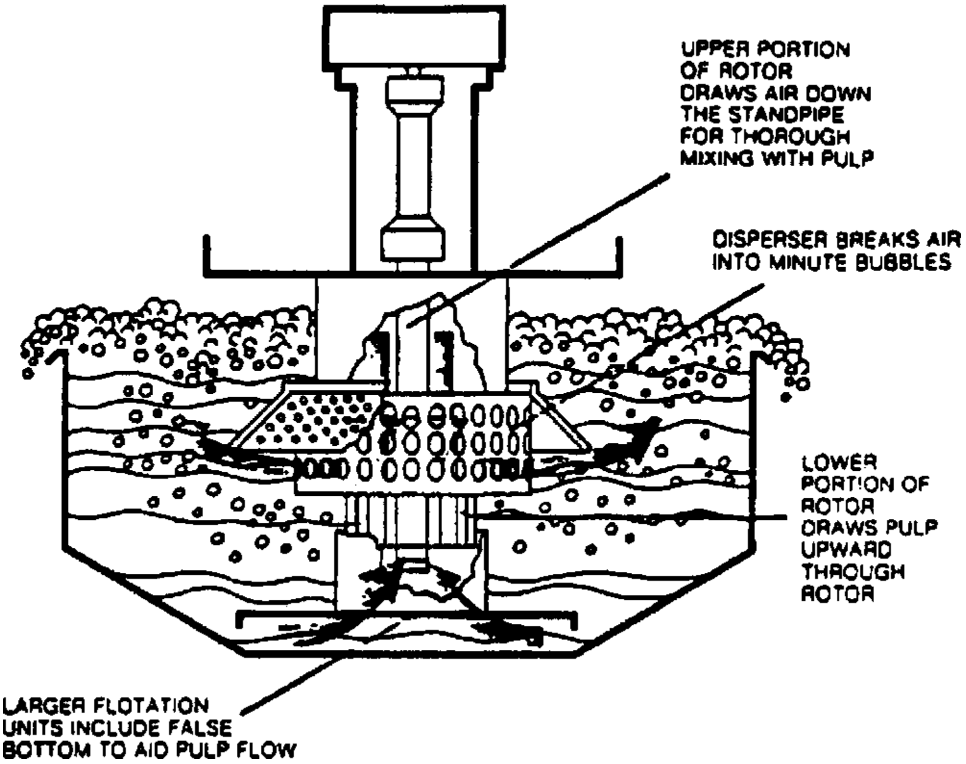

Fig. 1.17. WEMCO IAF cell.

6. NOZZLE AIR FLOTATION

6.1. Process Description

An innovation in the IAF field is the development of the nozzle air-injection unit for which patents were issued to Degner and Colbert (94). There are four unique aspects of their injection system:

1. The injection device uses an educator or an exhauster (Fig. 1.19) as a gas aspiration nozzle to draw air into recycled treated wastewater, truly developing a two-phase mixture of air and water that is subsequently discharged into the flotation vessel.
2. Successful operation of the systems depends on being in a flow regime in the curve (Fig. 1.20) in which effluent energy density (defined by the kinetic energy of the discharged liquid equals ½ mv^2/g) divided by the tank volume is plotted against the density of the effluent mixture (air plus water). In Region 1, one obtains excellent removals. When operating in this region, the liquid in the tank is filled with gas bubbles and the liquid surface is relatively quiet but frothy.
3. More than one cell used: conventionally four are employed, each with a residence time approximating 1 min; wastewater flows from cell to cell passing under a baffle that divides each compartment from another.

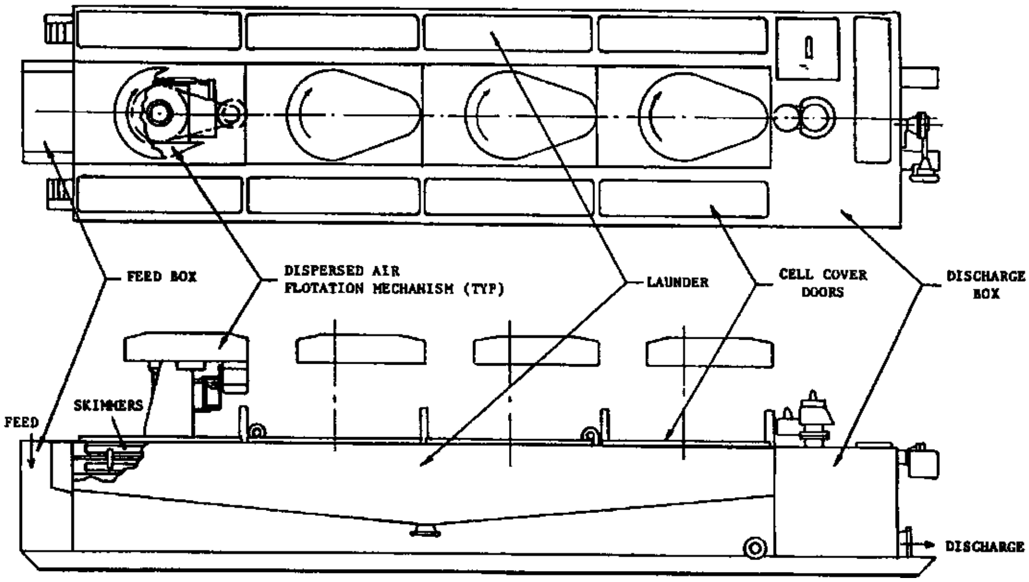

Fig. 1.18. Impeller-type IAF WEMCO system.

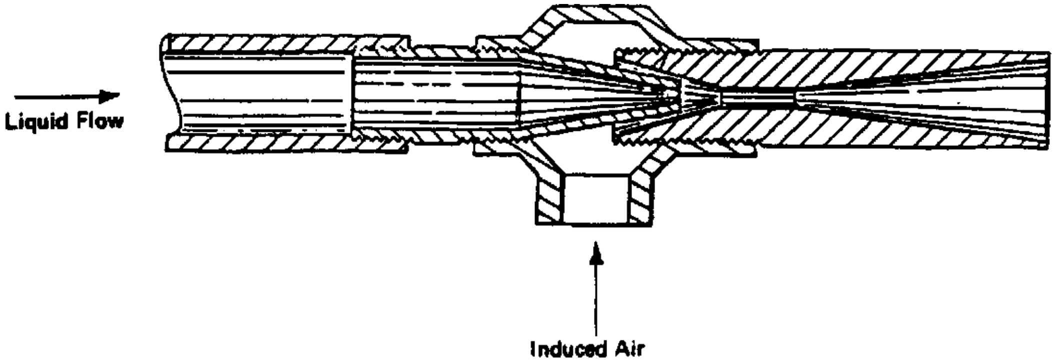

Fig. 1.19. Aspiration of air into a fluid at the throat of a contraction.

4. A back pressure of 0.5–1.0 oz maintains a gas blanket between the liquid level and the gas-tight cover that eliminates odors and would allow any off-gas to be treated in an air-pollution treatment device, thus reducing hydrocarbon emissions to the atmosphere.

6.2. Equipment Development

Based on the fundamental principles discussed in the previous section, WEMCO (an equipment manufacturer) has developed the system shown in Fig. 1.21. Shown here is a single-cell, NAF unit that is available in laboratory to plant-scale sizes (64).

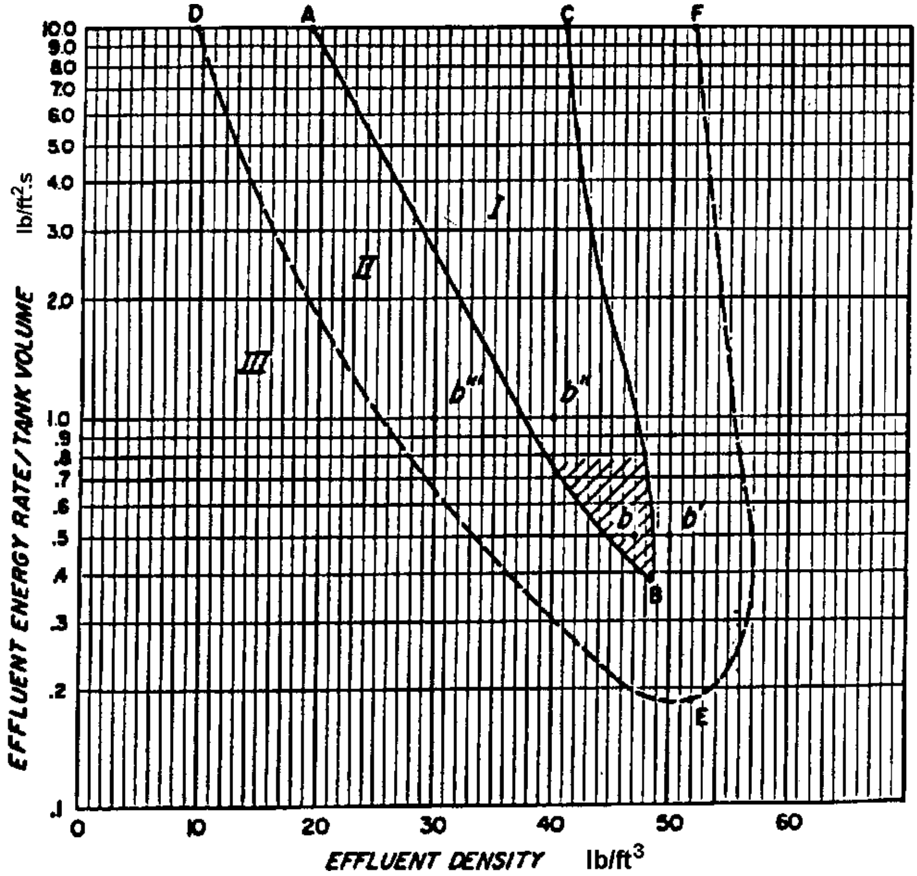

Fig. 1.20. Energy/density curves for nozzle air flotation defining the flow regime for optimum operation.

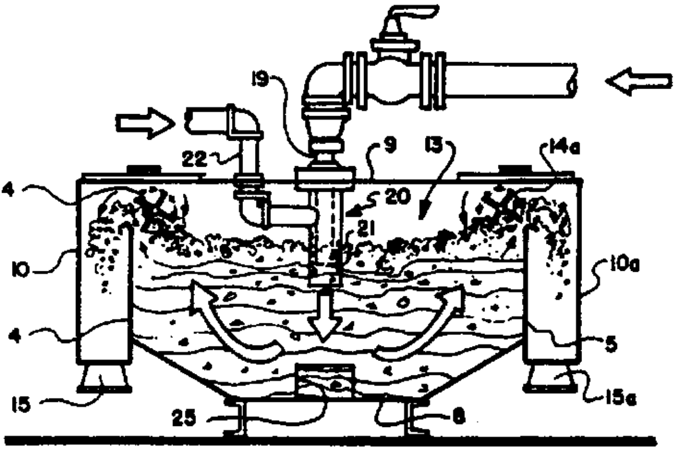

Fig. 1.21. Single-stage nozzle air flotation unit.

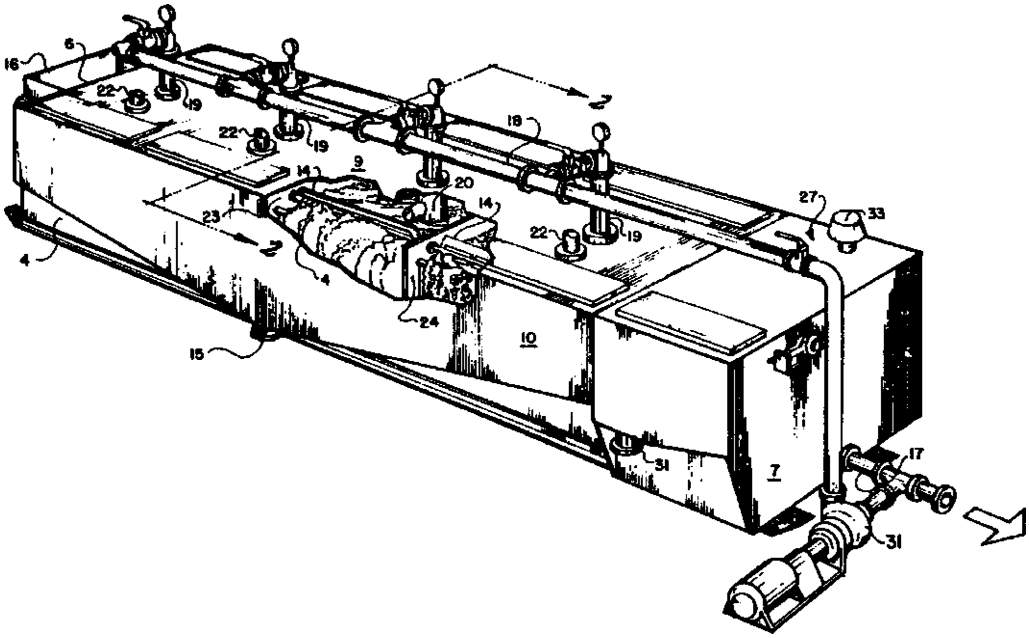

Fig. 1.22. Multistage nozzle air flotation system.

Four of these units have been put together in the plant-sized model in a multicellular design very similar to WEMCO's conventional rotor IAF system (Fig. 1.22). WEMCO, the manufacturer, claims several advantages of the nozzle unit over conventional IAF systems:

1. Lower power since a single pump provides mixing and air
2. Eliminating need for separate flocculating chemical, and external mixing chambers, as mixing is accomplished in the first flotation cell
3. Lower maintenance and longer life since there are no high-speed parts to wear out

6.3. *Performance Data*

Gotzy (95) reported on bench (batch)-scale treatment of aluminum-forming and refinery wastewaters; Steiner et al. (96) and Hobe (97) reported on pilot plant-scale tests on refining and tuna-cannery wastewater, respectively, while Cardile and Fronczak (98) provided data on an operating system. Davies and Vose (99) noted that Chevron prefers the IAF process and has a number of units in refinery service in North America, but provides no data.

Hobe (97) gives few experimental details other than the need for chemicals and a comparison of the degree of removal with and without chemicals. The removal using 25 mg/L of polymer averaged 85% based on 1,045 mg/L of oil and grease in the influent; without chemicals, the removal averaged 67%; the supernatant oil and grease averaged 25–30% FOG (fat, oil, and grease), 30–35% total solids, and 3–8% total protein.

Table 1.17
Performance of nozzle IAF in industrial wastewater treatment

Author	Wastewater	Chemicals	Flow (gal/min)	Influent (mg/L)	Effluent (mg/L)	Removal (%)
Cardile and Fronczak (101)	Railroad maintenance	Polyelectrolytes	2,150	450 116	7.0 7.6	98 O & G[a] 96 TSS
Steiner et al. (96)	Refinery	Polyelectrolytes (10 mg/L)	28	31	6	81 O & G
			(Pilot)	38	11	71 SS
Hobe (97)	Tuna cannery	Polyelectrolytes (25 mg/L)	(Pilot)	1,045	145	86 O & G
Gotzy (95)	Al-forming cast house cooling water	Variable	(Bench)	Improvement in percent transmittance noted		

[a] O & G, oil and grease.

NATCO (100) reported that its Tridair hydraulic induced gas flotation cell accomplished 90–98% removal of insoluble oil/organic and SS. Removal efficiency was influenced by physical characteristics of the incoming stream such as pH, total dissolved and SS, temperature, presence of chemicals, mixtures of different streams, and zeta potential. The nozzle/educator design ensured even dispersion of the finely divided air/gas bubbles throughout the liquid. By controlling the volume and rate of air/gas induced, the development of the proper bubble size for the efficient lifting of oil/organic and SS is achieved.

Table 1.17 summarizes the performance of NAF in the treatment of various industrial wastewaters.

6.4. *Multicell Units*

A test comparing a full-stream pressurization single-cell system to a multicell impeller induction system yielded an effluent oil concentration of 10–21 mg/L for the single cell vs. 2–10 mg/L for the multicell system, even though the latter system cost 60% as much as the former.

An innovation in equipment design was revealed by a sales brochure from Clow Corporation depicting a multicell DAF unit (Fig. 1.23). Unfortunately, no comparative operating data to a single-cell DAF unit were provided in this document.

6.5. *Theoretical Analysis*

In an investigation of the relative importance of the variables in an IAF system, Burkhardt (102) passed a sidestream from a batch IAF cell through a spectrophotometer and measured absorbance (due to oil concentration) as a function of time (Fig. 1.24). He concluded that the

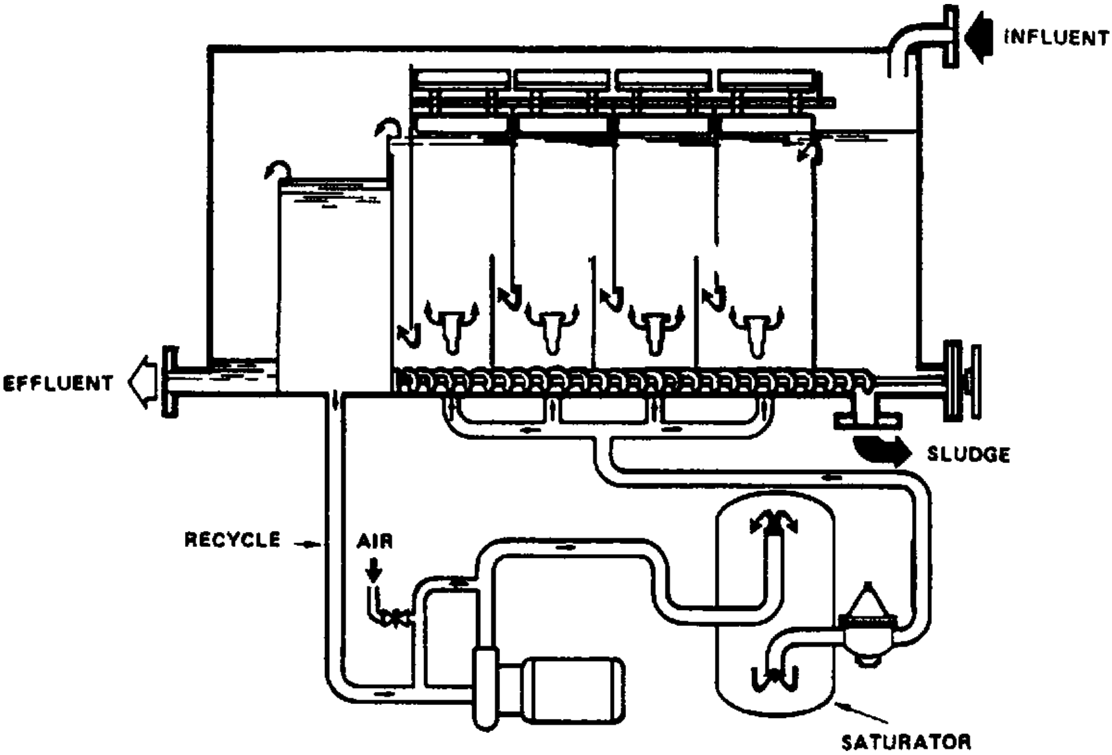

Fig. 1.23. Multicell DAF system.

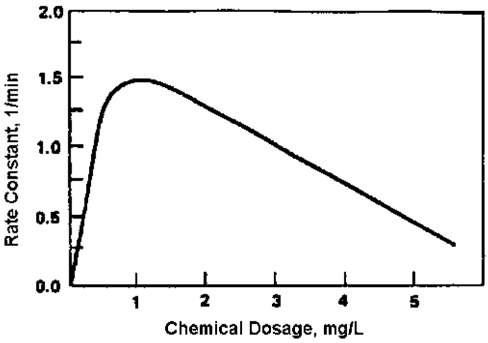

Fig. 1.24. Kinetic rate constant, k, as a function of chemical dosage for IAF treating refinery wastewater.

data could be fitted by a first-order type "chemical" process reaction equation, which is given as follows:

$$\frac{dC}{dt} = -KC, \tag{8}$$

where t is the elapsed time of treatment in the batch system, K is the rate constant, and C is the contaminant (oil) concentration.

Extension of the equation from a single-stage reaction to a four-step, sequential, equal volume multicell system operating in series yielded the following equation (89):

$$\frac{C_4}{C_o} = \left(\frac{1}{1+Kt}\right)^4, \tag{9}$$

where C_4 is the contaminant (oil) concentration leaving the final (fourth) cell, C_o is the influent contaminant concentration, K is the rate constant, and t is the total hydraulic residence time for the cell system.

An interesting practical use of this analysis technique would be to analyze the performance of IAF systems as a function of the amount of chemicals (flotation aids) added. In Fig. 1.24, the kinetic constant has been plotted against chemical dose. One notes that there is an optimum chemical dose beyond which the performance of the IAF system decreases. Other research (63, 64, 96, 103, 104) shows this effect consistently.

7. FLOTATION SYSTEM PERFORMANCE

It is difficult to compare the efficiency and operability of various air flotation systems because few studies have been made under comparable operating conditions. However, an attempt has been made to compare DAF and IAF systems, based on the degree or percent of removal of contaminants, and to examine the effect of design variables. This attempt is complicated by the following (80):

1. Lack of certain design in many reports
2. Variety in equipment utilized – both in scale and design
3. Variation in wastewater type and flow rate
4. Difference in design and operational parameters of the many systems
5. Lack of monitoring data in some reports
6. Variation in type and amount of chemicals added

Performance data can be found from the literature (2, 32, 51–58, 76–80, 86–88, 105–108). Results from several systems treating refinery wastewater, ballast water, paint-manufacturing effluent, tannery effluent, glass-plant effluent, chemical-plant wastewater, vehicle-maintenance wastewater, metal-bearing oily wastewater, and food-processing wastewater are reported in Chapter 3 of this book. Because of the numerous variables associated with the data/testing (especially the type and amount of chemical additives), it is essentially futile to try to construct correlations. However, recently, several models have been developed to describe the performance of air flotation systems (104, 115–119). Such modeling techniques should help researchers to be able to construct dependable correlations in the future.

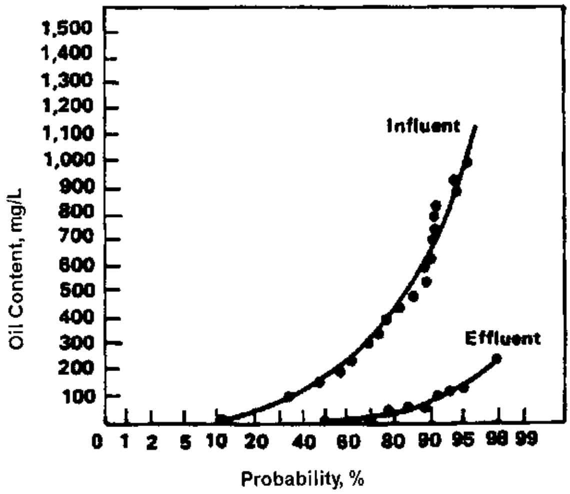

Fig. 1.25. Probability plot of influent and effluent oil concentration for IAF treatment of refinery wastewater.

Average effluent contaminant concentrations tell only part of the story. In real-world situations, there are major variations in flow, incoming concentration, pH, etc. Hence, typical performance data are often reported on probability plots as shown in Fig. 1.25 from Burkhardt's (102) paper.

8. COSTS

All data dealing with capital and/or operating cost are given as reported and have not been updated; the year of the cost analysis is given at the end of each discussion. To allow the reader to adjust the cost data to current prices, the U.S. Army Corps of Engineers Civil Works Construction Yearly Average Cost Index for Utilities is given in the Appendix of Chapter 3 (120).

8.1. Poultry-Process Waste

Woodward et al. (49) reported that a DAF plant to treat 1,200 gpm of poultry-processing waste was installed at a cost of approximately $75,000. Daily operating costs were $30 (power), $50 (labor), and $61 (chemicals) for a total of $141 not including fixed costs. The net operating cost was $0.07/1,000 gal (1977).

8.2. Tuna-Cannery Waste

Hobe (97) compared the cost of DAF vs. IAF (nozzle) treatment of tuna-canning wastewater (Table 1.18). In this analysis, the DAF system appeared to be a clear winner in cost (1978).

Table 1.18
Cost comparison of IAF and DAF treatment of Tuna-processing wastewater

	IAF		DAF
	Without chemicals	With chemicals	
Capital cost ($)	115,000	115,000	354,000
Operation cost ($/year)	14,600	29,200	52,800
Area requirements (ft^2)	750	750	3,000
Power requirements (hp)	30	30	50
Treatment efficiencies (%)			
BOD_5	41	50	37
SS	25	30	82
Oil and grease	67	90	92
Sludge yield (gal/d)	1,200	1,200	2,000

8.3. *Refinery Wastewater*

Thompson et al. (121) have compared several refinery oily wastewater-treatment systems. For a flow of 1,000 gpm, the 1972 capital cost for a flotation system was $330,000; the operating cost (including fixed costs) was $0.15/1,000 gal.

In a further refinement of the data, Thompson et al. (121) tabulated costs for the three basic air flotation systems: (1) rectangular DAF, (2) circular DAF, and (3) rectangular IAF. Their data concur with previous reports that cylindrical systems appear to be the most economical (and Thompson says require less steel in their construction and less space for installation, 1972).

8.4. *Comparative Costs*

One of the best comparative articles on costs was written by Biesinger et al. (53) He compared several different systems. Flow rates ranged from 100 to 300 gpm, but construction costs did not vary that widely ($40,000–$125,000); operational costs varied significantly, however, from $0.03 to $0.49/1,000 gal.

NOMENCLATURE

A/S = Air/solids plus oil, mg/mg
C = Concentration of gas or contaminant in solution, mg/L
C_o = Influent contaminant (oil) concentration, mg/L
C_4 = Contaminant (oil) concentration leaving the final (fourth) cell, mg/L
C_s = Gas (air) solubility at 1.0 atm pressure and operating temperature, mg/L
D = Effective diameter of the agglomerate, cm
f = System dissolving-efficiency factor
g = Gravitational acceleration constant, 980 cm/s^2

k = Henry's Law constant
K = Rate constant
K = Rate constant
p = Partial pressure of the gas, atm (psi)
P = Gauge pressure, atm (psig)
P_a = Absolute pressure, atm absolute (psi)
Q = Wastewater flow rate, L/min or gpm
Q_{air} = Air flow rate, L/min (gpm)
Q_L = Feed flow rate, L/min (gpm)
Q_u = Underflow rate, L/min (gpm)
Q_o = Overflow rate, L/min (gpm)
R = Pressurized liquid flow or recycle stream, L/d (gpm)
S = Gas released at atmospheric pressure, mg/L
S = Suspended solids (oil) in the pressurized liquid stream, mg/L
S_g = Gas saturation at atmospheric pressure, mg/L
S_o = Suspended solids (or oil) in wastewater, mg/L
t = Hydraulic residence time, min
V_T = Terminal rising velocity of the aggregate bubble plus floc, cm/s
X_f = Concentration of suspended solids plus oil in the feed, mg/L
μ = Viscosity of the aqueous phase, cp
ρ_a = Density of the agglomerate, g/cm^3
ρ_o = Density of the aqueous phase, g/cm^3
ρ_1 = Density of the continuous phase (water), g/cm^3

REFERENCES

1. ADEQ (1996) Pretreatment with oil/water separators. Arizona Department of Environmental Quality, Water Quality Division, Aquifer Protection Program, OFR 96–15, July
2. Wang LK, Fahey EM, Wu Z (2005) Dissolved air flotation. In: Wang LK, Hung YT, Shammas NK (eds.) Physicochemical treatment processes. Humana Press, Inc., Totowa, NJ, pp 431–500
3. Wang LK (2006) Adsorptive bubble separation and dispersed air flotation. In: Wang LK, Hung YT, Shammas NK (eds.) Advanced physicochemical treatment processes. Humana Press, Inc., Totowa, NJ, pp 81–122
4. Wang LK, Shammas NK, Selke WA, Aulenbach DB (2007) Flotation thickening. In: Wang LK, Shammas NK, Hung YT (eds.) Biosolids treatment processes. Humana Press, Totowa, NJ, pp 71–100
5. Alkhatib EA, Thiem LT (1991) Wastewater oil removal evaluated. Hydrocarbon Process 70:77–80
6. Melo MV, de Pereira OA, de Jesus RF, Duarte dos Santos LA (2006) Advances in non-conventional flotation for oily water treatment. J Filtration 6:1. Also available at: http://www.lboro.ac.uk/departments/cg/research/filtration/journal_papers_volume_6.htm, 2009
7. PEC (1999) Treatment and utilization of oil-containing produced-water in Oman. Petroleum Energy Center, Oman
8. Peters RW, Bennett GF (1989) The simultaneous removal of oil and heavy metals from industrial wastewaters using hydroxide or sulfide precipitation coupled with air flotation. Hazard Waste Hazard Mater 6(4):327–345

9. Shammas NK, Wang LK, Hahn HH (2010) Fundamentals of wastewater flotation, Chapter 4. In: Wang LK, Shammas NK, Selke WA, Aulenbach DB (eds.) Flotation technology. Humana Press, Totowa, NJ, pp 121–164
10. Wang LK (1985) Theory and applications of flotation processes, US Department of Commerce. National Technical Information Service, Springfield, VA. PB 86–194198/AS, 15p, Nov
11. Krofta M, Wang LK (2000) Flotation engineering, 1st edn. Technical Manual No. Lenox/1–06–2000/368. Lenox Institute of Water Technology, Lenox, MA
12. Shammas NK (1997) Physicochemically-enhanced pollutants separation in wastewater treatment. Proceedings of international conference: rehabilitation and development of civil engineering infrastructure systems – upgrading of water and wastewater treatment facilities, The American University of Beirut and University of Michigan, Beirut, Lebanon, 9–11 June 1997
13. Shammas NK (2010) Wastewater renovation by flotation, Chapter 9. In: Wang LK, Shammas NK, Selke WA, Aulenbach DB (eds.) Flotation technology. Humana Press, Totowa, NJ, pp 327–346
14. Shammas NK (2010) Flotation-filtration system for wastewater reuse, Chapter 10. In: Wang LK, Shammas NK, Selke WA, Aulenbach DB (eds.) Flotation technology. Humana Press, Totowa, NJ, pp 347–362
15. Krofta M, Wang LK (1999) Flotation and related adsorptive bubble separation processes, 4th edn. Technical Manual No. Lenox 7–25–1999/348. Lenox Institute of Water Technology, Lenox, MA
16. Ata S, Jameson GJ (2005) The formation of bubble clusters in flotation cells. Int J Miner Process 76:1–2
17. Gelinas S, Finch JA (2005) Colorimetric determination of common industrial frothers. Miner Eng 18:2
18. Yapijakis C, Wang LK (2004) Treatment of soap and detergent industry wastes. In: Wang LK, Hung YT, Lo HH, Yapijakis C (eds.) Handbook of industrial and hazardous wastes treatment. CRC Press/Marcel Dekker, New York, NY, pp 323–378
19. Wang LK, Shammas NK, Wu BC (2010) Electroflotation, Chapter 5. In: Wang LK, Shammas NK, Selke WA, Aulenbach DB (eds.) Flotation technology. Humana Press, Totowa, NJ, pp 165–198
20. McKay Creek Technologies Ltd (2003) New electrocoagulation process treats emulsified oily wastewater at Vancouver Shipyards. http://www.esemag.com/0103/electro.html, Jan
21. Chen G, Yue PL (2000) Electrocoagulation and electroflotation of restaurant wastewater. J Environ Eng 126(9):858–863
22. Ibrahim MY, Mostafa RR, Fahmy MFM, Hafez AI (2001) Utilization of electroflotation in remediation of oily wastewater. Sep Sci Technol 36:16
23. Rohlich GA (1954) Application of air flotation to refinery waste waters. Ind Eng Chem 46:304
24. Goel RK, Flora JR, Chen JP (2005) Flow equalization and neutralization. In: Wang LK, Hung YT, Shammas NK (eds.) Physicochemical treatment processes. Humana Press, Inc., Totowa, NJ
25. Paulson EG (1972) Water pollution control programs and systems. In: Lund HF (ed.) Industrial pollution control handbook. McGraw-Hill, New York, NY
26. Adams CE Jr, Stein RM, Joseph JJ, Walsh T (1975) Design and performance of physical-chemical and activated sludge treatment for an edible oil plant. Proceedings of Purdue industrial waste conference, vol 30. Purdue University, West Lafayette, IN, p 457

27. Sansalone Voon JE, Srinivasan V (2001) Management of invasive species transported in ballast water by dissolved air flotation. Proceedings of the second international conference on marine bioinvasions, New Orleans, La, 9–11 Apr 2001, pp 119–120
28. Volesky B, Agathos S (1974) Oil removal from refinery wastes by air flotation. Water Quality Res J. Can 9:328–339
29. Roberts KL, Weeter DW, Ball RO (1978) Dissolved air flotation performance. Proceedings of industrial waste conference, vol 33. Purdue University, West Lafayette, IN, p 194
30. Massaldi HA, Newman EJ, King CJ (1975) Maximum droplet growth when cooling a saturated solution. Chem Eng Sci 30:563
31. Bratby J, Marais GVR (1975) Saturator performance in dissolved air (pressure) flotation. Water Res 9:929–936
32. Franzen AE, Skogan VG, Grutsch JF (1972) Chem Eng Prog 68:65
33. Gardner NA (1972) Flotation techniques applied to the treatment of effluents. Effluent Water Treat J 12:82
34. Conway RA, Nelson RF, Young BP (1981) High-solubility gas flotation. Water Pollut Control Fed 53:1198
35. Ellis MM, Fischer PW (1973) Clarifying oil field and refinery waste waters by gas flotation. J Pet Technol 25 Apr, pp 426–430
36. Sport MC (1970) Design and operation of dissolved gas-flotation equipment and the treatment of oil field produced brine. J Pet Technol 22 Aug, pp 918–920
37. Travers SM, Lovett DA (1985) Pressure flotation of abattoir wastewaters using carbon dioxide. Water Res 19:1479
38. Sato Y, Murakami V, Hirose T, Yamamoto H, Uryu Y (1979) Removal of emulsified air particles by dissolved air flotation. J Chem Eng Jpn 12:454
39. Vrablik ER (1959) Fundamental principles of dissolved air flotation of industrial wastes. Proceedings of Purdue industrial waste conference, vol 14. Purdue University, West Lafayette, IN, p 743
40. Katz WJ (1960) Dissolved air flotation as applied to the treatment of oil production waste and refinery waste. API Drilling Prod Pract conference
41. Shannon WT, Buisson DH (1980) Dissolved air flotation in hot water. Water Res 14:759
42. Ramirez ER (1979) Comparative physicochemical study of industrial waste-water treatment by electrolytic dispersed air and dissolved air flotation technologies. Proceedings of Purdue industrial waste conference, vol 34. Purdue University, West Lafayette, IN, p 699
43. Degremont (1979) Water treatment handbook. John Wiley & Sons, New York, NY
44. Schmidt L, Morfopoulos V (1983) Bubble formation in the dissolved air flotation process, paper presented at AIChE Meeting. Houston, TX, May
45. Beychock MR (1967) Aqueous wastes from petroleum and petrochemical plants. John Wiley & Sons, New York, NY
46. Katz WJ, Geinopolos A (1967) Sludge thickening by dissolved air flotation. Water Pollut Control Fed 39:946
47. Eckenfelder WW Jr, O'Connor DJ Biological waste treatment. Pergamon Press, New York, NY
48. Woodward FE, Sproul OJ, Hall MW, Ghosh MM (1972) Abatement of pollution from a poultry processing plant. J Water Pollut Control Fed 44:1909
49. Woodward FE, Hall MW, Sproul OJ, Ghosh MM (1977) New concepts in treatment of poultry processing wastes. Water Res 11:873

50. Shammas NK, DeWitt N (1992) Flotation: a viable alternative to sedimentation in wastewater treatment plants. Water environment federation 65th annual conference, Proceedings of liquid treatment process symposium, New Orleans, LA, 20–24 Sept 1992, pp 223–232
51. Steiner JL (1977) A study of dissolved and induced air flotation to remove oil and suspended solids from petroleum refinery wastewater. MS thesis, University of Toledo, Toledo, OH
52. Eckenfelder WW Jr (1980) Principles of water quality management. CBI Publishing, Boston, MA
53. Biesinger MG, Vining TS, Shell GL (1974) Industrial experience with dissolved air flotation. Proceedings of Purdue industrial waste conference, vol 29. Purdue University, West Lafayette, IN, p 290
54. Reed SW, Woodward FF (1976) Dissolved air flotation of poultry processing waste. J Water Pollut Control Fed 48:107
55. Abo-El Ela SEA, Nawar SS (1980) Treatment of wastewater from an oil and soap factory via dissolved air flotation. Environ Int 4:47
56. Zimmerman MH, Jacquez RB (1981) Poultry waste pretreatment through dissolved air flotation coupled with lime-polymer conditioning. Proceedings of industrial waste conference, vol 35. Purdue University, West Lafayette, IN, p 586
57. McIntyre JP (1983) Dual systems best for dual wastes. Pollut Eng 46, Sept
58. Moursy AS, El-Ela SEA (1982) Treatment of oily refinery wastes using a dissolved air flotation process. Environ Int 7:267
59. Wood RF, Dick RI (1973) Factors influencing batch flotation tests. J Water Pollut Control Fed 45:304
60. Adams CE Jr, Ford DL, Eckenfelder WW (1981) Development of design and operational criteria for wastewater treatment. Enviro Press, Nashville, TN
61. AAPSE (1971) Sanitary engineering unit operations and unit processes laboratory manual. American Association of Professors of Sanitary Engineering
62. Berne F (1982) Physical-chemical methods of treatment for oil-containing effluents. Water Sci and Technol 14:1195
63. Ching LA (1981) A study of the simultaneous removal of heavy metals and oil and grease by dissolved air flotation. MS thesis, University of Toledo, Toledo, OH
64. Nipper RD (1978) A study of induced air flotation and removal of emulsified oil from a drum recycling plant wastewater. MS thesis, University of Toledo, Toledo, OH
65. Hillis MR (1970) Electrolytic treatment of effluents. Effluent Water Treat J 10:33
66. Backhurst JK, Mails KA (1981) Electrolytic flotation in effluent treatment. J Chem Tech Biotechnol 31:431–434
67. Matis KA (1980) Treatment of industrial liquid wastes by electroflotation. Water Pollut Control 19:136
68. Roth HP, Ferguson PV (1977) An integrated industrial waste water treatment using electroflotation and reverse osmosis. Desalination 23:49
69. Chambers DB, Cottrell WRT (1976) Flotation: two fresh ways to treat effluents. Chem Eng 83:95
70. Ramirez ER (1981) Physicochemical treatment of rendering wastewater by electrocoagulation. Proceedings of Purdue industrial waste conference, vol 36. Purdue University, West Lafayette, IN, p 437
71. Oblinger FG, Weintraub MH, Gealer RL, Blais EJ (1984) In-plant operation of electrolytic cell for oily wastewater treatment. Environ Prog 3:1
72. Oblinger FG, Weintraub MH, Blais EJ, Gealer RL (1986) Automation of the electrolytic cell for the treatment of oily wastewater. Environ Prog 5:283

73. Weintraub MH, Dzieciuch MA, Gealer RL (1980) US Patent 4,194,972, 25 Mar 1980, Method for Breaking an oil-in-water emulsion
74. Weintraub MH, Gealer RL, Golovoy A, Dzieciuch MA (1983) Development of electrolytic treatment of oily wastewater. Environ Prog 2:32
75. Krofta M, Wang LK (1984) Development of innovative flotation-filtration systems for water treatment, part C: an electroflotation plant for single families and institutions. Proceedings of American water works association, Water reuse symposium II, vol 3. San Diego, CA, pp 1251–1264
76. Shammas NK, Wang LK, Gould J, Pollock D (2009) Vertical shaft bioreactors. In: Wang LK, Shammas NK, Hung YT (eds.) Advanced biological treatment processes. Humana Press, Totowa, NJ, pp 59–108
77. Wang LK, Mahoney WJ (1994) Treatment of storm run-off by oil water separation, flotation, filtration and adsorption. Water Treat 9:223–233
78. Wang LK, Wang MHS, Mahoney WJ (1990) Treatment of storm run-off by oil water separation, flotation, filtration and adsorption, Part B: waste sludge management. Proceedings of Purdue industrial waste conference, vol 44. Purdue University, West Lafayette, IN, pp 667–673
79. Cheremisinoff PN (1993) Oil/water separation. Natl Environ J 3:32–36
80. Bennett GF (1988) The removal of oil from wastewater by air flotation: a review. Crit Rev Environ Control 18:189–253
81. Ettelt GA (1977) Control of flotation separator equipment including integrating with chemical pretreatment processes. Prog Water Technol 9:363
82. De Renzo DJ (ed) (1981) Pollution control technology for industrial wastewaters. Noyes Data Corp., Park Ridge, NJ
83. Hart JA (1970) On improving wastewater quality. Water Sew Works 117, JW 20–26, Sept/Oct
84. Pearson SC (1976) Factors influencing oil removal efficiency in dissolved air flotation units. Proceedings of 4th annual industrial pollution conference, WWEMA, Philadelphia, PA
85. API (1969) Manual on disposal of refinery wastes. American Petroleum Institute, New York, NY
86. Quigley RF, Hoffman EL (1966) Flotation of oily waste. Proceedings of Purdue industrial waste conference, vol 21. Purdue University, West Lafayette, IN, p 527
87. Hart JA (1970) Air flotation treatment and reuse of refinery waste water. Proceedings of Purdue industrial waste conference, vol 25. Purdue University, West Lafayette, IN, p 406
88. Barker JE, Foltz VW, Thompson RJ (1971) Treatment of waste oil: wastewater mixture. In: Cecil LK (ed.) Water – 1970, AIChE symposium series, AIChE, vol 67. New York, NY, p 107
89. Churchill RJ, Tacchi KJ (1978) A critical analysis of flotation performance. In: Bennett GF (ed.) Water – 1977. AIChE symposium series, AIChE, New York, NY, p 74
90. Bassett MG (1971) WEMCO depurator system, Paper SPE 3349, presented at the SPE Rocky Mountain Regional Meeting. Billings, MT, June
91. Degner VR, Winter MK (1979) Recent advances in wastewater treatment using induced-air flotation. In: Bennett GF (ed.) Water – 1978, AIChE symposium series, vol 75. New York, NY, p 190
92. Degner VR (1976) Dispersed air flotation cell design and operation. In: Bennett GF (ed.) Water – 1975, AIChE symposium series, vol 71. New York, NY, p 151
93. Puget FP, Melo MV, Massarani G (2004) Comparative study of flotation techniques for the treatment of liquid effluents. Environ Tech 25(1):79–67

94. Degner VR, Colbert WV (1978) Dispersed gas flotation process. US Patent 4,110,210, 29 Aug 1978; Degner VR, Colbert WV (1980) Dispersed air flotation machine. US Patent, 4,226,706, 7 Aug 1980
95. Gotzy E (undated) Evaluation of chemicals and their cleaning ability on oil and suspended solids in cast house cooling water using induced-air flotation. National-Southwire Aluminum Co., Hawesville, KY
96. Steiner JL, Bennett GF, Mohler EF, Clere LT (1978) Air flotation of refinery waste water. Chem Eng Prog 74:39
97. Hobe D (1978) Tuna cannery waste treatment, Pacific Northwest Pollution Control Assoc., 1978. Annual conference, Victoria, BC, Oct
98. Cardile RP, Fronczak R (1981) Resolution of an industry's oil waste problem. Proceedings of Purdue industrial waste conference, vol 36. Purdue University, West Lafayette, IN, p 395
99. David BT, Vose RW (1977) Custom designs cut effluent treating costs: case histories at Chevron, U.S.A. Inc. Proceedings of Purdue industrial waste conference, vol 32. Purdue University, West Lafayette, IN, p 1035
100. NATCO (2008) Tridair Hydraulic Induced Gas Flotation System, NATCO Group. http://www.natcogroup.com/TRIDAIR%20HYDRAULIC%20Induced%20Gas%20Flotation%20System.htm
101. Cardile RP, Fronczak R (1982) Railroad shops control an oily waste problem. Ind Wastes (Chicago), 20, Jan/Feb
102. Burkhardt CW (1983) Control pollution by air flotation. Hydrocarbon Process 62, May, p 59
103. Daukss P (1980) Metal ion removal by precipitating flotation, unpublished report. University of Toledo, Toledo, OH
104. Ciribeni ODV, Gutierrez LV (2005) Froth collapse in column flotation: a prevention method using froth density estimation and fuzzy expert systems. Miner Eng 18:5
105. Boyd JL, Shell GL, Dahlstrom DA (1972) Treatment of oily wastewaters to meet regulatory standards. In: Cecil LK (ed.) Water – 1971, AIChE symposium series, vol 68. New York, NY, p 124
106. Smith W, Robe K (1976) Heavy-emulsion oil waste reduced from 2,000 to 10 ppm. Chem Proc 22, Nov
107. Finkler ML, Olds SD, Applegate CS (1976) Pilot plant testing develops treatment for petroleum refinery. Proceedings of Purdue industrial waste conference, vol 31. Purdue University, West Lafayette, IN, p 26
108. Kirkup WM (1977) Refinery oil/water separation equipment and its applications. Filtr Sep 14(3):259–265, May/June
109. Boyd JL, Shell GL (1972) Dissolved air flotation application to industrial wastewater treatment. Proceedings of Purdue industrial waste conference, vol 27. Purdue University, West Lafayette, IN, p 705
110. Envirex (1982) Dissolved air flotation, product brochure. U.S. Filter/Envirex, Waukesha, WI
111. Arnoldi HW, Corning DP, Sykes RL (1980) The application of flotation techniques to the treatment of tannery waste waters. J Soc Leather Technol Chem 64:69
112. Katnik KE, Pavilcius AM (1979) A simplified approval and purifying oily wastewater. Plant Eng 33, 18 Oct
113. Lynes PF (1980) Evaluation of induced air flotation for railyard wastewater. Proceedings of 8th annual WWEMA conference

114. Kreye WC, Oliver JW, Sutton HC, Voreh FR (1978) Treatment of zinc plating and oil bearing wastewater. Proceedings of Purdue industrial waste conference, vol 33. Purdue University, West Lafayette, IN, p 155
115. Murakami ES, Robe K (1975) Before: sewage changes $55,660/yr, now: $4,340, Food Process 36, p 80
116. Rigas F, Panteleos P, Laoudis C (2000) Chemical composite design in a refinery's wastewater treatment by air flotation. Global Nest Int J 2(3):245–253
117. Liers S, Baeyens J, Mochtar I (1996) Modeling dissolved air flotation. Water Environ Res 68:1061–1075
118. Beckley CT, Eades AA (2001) A multiphase CFD model of DAF process. Water Sci Tech 43(8):145–152
119. Leppinen DM (2000) A kinetic model of dissolved air flotation including the effects of interparticle forces. J Water Supply: Res Technol – Aqua 49(5):258–259
120. U.S. ACE (2009) Civil works construction cost index system manual. 110–2–1304, Yearly Average Cost Index for Utilities, US Army Corps of Engineers, Tables, Washington, DC, p 44. PDF file is available on the Internet at http://www.nww.usace.army.mil/cost
121. Thompson CS, Stock J, Mehta PL (1972) Cost and operating factors for treatment of oily waste water. Oil Gas J 70:53

2
Gas Dissolution, Release, and Bubble Formation in Flotation Systems

Lawrence K. Wang, Nazih K. Shammas, William A. Selke,
and Donald B. Aulenbach

CONTENTS

Abstract The theories and principles of gas dissolution, release, and bubble formation in gas flotation systems are introduced in detail for process design, optimization, and operation. Also introduced is a new instrument for real-time measurement of bubble content and size distribution in a typical flotation system consisting of gas bubbles (gas phase) and bulk water (liquid phase). Specific engineering topics included in this chapter are: gas dispersion principles, gas dispersion tester, bubble tester operation, gas dispersion example, gas transfer principles, Henry's Law constants, partial pressures, solubilities of various gases, gas dissolution and release, gas bubble formation and size distribution, bubble attachment, bubble rising and flotation, gas dissolution in water containing high dissolved solids or high salinity, and engineering design examples.

Key Words Adsorptive bubble separation processes • dissolved gas flotation • dispersed gas flotation • air flotation • gas dissolution • bubble formation • flotation systems • process design • gas dispersion tester • gas solubility • dissolved oxygen concentration • DO.

1. INTRODUCTION

Bubble dynamics is of great importance in optimizing the engineering design and operating parameters of various adsorptive bubble system operations, such as dissolved air flotation and dispersed air flotation, for the separation of solids from a liquid.

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The purpose of this chapter is to present a new instrument for real-time measurement of bubble content and size distribution in a typical bubble flow reactor where air bubbles and bulk water are the gas phase and liquid phase, respectively. This chapter introduces the operation of a newly developed air dispersion tester (or bubble generation tester), its theory, principles, operational procedures, analysis, typical examples, and design applications for air flotation systems.

2. BUBBLE SEPARATION PROCESSES

Adsorptive bubble separation processes are used to concentrate or separate materials that may be molecular, colloidal, or macroparticulate in size. The material is selectively adsorbed at the surfaces of bubbles rising through the liquid, and the efficiency of the separation process depends partly on differences in surface activity and, importantly, also on the number and size of the gas bubbles.

Adsorptive bubble separation processes (such as dissolved air flotation and dispersed air flotation) have many significant industrial applications including liquid industrial effluent treatment, water purification, activated sludge thickening, oil–water separation, cellulose fiber concentration, etc. (1–14). A 37.5 MGD flotation–filtration plant (14) and a 1.1 MGD flotation–filtration plant (3, 4) have been operating in Pittsfield, Massachusetts and Lenox, Massachusetts, respectively, for potable water production. A dissolved air flotation clarifier is operating for secondary clarification at an 18-MGD activated sludge plant in Texas (11). Here 1 MGD = one million gallons per day = 3.785 MLD = 3.785 million liters per day. Theoretical explorations and investigations of bubble dynamics and air dispersion mechanisms have become increasingly important to engineers in the design of such flotation systems.

The air pressure for generation of the air bubbles is the major parameter controlling air solubility in an air flotation unit and is an important factor in flotation operation. The total volume and size of air bubbles produced on depressurization is proportional to the pressure of the process stream, the rate of flow, and the pressure reducing mechanism. Large air bubbles produce a fast, turbulent rise rate resulting in reduced air–solids contact time and bubble surface area. More efficient solids removal is obtained with smaller air bubbles because of increased contact time and total bubble surface area.

An adequate air pressure generation system for optimum results in an adsorptive bubble separation process involving the use of dissolved air is needed to satisfy the requirements of air volumetric flow rate, bubble rising velocity, and power consumption. Usually, the amount of dissolved air is about 0.5–3.0% of the water volume. This amount should be adjustable and measurable. The optimum rising velocity of the air bubbles is about 12 in/min (30.5 cm/min) and should not be below 5 in/min (12.5 cm/min), nor over 20 in/min (50 cm/min). The air dispersion system must allow adjustment of the bubble rising velocity, and the proportion of the different rising velocities of the dispersed air bubbles. Power consumption is an important economic factor. For a dissolved air flotation system operated at full flow pressurization mode, the power consumption should be less than 13 Hp/m^3/min (50 Hp/1,000 gpm). For DAF systems operated at partial flow pressurization mode, the power consumption should be less than 7 Hp/m^3/min (27 Hp/1,000 gpm). Here 1 Hp = 1 horsepower = 746 watts = 0.746 kW. All the aforementioned parameters need to be optimized for a specific system. Additional references on various adsorptive bubble separation processes can be found from the literature elsewhere (15, 16).

3. GAS BUBBLE DISPERSION

3.1. Gas Dispersion Tester

A quick method for determining percent air, bubble size, and volume distribution would be useful for evaluating and improving the efficiency of air dissolving, power consumption, and bubble formation in an air flotation unit. An air dispersion tester (see Figs. 2.1 and 2.2) has

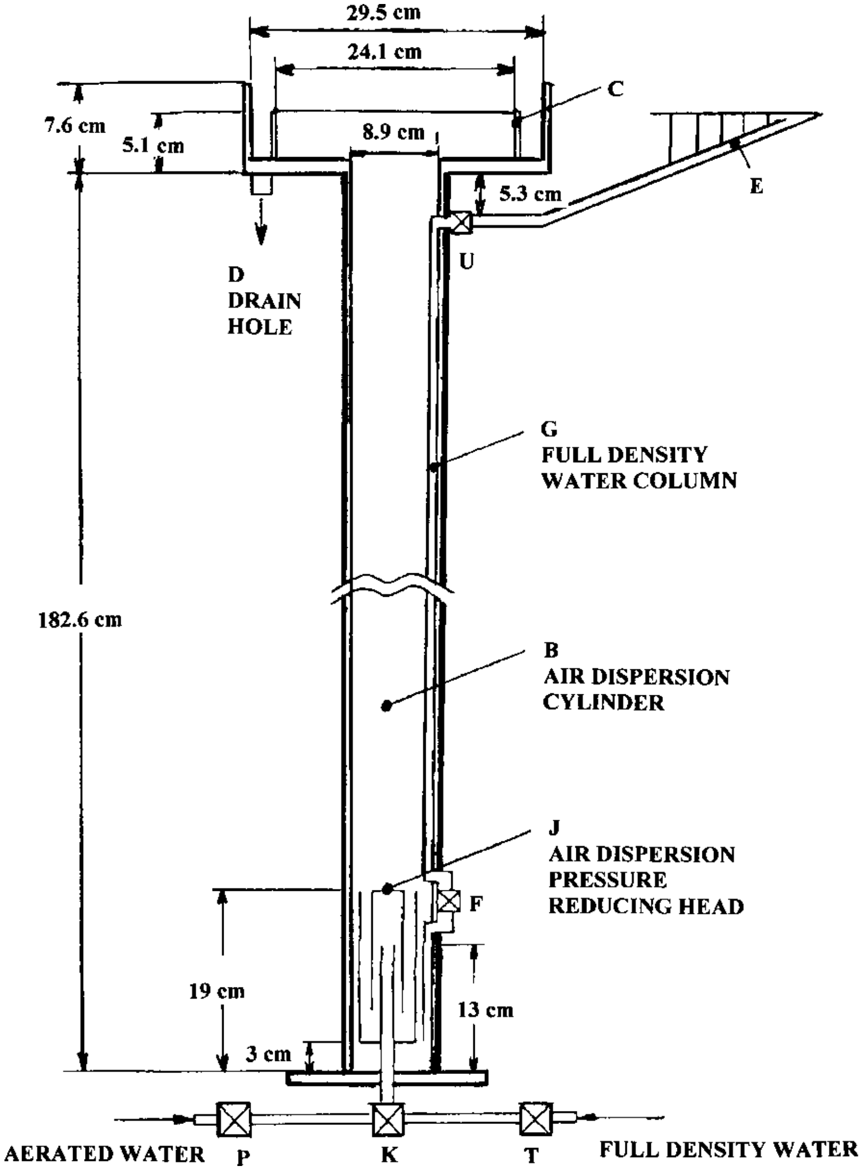


Fig. 2.1. Air dispersion tester.

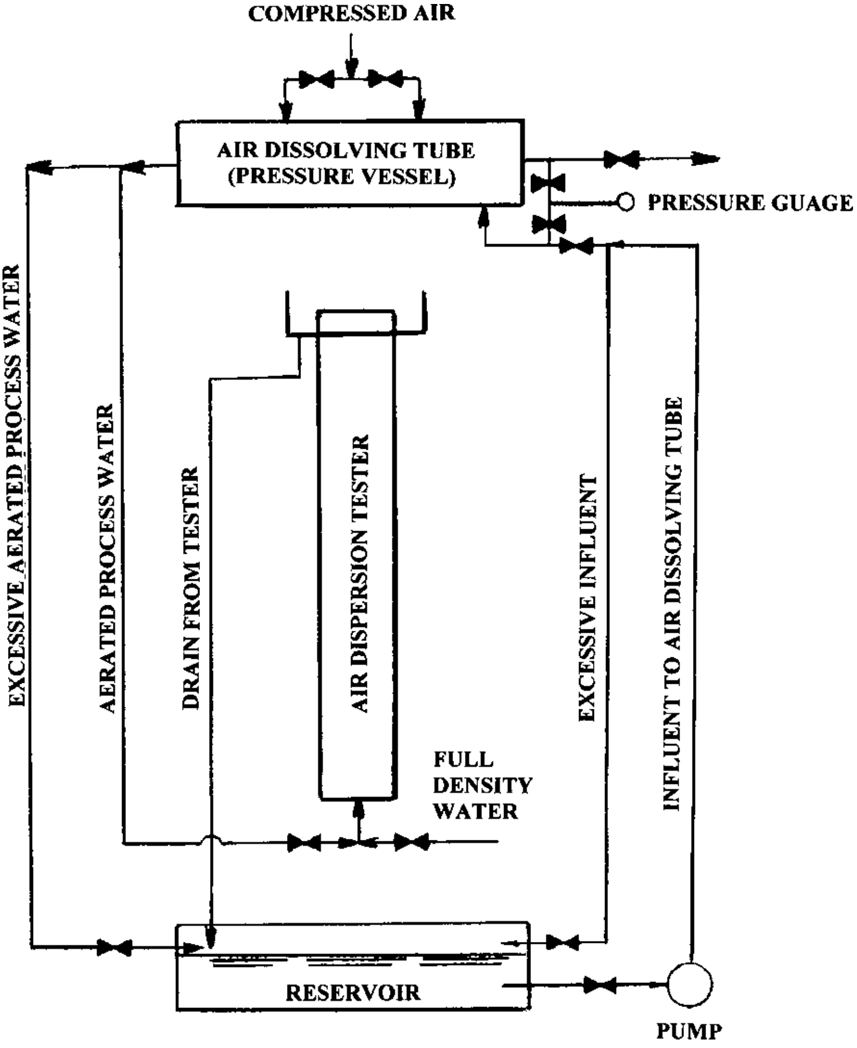
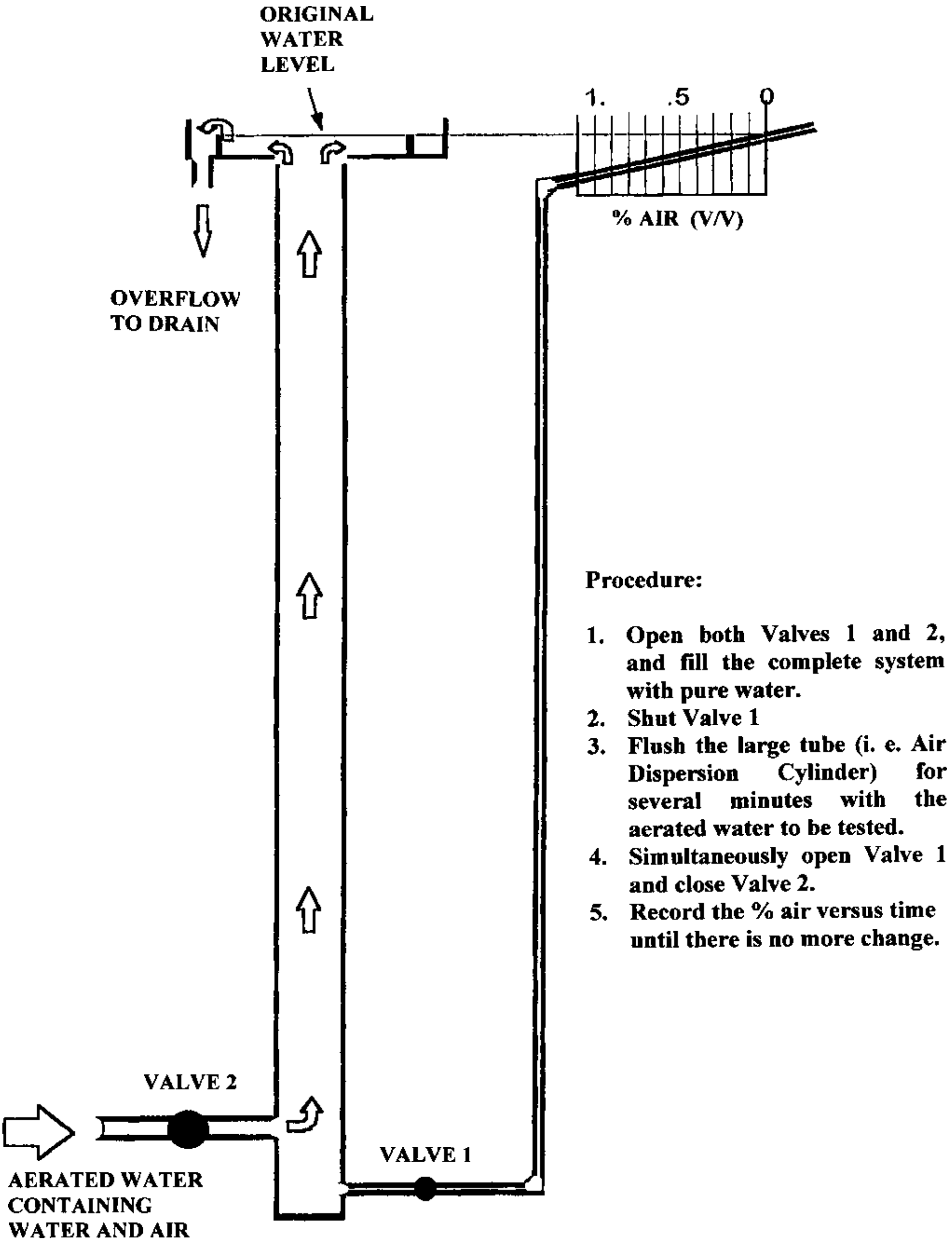


Fig. 2.2. Experimental system setup.

been developed to measure the percent air content in an air flotation process stream. A narrow Plexiglas cylinder is attached to a larger diameter Plexiglas air dispersion cylinder, and both are open to atmospheric pressure at the top. An overflow is provided with a drain to allow continuous feed through the tester. Separate inlet valves for water at atmospheric pressure and pressurized process flow are mounted at the bottom of the instrument. A small untreated water column is a few centimeters above the bottom plate and rises vertically to the bottom of the large, outside Plexiglas air dispersion cylinder. The untreated water column is then extended with a transparent plastic tube around the perimeter of the large cylinder stopping at the top level of the tester. The transparent plastic tube is calibrated in percent air volumes, and the slope of the tube is determined by the percent change in height. The difference in level



Procedure:

1. **Open both Valves 1 and 2, and fill the complete system with pure water.**
2. **Shut Valve 1**
3. **Flush the large tube (i. e. Air Dispersion Cylinder) for several minutes with the aerated water to be tested.**
4. **Simultaneously open Valve 1 and close Valve 2.**
5. **Record the % air versus time until there is no more change.**

Fig. 2.3. Experimental procedure.

in the transparent tube expressed in percent of the total height of the tester is equal to the percent air content. Extending the tube on a horizontal incline over 7.6 cm in height facilitates in establishing a precise graduation for percent air readings.

Supersaturated process water from the air flotation unit enters through a pressure reducing valve into the main air dispersion cylinder for a period of a few minutes. The flow is stopped and the gate valves separating the aerated process water and untreated are opened (see Fig. 2.3). This causes the level in the small transparent tube to drop in proportion to the percent air content of the process water in the air dispersion cylinder. Calibrated readings are recorded at 30–120 s time intervals and graphically plotted vs. time. The curve can be approximated with a number of straight lines, each corresponding to fine, medium, or coarse bubble diameters and their respective rising velocities.

3.2. *Gas Dispersion Principles*

Discrete particle flotation in a bubble separation process unit under laminar flow conditions is given by Stoke's law: Stoke's law can be used to calculate the bubble rise rate, or the falling rate of a spherical object in a fluid, such as water. Such an object reaches a terminal velocity when the gravitational force, buoyancy, and the viscous drag reach a net equilibrium. For a gas bubble with essentially no mass, the terminal velocity is reached when the buoyancy force equals the drag force.

$$(3.14)(D^3)(d_\mathrm{W} - d_\mathrm{B})\,g = 18(3.14)vDV_\mathrm{T}, \tag{1a}$$

$$V_\mathrm{T} = g(d_\mathrm{W} - d_\mathrm{B})\,D^2/(18v), \tag{1b}$$

where D is the diameter of a spherical gas bubble, m; V_T is the terminal velocity of a spherical bubble diameter D, m/s; d_W is the density of water, kg/m^3; d_B is the density of gas bubble, kg/m^3; v is the water viscosity, Pa s; and g is the gravitational acceleration = 9.8 m/s^2.

The Reynolds number must be less than 1.0 for Stoke's law to apply. The spherical particle can be a bubble or an air–solid–oil floc having a specific gravity of less than 1, thus causing a negative terminal velocity, or a rising velocity. The bubble size is affected by the pressure in the bubble formation, viscosity, and surface tension of the fluid.

Free air is defined as air under the conditions prevailing at the air pump or air blower inlet. Standard air is defined in air blower work as air at a temperature of 68°F (20°C), a pressure of 14.7 psig (101.3 kPa), and a relative humidity of 36%. Standard air has a specific weight of 0.0750 lb/ft^3 (1.20 g/L). The specific weight of air varies at sea level from 0.0776 lb/ft^3 (1.24 g/L) at 50°F (10°C) to 0.0724 lb/ft^3 (1.16 g/L) at 86°F (30°C). One standard atmosphere pressure = 10.333 m of water = 33.899 ft of water = 14.696 lb/in^2 = 101.325 kPa = 101.325 kN/m^2 = 1.013 bar.

3.3. *Gas Dispersion Tester Operation*

The installation of the newly developed air dispersion tester (or bubble generation tester) is described in Figs. 2.1 and 2.2. Figures 2.4 and 2.5 illustrate two different types of tester operations, types 1 and 2 consecutively.

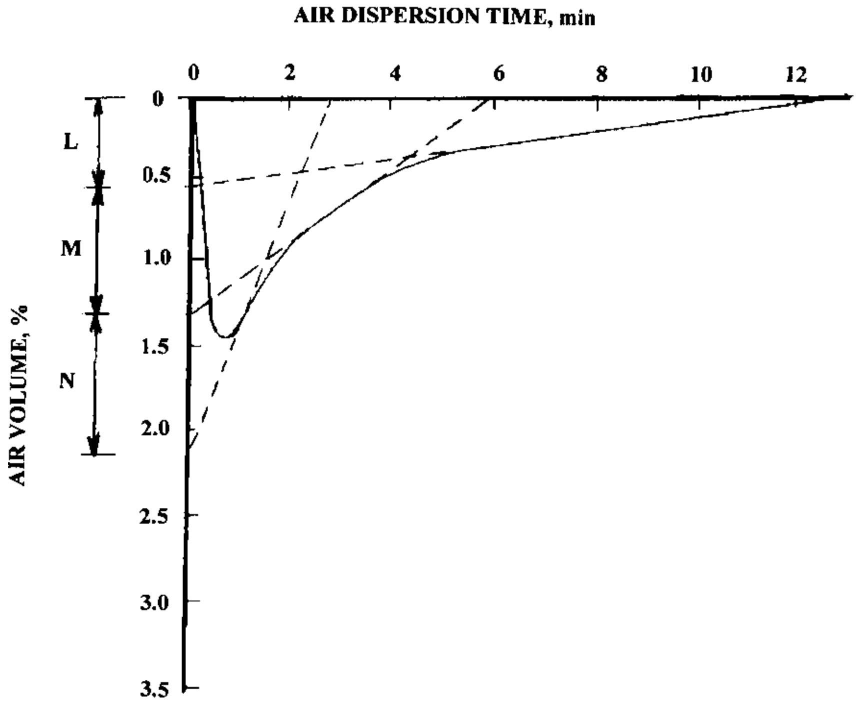


Fig. 2.4. Type I air dispersion test.

3.3.1. Type I Test

The air dispersion tester is initially filled with tap water or process water with valve P closed and valves T, F, and U open. After the tester is full, valves T and F are closed and valve P is opened for continuous and uniform feed of aerated process water. The aerated process stream is introduced through inlet valve P and is allowed to flow until it has filled the vertical air dispersion cylinder B and the larger open cylinder at the top C (exposed to atmospheric pressure) and has overflowed through drain D. The pipe connection between valve P and the inlet into the tester should be as short as possible. After a period of 2–5 min, valve P is closed and valve F is opened, timing is begun and the percent air level in the transparent tube E is measured in adequate time intervals. At this time, the water in tube E and column G (at least 80% smaller in diameter than cylinder B) is allowed to enter the main air dispersion cylinder B. The water from tube E replaces a portion of the aerated process stream in cylinder B in direct proportion to its greater density. The drop in level of water in tube E is determined by calibration markings on the tube and converted by a calibration curve (Fig. 2.1) to percent air in the aerated process stream. The change in density with time can be charted as shown in Fig. 2.4 for this testing (Type I Test). Tangents to the curve shown in Fig. 2.4 are denoted L, M, and N. Their intersection with the upper abscissa gives the average time, in min, for a bubble to rise through the height of cylinders B and C. The intersection of L tangent with the ordinate indicates the percent air in water for the L size bubbles. When the

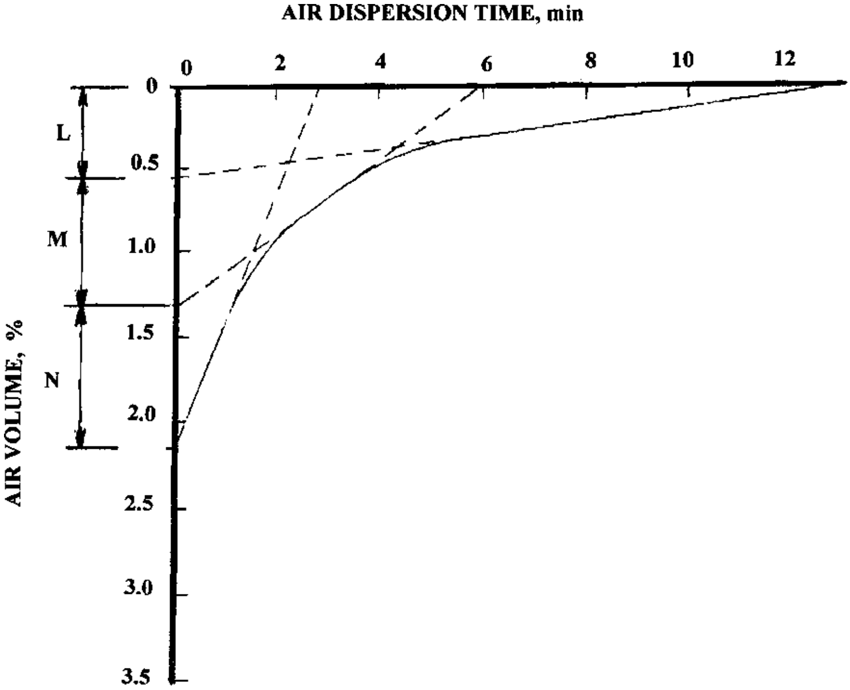


Fig. 2.5. Type II air dispersion test.

value is subtracted from the intersection point of the M tangent, the percent air in water is determined for the M size bubbles, etc. Thus the total volume of generated air for each size of bubbles may be determined.

3.3.2. Type II Test

The air dispersion tester is initially filled with tap water or process water with valve P closed and valves T, F, and U open. After the tester is full, valve T is closed and valve P is opened for continuous and uniform feed of aerated process water. After over 5 min and when a steady-state condition is reached, valve P is closed, timing is begun, and percent air vs. time is recorded. Figure 2.5 is explained in a typical example.

Application of Stokes law to the available data enables the bubble size distribution to be assessed. This can be accomplished automatically by interposing a pressure transducer to sense the pressure differential between column G and cylinder B. The transducer generates an electronic signal outputted to an appropriately programmed computer so that real-time bubble size distribution data can be displayed.

Tests should be carried out with water or wastewater with known characteristics. Results and conclusions should be reported of investigations that have been undertaken with the bubble generation instrument (air dispersion tester) to determine the effect on bubble size distribution under various operating conditions: air compressor pressure, dissolving tube pressure, pump pressure, rotameter levels, air flow rate, bubble rise rate, water and air temperatures, surface tension and viscosity of water (bubble formation conditions), chemical addition (if any), and presence of various particulates (if any).

The tester should be carefully examined and all its dimensions (diameters, heights, tube volume, overflow volume, etc.) measured. A flow diagram illustrating the air dissolving tube and the air dispersion tester is presented in Fig. 2.2.

In actual operation, the bleed-off valve should be checked. The time of air input into the tester and the rise rate of air–water interface should be recorded.

The data to be presented for discussion should include, but not be limited to: the percent total air content, percent of air bubbles in the water, air bubbles rise rates, and bubble sizes.

3.4. Gas Dispersion Example

3.4.1. Construction and Testing of an Air Dispersion Tester

A vertical transparent plastic air dispersion cylinder B, 8.9 cm ID, 182.6 cm long is closed at the base by a 1.59 cm thick plastic base (see Fig. 2.1). An inlet tube rises from the base to 13 cm above the interior base where there is an air dispersion head. This inlet may either admit fresh tap water (or process water) from valve T or water with dissolved and entrained air to be tested from valve P. There is an additional base valve K with two positions that determine this source selection. When the pipe that normally supplies untreated water is opened to the drain, the water in the cylinder may be drawn down to the level of the input tube, which rises through the base to approximately 13 cm above the base. Figures 2.1 and 2.2 show the entire system for air dispersion testing.

A copper tube called the raw water column G is inside the 8.9 cm ID air dispersion cylinder (for the sake of heat transfer). The top of the copper tube G which is 5.3 cm below the overflow drain hole is extended to a sloping transparent high-resolution volumetric level indicator, as shown in Fig. 2.1. The volumetric level indicator is made of transparent plastic tubing (74.3 cm effective length) and is calibrated for determination of "percent air in water." Zero to 5% air volume is uniformly scaled on a 73.7 cm horizontal line. The slope of the transparent plastic tubing E is 7.6 cm/73.7 cm equal to 0.103. There is a valve U at the point where the copper tube exits the air dispersion cylinder B to fill the high-resolution volumetric level indicator.

At the top of the air dispersion cylinder there is a 24.1 cm diameter overflow dish 5.1 cm deep. This overflow dish is made level. The volumetric indicator shown in Fig. 2.1 is a board with the high-resolution sloping tube for the untreated water. A supplemental volumetric indicator is the periphery of the 29.5 cm ID dish that receives the overflow.

The air dispersion cylinder B that contains the water samples for testing is mounted vertically with valves P and T positioned to permit a short path of direct transfer of water sample to the cylinder. The air dispersion cylinder B is sufficiently long and large in diameter, in order to slow the flow rate of the sample transfer, increase the resolution with the larger sample volume, permit an internal graduated mark to be used for measuring the rising velocity of bubbles, and allow the stages of changing bubble velocity to be observed for a wide range of bubble sizes.

Table 2.1
Experimental conditions for Type II test

Measurement	Value
Air dissolving tube effluent flow to reservoir, L/min	19
Air dissolving tube effluent flow to tester, L/min	12
Air dissolving tube total flow, L/min	31
Air flow, std (Meter A), L/min	0.2
Air flow, std (Meter B), L/min	0.2
Air pressure, psig	80
Air dissolving tube water pressure, psig	60*
Air dissolving tube diameter, cm	11.4
Air dissolving tube length, cm	88.9
Wastewater source	Gray water
Wastewater temperature, °C	24

*60 psig = 413.7 kPa.

Table 2.2
Air dispersion data for Type II test

Time, min	Air volume, %
0	2.10
0.25	1.95
0.50	1.80
1.00	1.50
1.50	1.15
2.00	0.90
4.00	0.50
6.00	0.34
8.00	0.25
10.00	0.15
12.00	0.05
12.50	0

3.4.2. *Experimental Results*

As an example, the Type II Test was conducted for an aerated wastewater whose experimental conditions are shown in Table 2.1. The air dispersion data for the Type II Test were recoded as shown in Table 2.2.

The air dispersion data are plotted in Fig. 2.5 and the calculations are shown below:

Fine bubbles (L):

Fine air bubbles in water = 0.55%
Fine bubbles in all bubbles = 25.6%
Fine bubbles rising velocity = 14.4 cm/min

Medium bubbles (M):

Medium air bubbles in water = 0.8%
Medium bubbles in all bubbles = 37.2%
Medium bubbles rising velocity = 42.7 cm/min

Coarse bubbles (N):

Coarse air bubbles in water = 0.8%
Coarse bubbles in all bubbles = 37.2%
Coarse bubbles rising velocity = 125 cm/min

Total bubbles:

All air bubbles in water = 2.15%
Sum of all bubbles = 100%

The air bubbles rising velocities were estimated by the following equation:

$$V_{\mathrm{T}} = D_{\mathrm{e}}/t, \tag{2}$$

where V_{T} is the bubbles vertical rising velocity, cm/min; D_{e} is the effective depth of air dispersion cylinder, cm; and t is the bubbles traveling time to water surface, min.

The aforementioned bubbles rising velocities were calculated as follows:

Fine bubbles rising velocity = 187.7/13 = 14.4 cm/min
Medium bubbles rising velocity = 187.7/4.4 = 42.7 cm/min
Coarse bubbles rising velocity = 187.7/1.5 = 125 cm/min

This is an example of too much air (2.15% of air bubbles in water) and too coarse air dispersion (37.2% of air bubbles are coarse bubbles).

Knowing the water temperature, bubble terminal rising velocity, kinematic viscosity (from Table 2.3), specific gravity of air bubbles (from Table 2.4), and gravitational acceleration coefficient, one can then calculate the average diameter of spherical air bubbles using Eq. (1a). Application of Eq. (1a) for determination of the rise rate of a gas bubble is presented in Sect. 4.

4. GAS TRANSFER, DISSOLUTION, RELEASE, AND FLOTATION

4.1. Gas Transfer Principles

When a gas is in contact with the surface of a liquid, the amount of the gas that will go into solution is proportional to the partial pressure of that gas. A simple rationale for Henry's law is that if the partial pressure of a gas is twice as high, then on the average twice as many molecules will hit the liquid surface in a given time interval, and on the average twice as many will be captured and go into solution. For a gas mixture, Henry's law helps to predict the amount of each gas that will go into solution. However, different gases have different solubilities and this also affects the rate. The constant of proportionality in Henry's law must take this into account (17–25).

Table 2.3
Viscosity and specific weight of water

Temperature, °F	Specific wt, lb/ft^3	Absolute viscosity[a,c], lb-s/ft^2	Kinematic viscosity[b,c], ft^2/s
32	62.42	3.746	1.931
40	62.43	3.229	1.664
50	62.41	2.735	1.410
60	62.37	2.359	1.217
70	62.30	2.050	1.059
80	62.22	1.799	0.930
90	62.11	1.595	0.826
100	62.00	1.424	0.739
130	61.55	1.069	0.558

[a] To convert to centipoise, divide by 2.088×10^{-5}. 1 centipoise = 10^{-2} g/cm-s.
[b] To convert to centistokes, divide by 1.075×10^{-5}. 1 centistoke = 10^{-2} cm^2/s.
[c] Values, $\times 10^{-5}$.

Table 2.4
Typical values for the specific weight of ambient air at relative humidity of 36%

Elevation (ft)	Pressure (psi)	Temperature		
		10°C	20°C Specific weight of air	30°C
0	14.7	0.0776	0.0750	0.0724
1,000	14.2	0.0750	0.0724	0.0701
2,000	13.7	0.0722	0.0697	0.0674
4,000	12.7	0.0670	0.0648	0.0625

All specific weights are in lb/ft^3 (1 g/cm^3 = 62.43 lb/ft^3). 1 ft = 0.3048 m. 1 psi = 6.895 kPa.

Table 2.5 gives the Henry's law constants for sparingly soluble gases, such as air, carbon dioxide, carbon monoxide, hydrogen, hydrogen sulfide, methane, nitrogen, and oxygen (23). The values in Table 2.5 should be multiplied by 10^4 to obtain atm/mol fraction.

The partial pressure of gases at sea-level (i.e., 1.0 atm total pressure, or 0.0 m elevation above mean sea level) is given in Table 2.6. Specifically, Table 2.6 presents the partial pressures of the gases in air (nitrogen, oxygen, argon, carbon dioxide, methane, and carbon monoxide) in a natural atmosphere under 1 atm total pressure and dry air conditions. The same table also shows the percent volume of various gas components in dry air. For instance, the percent volumes of nitrogen, oxygen, argon, and carbon dioxide gases in dry air are 78.9%, 20.95%, 0.93%, and 0.032%, respectively.

When aquatic environmental systems are open to the atmosphere, there are two ways for gas transfer: (a) gases from the atmosphere are free to dissolve into the aqueous phase; and (b) gases from the aqueous phase are free to escape into the atmosphere. Equilibrium is defined as

Table 2.5
Henry's law constants for sparingly soluble gases

T(°C)	Air	CO_2	CO	H_2	H_2S	CH_4	N_2	O_2
0	4.32	0.073	3.52	5.79	0.0268	2.24	5.29	2.55
10	5.49	0.104	4.42	6.36	0.0367	2.97	6.68	3.27
20	6.64	0.142	5.36	6.83	0.0483	3.76	8.04	4.01
30	7.71	0.186	6.20	7.29	0.0609	4.49	9.24	4.75
40	8.70	0.233	6.96	7.51	0.0745	5.20	10.4	5.35
50	9.46	0.283	7.61	8.65	0.0884	5.77	11.3	5.88
60	10.1	0.341	8.21	7.65	0.1030	6.26	12.0	6.29

Multiply values in the table by 10^4 to obtain atm/mol fraction.

Table 2.6
Partial pressure of gases in a natural atmosphere (23)

Gas	$p_{i,h}$
N_2	0.7809
O_2	0.2095
Ar	0.0093
CO_2	0.00032
CH_4	0.0000015
CO	0.0000001

1 atm total pressure and dry air conditions.

the conditions when the number of gas molecules that enter the aqueous phase is equal to the number escaping into the gas phase. Equilibrium conditions represent the maximum (i.e., saturation) concentration of a dissolved gas in solution (26, 27).

4.2. *Henry's Law Constants, Partial Pressures, and Solubilities of Various Gases*

Gas solubility in fresh water depends mainly on: (a) temperature; (b) type of gas; and (c) partial pressure of the gas. In addition to the above three parameters, the gas solubility in saline water also depends upon the salinity.

One may use Henry's law to compute dissolved gas mole fraction of any gas, X_i, at equilibrium conditions:

$$X_i = P_{i,h}/H_i, \qquad (3)$$

where X_i is the dissolved gas mole fraction of any gas; $P_{i,h}$ is the partial pressure of the gas, i, at an elevation h ($h = 1.0$ if elevation $= 1000$ m); i is a gas; h is an elevation; and H_i is the Henry's law constant for the particular gas, i.

Since barometric pressure decreases with elevation, or lower atmospheric pressure, the partial pressure of gases in Table 2.6 must be corrected for elevation or any atmospheric pressure. The following equation is used to correct the partial pressures in Table 2.6 to take into account elevation effects.

$$P_{\mathrm{i},h} = P_{\mathrm{i},0}\mathrm{e}^{-0.121h}, \tag{4}$$

where H is the elevation above sea level in thousands of meters and $P_{\mathrm{i},0}$ is the partial pressure of the gas, i, at sea level where h is 0 m. e value is 2.71828.

The concentration of dissolved gas (mole/L) can be calculated using the following approximation:

$$C_{\mathrm{i}} = X_{\mathrm{i}}C_{\mathrm{water}}, \tag{5a}$$

where C_{i} is the concentration of dissolved gas, mole/L; X_{i} is the dissolved gas mole fraction of any gas; and C_{water} is the molar concentration of water.

$$C_{\mathrm{water}} = (1{,}000\ \mathrm{g/L})/(18\ \mathrm{g/M}) = 55.56\ \mathrm{M/L}. \tag{5b}$$

The following example shows how the saturation concentration of dissolved oxygen in Las Cruces, New Mexico (elevation = 1,160 m; temperature = 30°C) can be calculated.

According to Table 2.6, the partial pressure of oxygen at sea level is 0.2095 atm. At the elevation of 1,160 m ($h = 1.160$), the atmospheric pressure decreases to 87% of sea level conditions.

$$\begin{aligned} P_{\mathrm{oxygen},1.1} &= P_{\mathrm{i},0}\mathrm{e}^{-0.121h} \\ &= 0.2095\,\mathrm{e}^{-0.121(1.160)} \\ &= 0.2095(0.87) \\ &= 0.182\ \mathrm{atm.} \end{aligned} \tag{4}$$

Using Henry's constant corresponding to oxygen at 30°C, from Table 2.5 one obtains the mol fraction of oxygen in water using Eq. (3):

$$X_{\mathrm{i}} = P_{\mathrm{i},h}/H_{\mathrm{i}}, \tag{3}$$

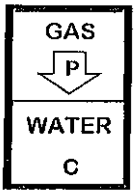
$$\begin{aligned} X_i = X_{\mathrm{oxygen}} &= P_{\mathrm{oxygen},1.1}/(4.75 \times 10^4\ \mathrm{atm/mole\ fraction}) \\ &= 0.182\ \mathrm{atm}/(4.75 \times 10^4\ \mathrm{atm/mole\ fraction}) \\ &= 3.83 \times 10^{-6}\ \mathrm{mole\ fraction.} \end{aligned}$$

The molar concentration of dissolved oxygen at saturation can then be calculated:

$$C_{\mathrm{i}} = X_{\mathrm{i}}C_{\mathrm{water}}, \tag{5}$$

$$\begin{aligned} C_{\mathrm{oxygen}} &= (3.83 \times 10^{-6}\ \mathrm{mole\ fraction})(55.56\ \mathrm{M/L}) \\ &= 2.13 \times 10^{-4}\ \mathrm{M/L} \\ &= (2.13 \times 10^{-4}\ \mathrm{M/L})(32{,}000\ \mathrm{mg/M}) \\ &= 6.8\ \mathrm{mg/L.} \end{aligned}$$

Table 2.7
Solubilities of air, oxygen, nitrogen, hydrogen, and carbon dioxide in water at 1 atm and various temperatures (22).



P = Pressure of the the gas

Note: 1 atm = 1.01 Bar = 14.7 psi

C = Concentration of the gas in a saturated solution

Solubilities of gas in water at 1 atm*

Temp °C	Air	Oxygen	Nitrogen	Hydrogen	CO_2
4	2.63	4.40	2.14	0.206	14.7
20	1.87	3.10	1.54	0.182	8.78
50	1.30	2.09	1.09	0.161	4.36

*% v/v = % gas volume/water volume = solubilities of gas in water at 1 atm.

4.3. *Gas Dissolution and Release*

Table 2.7 presents the solubilities (% v/v = % gas volume/water volume) of some common gases, (air, oxygen, nitrogen, hydrogen, and carbon dioxide) under normal atmospheric pressure ($P = 1$ atm = 1.01 Bar = 14.7 psi) at various water temperatures (4–50°C). Table 2.7 also shows how a gas can be pressurized and dissolved in water. P is the pressure of a gas over the water, and C is the concentration of the gas in a saturated solution (22).

At constant temperature the solubility of a gas in a liquid is directly proportional to the pressure of the gas above the solution, as shown in the small diagram in Table 2.7.

$$C_1 = f \times P_1, \tag{6}$$

$$C_2 = f \times P_2, \tag{7}$$

$$f = C_2/P_2 = C_1/P_1, \tag{8}$$

$$C_2 = C_1(P_2)/P_1, \tag{9}$$

where C_1 is the solubility of a gas in water (% v/v) under pressure P_1 (atm), C_2 is the solubility of a gas in water (% v/v) under pressure P_2 (atm), P_1 is the normal atmospheric pressure = 1 atm (which may be corrected by elevation), P_2 is the pressure of a gas above the water, atm, and F is a constant.

The percent volume of gas bubbles released due to pressure change can be calculated by the following equation:

$$V_{\mathrm{br}} = C_2 - C_1, \tag{10}$$

where V_{br} is the percent volume of gas bubble released from a previously pressurized water, %.

It should be noted that Table 2.7 presents the technical data for air and pure gases, such as oxygen, nitrogen, hydrogen, and carbon dioxide. When evaluating an environmental system, we are neither dealing with pure oxygen nor with pure nitrogen gases. Oxygen and nitrogen and others are the gas components of air. Actual concentration of a gas component, $C_{\text{gas-a}}$, which is only a fraction of the gas solubility shown in Table 2.7, can be calculated by Eqs. (11a) to (11d).

$$C_{\text{gas-a}} = P_{\mathrm{i},h} \times C_{\text{gas}}, \tag{11a}$$

$$C_{\text{oxygen-a}} = 0.2095 \times C_{\text{oxygen}}, \tag{11b}$$

$$C_{\text{nitrogen-a}} = 0.7809 \times C_{\text{nitrogen}}, \tag{11c}$$

$$C_{\text{carbondioxide-a}} = 0.00032 \times C_{\text{carbondioxide}}, \tag{11d}$$

where $C_{\text{gas-a}}$ is the actual concentration or solubility of a gas component in water, % v/v (% gas volume/water volume); C_{gas} is the concentration or solubility of a pure gas in water, % v/v (% gas volume/water volume = mL gas/100 mL water); $C_{\text{oxygen-a}}$ is the actual concentration or solubility of oxygen component in water, % v/v (% oxygen volume/water volume); C_{oxygen} is the concentration or solubility of pure oxygen in water, % v/v (% oxygen volume/water volume); $C_{\text{nitrogen-a}}$ is the actual concentration or solubility of nitrogen component in water, % v/v (% nitrogen volume/water volume); C_{nitrogen} is the concentration or solubility of pure nitrogen in water, % v/v (% nitrogen volume/water volume); $C_{\text{carbondioxide-a}}$ is the actual concentration or solubility of carbon dioxide component in water, % v/v (% carbon dioxide volume/water volume); $C_{\text{carbondioxide}}$ is the concentration or solubility of pure carbon dioxide in water, % v/v (% carbon dioxide volume/water volume); and $P_{\mathrm{i},h}$ is the partial pressure of the gas, i, at an elevation h.

Actual percentage of a gas component in water can be calculated by Eq. (12a):

$$\mathrm{PCT}_{\text{gas}} = (100)(C_{\text{gas-a}})/(C_{\text{air}}), \tag{12a}$$

$$\mathrm{PCT}_{\text{oxygen}} = (100)(C_{\text{oxygen-a}})/(C_{\text{air}}), \tag{12b}$$

$$\mathrm{PCT}_{\text{nitrogen}} = (100)(C_{\text{nitrogen-a}})/(C_{\text{air}}), \tag{12c}$$

where $\mathrm{PCT}_{\text{gas}}$ is the actual percentage of a gas component, %; $\mathrm{PCT}_{\text{oxygen}}$ is the actual percentage of oxygen component, %; $\mathrm{PCT}_{\text{nitrogen}}$ is the actual percentage of nitrogen component, %; $C_{\text{gas-a}}$ is the actual concentration or solubility of a gas component in water, % v/v (% gas volume/water volume); $C_{\text{oxygen-a}}$ is the actual concentration or solubility of oxygen component in water, % v/v (% oxygen volume/water volume); $C_{\text{nitrogen-a}}$ is the actual concentration or solubility of nitrogen component in water, % v/v (% nitrogen volume/water volume); and C_{air} is the concentration or solubility of air in water, % v/v (% air volume/water volume).

The following are examples on engineering calculations for gas pressurization, dissolution, and bubble release (22).

4.3.1. Example 1

What is the solubility of air in water at 4°C and 5 atm pressure?

Solution

Select $C_1 = 2.63\%$ v/v for air from Table 2.7, and adopt Eq. (9).

$$C_2 = C_1(P_2)/P_1, \tag{9}$$

$$C_2 = (2.63\%\ \mathrm{v/v})(5\ \mathrm{atm})/(1\ \mathrm{atm}) = 13.15\%\ \mathrm{v/v}.$$

Therefore, the solubility of air in water at 4°C and 5 atm pressure is equal to 13.15 mL of air per 100 mL of water.

4.3.2. Example 2

The pressure of air is approximately 0.21 atm oxygen and 0.79 atm nitrogen. What is the concentration of oxygen and nitrogen in water at 4°C with 1 atm of air above it?

Solution

Select both $C_{\text{oxygen}} = 4.40$ and $C_{\text{nitrogen}} = 2.14$ from Table 2.7, and adopt Eqs. (11b), (11c), (12b), and (12c) for calculations:

$$\begin{aligned} C_{\text{oxygen-a}} &= 0.2095 \times C_{\text{oxygen}} \\ &= 0.2095 \times 4.40 = 0.924\%\ \mathrm{v/v}, \end{aligned} \tag{11b}$$

$$\begin{aligned} C_{\text{nitrogen-a}} &= 0.7809 \times C_{\text{nitrogen}} \\ &= 0.7809 \times 2.14 = 1.69\%\ \mathrm{v/v}, \end{aligned} \tag{11c}$$

$$\begin{aligned} \mathrm{PCT}_{\text{oxygen}} &= (100)(C_{\text{oxygen-a}})/(C_{\text{air}}) \\ &= (100)(0.924)/(2.63) \\ &= 35.13\%\ \text{oxygen}. \end{aligned} \tag{12b}$$

It is important to note that the air above this solution contains only 21% oxygen.

$$\begin{aligned} \mathrm{PCT}_{\text{nitrogen}} &= (100)(C_{\text{nitrogen-a}})/(C_{\text{air}}) \\ &= (100)(1.69)/(2.63) \\ &= 64.28\%\ \text{nitrogen}. \end{aligned} \tag{12c}$$

4.3.3. Example 3

Air is dissolved in water at 20°C and 80 psi. What will be the % volume of air bubbles released when the pressure is reduced to 14.7 psi? What will be the % volume of air bubbles released?

Solution

$$(80\ \mathrm{psi})(1\ \mathrm{atm}/14.7\ \mathrm{psi}) = 5.4\ \mathrm{atm}.$$

Table 2.8
Concentration of air dissolved in water (22)

Temp °C	Pressure of air above the water in atmospheres							
	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
	Concentration of air dissolved in water in mg/L							
0	37.27	74.55	111.82	149.09	186.37	223.64	260.92	298.19
5	33.00	65.99	98.99	131.99	164.98	197.98	230.97	263.97
10	29.33	58.66	87.99	117.32	146.65	175.98	205.31	234.64
15	26.53	53.06	79.58	106.11	132.64	159.17	185.69	212.22
20	24.25	48.50	72.75	97.00	121.25	145.50	169.75	194.00
25	22.36	44.73	67.09	89.46	111.82	134.19	156.55	178.91
30	20.88	41.77	62.65	83.54	104.42	125.31	146.19	167.08
40	18.51	37.02	55.53	74.03	92.54	111.05	129.56	148.07
50	17.02	34.04	51.06	68.09	85.11	102.13	119.15	136.17
60	15.94	31.89	47.83	63.77	79.71	95.66	111.60	127.54
80	15.05	30.10	45.15	60.20	75.24	90.29	105.34	120.39
100	15.05	30.10	45.15	60.20	75.24	90.29	105.34	120.39

All concentrations are in mg/L. 1 atm = 101.325 kPa = 101.325 kN/m^2 = 1.013 bar.

Select $C_1 = 1.87\%$ v/v for air from Table 2.7, and adopt Eq. (9):

$$\begin{aligned} C_2 &= C_1(P_2)/P_1 \\ &= (1.87\%\ \mathrm{v/v})(5.4\ \mathrm{atm})/(1\ \mathrm{atm}) \\ &= 10.10\%\ \mathrm{v/v}. \end{aligned} \tag{9}$$

Therefore, the solubility of air in water at 20°C and 5.4 atm is equal to 10.10 mL of air per 100 mL of pressurized water.

The percent volume of gas bubbles released due to pressure change can be calculated by Eq. (10):

$$\begin{aligned} V_{\mathrm{br}} &= C_2 - C_1 \\ &= 10.10 - 1.87 \\ &= 8.23\%\ \mathrm{v/v}. \end{aligned} \tag{10}$$

For every 100 mL of pressurized water at 5.4 atm, 8.23 mL of air bubbles will be released to the environment at 1 atm. This is the theoretical maximum. In actual engineering practice, there will be less volume of useful air bubbles due to the following factors: (a) efficiency of equipment for gas dissolution; (b) pressure losses; (c) bleed-off of excess gases; (d) distribution of air bubbles, and (e) pressurized water recycle.

For ease of engineering planning and design, much technical information has been precalculated or gathered (22). Table 2.8 predicts the concentration of air dissolved in water (mg/L) under various water temperatures (°C) and various air pressures above the water (atm). Table 2.9 presents the percent volume data of air bubbles released when the pressure is reduced from various air pressures to normal atmospheric pressure ($P = 1$ atm) over the water.

Table 2.9
Percent volume of bubbles released when pressure is reduced to 1 atm (22)

Temp °C	Original pressure of air above the water in atmospheres							
	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00
0	0.00	2.88	5.76	8.64	11.52	14.40	17.28	20.16
5	0.00	2.55	5.10	7.65	10.20	12.75	15.30	17.85
10	0.00	2.27	4.53	6.80	9.07	11.33	13.60	15.87
15	0.00	2.05	4.10	6.15	8.20	10.25	12.30	14.35
20	0.00	1.87	3.75	5.62	7.50	9.37	11.24	13.12
25	0.00	1.73	3.46	5.18	6.91	8.64	10.37	12.10
30	0.00	1.61	3.23	4.84	6.46	8.07	9.68	11.30
40	0.00	1.43	2.86	4.29	5.72	7.15	8.58	10.01
50	0.00	1.32	2.63	3.95	5.26	6.58	7.89	9.21
60	0.00	1.23	2.46	3.70	4.93	6.16	7.39	8.62
80	0.00	1.16	2.33	3.49	4.65	5.81	6.98	8.14
100	0.00	1.16	2.33	3.49	4.65	5.81	6.98	8.14

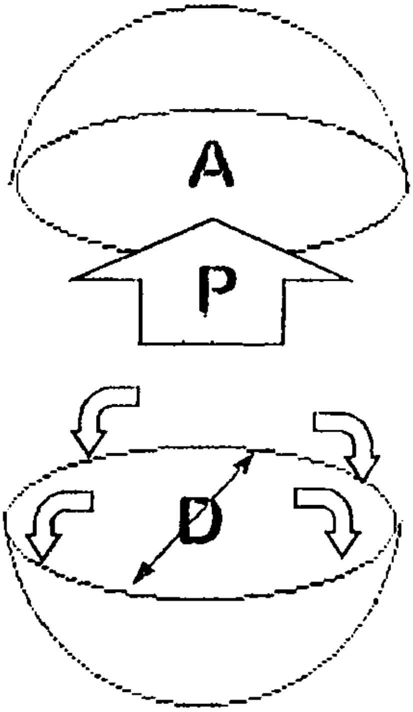


Fig. 2.6. Pressure inside a gas bubble.

4.4. *Gas Bubble Formation and Size Distribution*

The internal force of the air on the water is countered by the force holding the air in place that is caused by the surface tension, as shown by Fig. 2.6 (22).

Table 2.10
Bubble diameter vs. internal pressure (22)

Diameter (micrometers)	1,000	100	10	1
Net internal pressure (atm)	0.0029	0.029	0.29	2.9

1 atm = 101.325 kPa = 1.013 bar

Let r be the surface tension of the solution, D be the diameter of the gas bubble, P be the pressure of the bubble, and A be the area of a cross section (Fig. 2.6), then the internal force (F_{internal}) and surface force (F_{surface}) can be calculated by Eqs. (13) and (14).

$$F_{\text{internal}} = \text{internal force},$$

$$F_{\text{internal}} = (\text{pressure})(\text{area}),$$

$$F_{\text{internal}} = P(3.14D^2)/4, \tag{13}$$

$$F_{\text{surface}} = \text{surface force},$$

$$F_{\text{surface}} = (\text{surface tension})(\text{perimeter}),$$

$$F_{\text{surface}} = (r)(3.14\ D), \tag{14}$$

where F_{internal} is the internal force, dyne; F_{surface} is the surface force, dyne; r is the surface tension, dyne/cm (or lb/in); D is the bubble diameter, cm (or in); and P is the internal bubble pressure, dyne/cm^2 (or psi).

When the internal force is equal to the surface force during a bubble formation process, Eq. (15) is derived.

$$P(3.14\ D^2)/4 = (r)(3.14\ D), \tag{15}$$

$$P = 4\ r/D, \tag{16}$$

Table 2.10 indicates the relationship between the net internal pressure P (atm) and the gas bubble diameter D (micrometer) in pure water. The pressure required inside the bubble is strongly influenced by the surface tension of the solution. The addition of substances that reduce the surface tension leads to smaller bubbles, according to Eq. (16). The addition of milligram per liter amounts of surface-active agents can significantly alter the flotation process – sometimes by altering the attachment mechanism, sometimes by altering the gas bubble formation process, sometimes both; KSV Instruments Ltd, Finland has developed a modern gas bubble pressure tensiometer for such an investigation (28).

4.5. *Bubble Attachment, Rising, and Flotation*

Many researchers (29–35) have investigated the theories, principles of gas bubble formation, size distribution, absorption/adsorption, solids attachment, detachment, decompression, surface chemistry, rising velocities, and instrumentation (17–38).

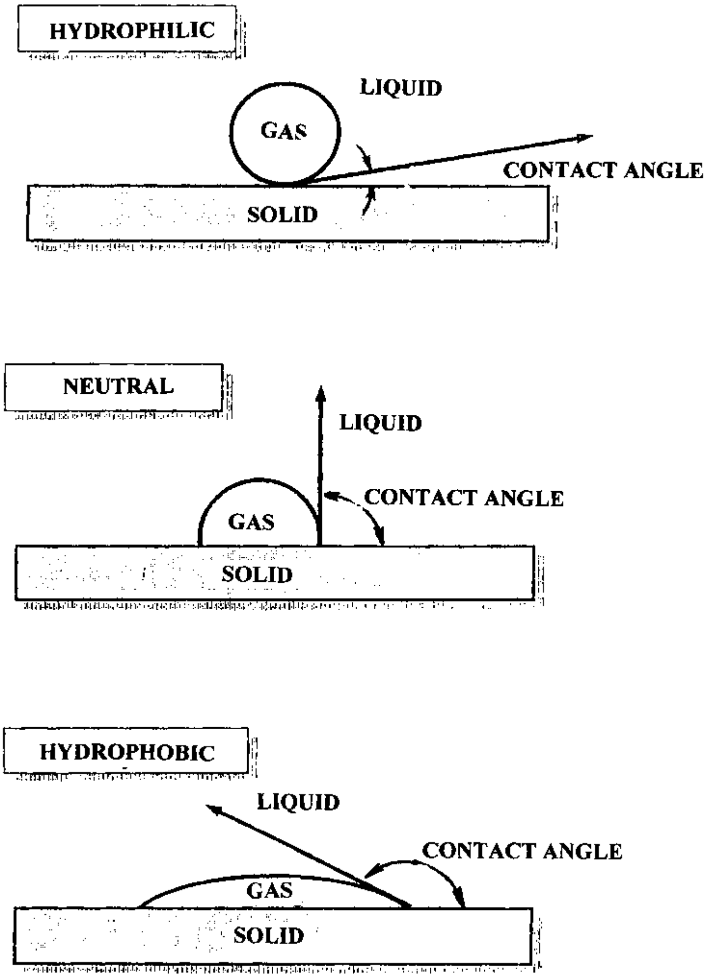


Fig. 2.7. Attachment of solids onto gas bubbles.

Figure 2.7 shows how the solids in a flotation system can be attached onto gas bubbles. Adsorptive bubble separation processes (including flotation) are surface-chemistry processes, mainly for separating fine solids that take advantage of the differences of wettability at solids particle-surfaces. Solid surfaces are often naturally wettable by water and termed hydrophilic. A surface that is nonwettable is water repelling and termed hydrophobic.

If a surface is hydrophobic, it is typically air attracting termed aerophilic, and is strongly attracted to an air interface, which readily displaces water at the solid's surface, as shown in Fig. 2.7. In a flotation system, separation of a binary solids mixture may be accomplished by the selective attachment of hydrophobic solid particles to gas bubbles (typically air bubbles). The other hydrophobic solid particles remain in the liquid (typically water). The difference in the density between the air bubbles and water provides buoyancy that preferentially lifts the hydrophobic solids particles to the surface where they remain entrained in a froth or scum that can be drained off or mechanically skimmed away, thus, effecting the separation.

A flotation system may be used to separate solids of similar densities and sizes, which cannot be achieved by other types of separations based on gravity alone. It is especially useful for particles below 100 μm, which are typically too small for gravity separation by sedimentation clarification. The lower size limit for flotation separation is approximately 35 μm; although particles as small as 1 μm can be separated. At these small particles sizes, it may be difficult to take advantage of surface properties differences to induce selective hydrophobicity. On the other hand, particles greater than 200 μm tend to be readily sheared from the bubble surfaces by collision with other particles or the vessel walls. However, relativity low density materials, such as coal, may be successfully separated at sizes up to 1,600 μm in some systems.

Lenox Institute of Water Technology (22) has developed engineering design data for use in various adsorptive bubble separation processes (including flotation process). Tables 2.11–2.15 introduce the design data relative to bubble attachment and bubble rising in the flotation systems.

4.5.1. Example

What is the rise rate of a bubble with a diameter of 50 μm at a water temperature of 20°C.

Solution

Stoke's law shown in Eqs. (1a) and (1b) can be used to calculate the rise rate, or falling rate of a spherical object in a fluid. The following is an example showing how Table 2.11 can be used and verified, and how Eq. (1b) can be applied to the determination of bubble rise rate in a flotation system.

$$V_{\mathrm{T}} = g(d_{\mathrm{W}} - d_{\mathrm{B}})D^2/(18v), \tag{1b}$$

where D is the diameter of a spherical gas bubble, m; V_{T} is the terminal velocity of a spherical bubble diameter D, m/s; d_{W} is the density of water, kg/m^3; d_{B} is the density of gas bubble, kg/m^3; v is the water viscosity, Pa-s; and g is the gravitational acceleration = 9.8 m/s^2.

From Table 2.11, the following data are obtained for water temperature at 20°C:

$$d_{\mathrm{W}} = \text{density of water} = 998.2\ \mathrm{kg/m^3},$$

$$d_{\mathrm{B}} = \text{density of gas bubble} = 1.2\ \mathrm{kg/m^3},$$

$$v = \text{water viscosity} = 1{,}002 \times 10^{-6}\,\text{Pa-s}.$$

The following data are given:

$$D = \text{diameter of a spherical gas bubble} = 50 \times 10^{-6}\,\mathrm{m},$$

$$g = \text{gravitational acceleration} = 9.8\ \mathrm{m/s^2}.$$

Table 2.11
Rise velocity of air bubbles in water by Stoke's law (22)

Temp °C	Visc. µPa-s	VP torr	Density (kg/m^3)		Effective diameter of air bubbles in micrometers (µm)										
			Water	Air	10	25	50	75	100	125	150	175	200	225	250
					Rise velocity in centimeters/second										
0	1,770	4.58	999.9	1.3	0.0031	0.019	0.077	0.173	0.307	0.480	0.691	0.941	1.229	1.555	1.920
10	1,304	9.21	999.7	1.2	0.0042	0.026	0.104	0.234	0.417	0.651	0.938	1.277	1.668	2.110	2.605
20	1,002	17.5	998.2	1.2	0.0054	0.034	0.135	0.305	0.542	0.846	1.219	1.659	2.167	2.743	3.386
25	890.3	23.8	997.1	1.2	0.0061	0.038	0.152	0.343	0.609	0.952	1.370	1.865	2.436	3.083	3.807
30	797.3	31.8	995.7	1.1	0.0068	0.042	0.170	0.382	0.679	1.061	1.528	2.080	2.717	3.438	4.245
50	546.9	92.5	988.1	1.0	0.0098	0.061	0.246	0.553	0.983	1.535	2.211	3.009	3.931	4.975	6.141
75	379.2	289	974.9	0.9	0.0140	0.087	0.350	0.787	1.399	2.185	3.147	4.283	5.594	7.080	8.741
100	284.0	760	958.4	0.6	0.0184	0.115	0.459	1.033	1.836	2.869	4.132	5.623	7.345	9.296	11.47

All rise velocities are in cm/s.

Table 2.12
Number of bubbles needed to lift a particle of density 1.1 (22)

Particle (density = 1.10)		Number of bubbles needed to lift a particle of density 1.10									
		Effective diameter of air bubbles in micrometers µm									
		10	25	50	75	100	125	150	175	200	225
		Multiplication factor for number of bubbles									
D µm	V µm^3	524	8,180	65,444	2.21E+05	5.24E+05	1.02E+06	1.77E+06	2.81E+06	4.19E+06	5.96E+06
10	524	1	1	1	1	1	1	1	1	1	1
25	8,180	2	1	1	1	1	1	1	1	1	1
50	65,444	13	1	1	1	1	1	1	1	1	1
75	2.21E+05	43	3	1	1	1	1	1	1	1	1
100	5.24E+05	101	7	1	1	1	1	1	1	1	1
125	1.02E+06	196	13	2	1	1	1	1	1	1	1
150	1.77E+06	338	22	3	1	1	1	1	1	1	1
175	2.81E+06	536	35	5	2	1	1	1	1	1	1
200	4.19E+06	801	52	7	2	1	1	1	1	1	1
225	5.96E+06	1,140	73	10	3	2	1	1	1	1	1
250	8.18E+06	1,563	101	13	4	2	1	1	1	1	1
300	1.41E+07	2,701	173	22	7	3	2	1	1	1	1
400	3.35E+07	6,401	410	52	16	7	4	2	2	1	1
500	6.54E+07	12,501	801	101	30	13	7	4	3	2	2
1,000	5.24E+08	1,00,001	6,401	801	238	101	52	30	19	13	9

The gas bubble rise velocity can then be calculated using Eq. (1b):

$$
\begin{aligned}
V_{\mathrm{T}} &= g(d_{\mathrm{W}} - d_{\mathrm{B}})D^2/(18v) \\
&= (9.8\ \mathrm{m/s^2})(998.2\ \mathrm{kg/m^3} - 1.2\ \mathrm{kg/m^3})(50 \times 10^{-6}\ \mathrm{m})^2/(18 \times 1{,}002 \times 10^{-6}\ \mathrm{Pa\text{-}s}) \\
&= 0.00135\ \mathrm{m/s} \\
&= 0.135\ \mathrm{cm/s}.
\end{aligned}
$$

One can then review the data in Table 2.11. When water temperature is 20°C, and the bubble diameter is 50 µm, Table 2.11 indicates that the bubble rise velocity should be 0.135 cm/s, which is identical to the calculated value of 0.135 cm/s.

4.6. *Gas Dissolution in Water Containing High Dissolved Solids or High Salinity*

4.6.1. *Environmental Engineering Significance*

The greater the solubility of a gas in water, the more gas bubbles can be generated, and in turn, the higher the efficiency of a flotation system. It is known that the gas solubility in water

Table 2.13
Number of bubbles needed to lift a particle of density 1.5 (22)

Particle (density = 1.5)		Number of bubbles needed to lift a particle of density 1.50									
		Effective diameter of air bubbles in micrometers µm									
		10	25	50	75	100	125	150	175	200	225
		Multiplication factor for number of bubbles									
D µm	V µm^3	524	8,180	65,444	2.21E +05	5.24E +05	1.02E +06	1.77E +06	2.81E +06	4.19E +06	5.96E +06
10	524	1	1	1	1	1	1	1	1	1	1
25	8,180	8	1	1	1	1	1	1	1	1	1
50	65,444	63	5	1	1	1	1	1	1	1	1
75	2.21E+05	211	14	2	1	1	1	1	1	1	1
100	5.24E+05	501	33	5	2	1	1	1	1	1	1
125	1.02E+06	977	63	8	3	1	1	1	1	1	1
150	1.77E+06	1,688	109	14	5	2	1	1	1	1	1
175	2.81E+06	2,680	172	22	7	3	2	1	1	1	1
200	4.19E+06	4,001	257	33	10	5	3	2	1	1	1
225	5.96E+06	5,696	365	46	14	6	3	2	2	1	1
250	8.18E+06	7,813	501	63	19	8	5	3	2	1	1
300	1.41E+07	13,501	865	109	33	14	7	5	3	2	2
400	3.35E+07	32,001	2,049	257	76	33	17	10	6	5	3
500	6.54E+07	62,501	4,001	501	149	63	33	19	12	8	6
1,000	5.24E+08	5,00,001	32,001	4,001	1,186	501	257	149	94	63	44

decreases with increasing water temperature, salinity, or dissolved solids concentration. These negative effects should be avoided when operating a flotation system.

On the other hand, the gas solubility in water increases with increasing the total pressure above the water, which is good for the flotation system.

This section demonstrates the negative effects (caused by high water temperature, high dissolved solids, and high salinity) as well as the positive effect (caused by high total pressure over the water) on a flotation system, using dissolved oxygen concentration in water as an example. Engineering approaches for overcoming the negative effects are also introduced.

4.6.2. Engineering Experience and Solutions

Both dissolved solids (or salinity) and water temperature have significant effects on bubble formation and solids attachment in flotation systems. In general gas solubilities decrease with increasing either the dissolved solids concentration or the water temperature. Since sea water contains high concentrations of dissolved solids (as shown in Table 2.16), generally special attention is needed if a flotation system is to be used for treatment of contaminated sea water (or another contaminated water with high dissolved solids concentration) or high temperature

Table 2.14
Number of bubbles needed to lift a particle of density 2.0 (22)

Particle (density = 2.00)		Number of bubbles needed to lift a particle of density 2.00									
		Effective diameter of air bubbles in micrometers µm									
		10	25	50	75	100	125	150	175	200	225
		Multiplication factor for number of bubbles									
D µm	*V* μm^3	524	8,180	65,444	2.21E+05	5.24E+05	1.02E+06	1.77E+06	2.81E+06	4.19E+06	5.96E+06
10	524	2	1	1	1	1	1	1	1	1	1
25	8,180	16	2	1	1	1	1	1	1	1	1
50	65,444	126	9	2	1	1	1	1	1	1	1
75	2.21E+05	422	28	4	2	1	1	1	1	1	1
100	5.24E+05	1,001	65	9	3	2	1	1	1	1	1
125	1.02E+06	1,954	126	16	5	2	2	1	1	1	1
150	1.77E+06	3,376	217	28	9	4	2	2	1	1	1
175	2.81E+06	5,360	344	43	13	6	3	2	2	1	1
200	4.19E+06	8,001	513	65	19	9	5	3	2	2	1
225	5.96E+06	11,391	730	92	28	12	6	4	3	2	2
250	8.18E+06	15,626	1,001	126	38	16	9	5	3	2	2
300	1.41E+07	27,001	1,729	217	65	28	14	9	6	4	3
400	3.35E+07	64,001	4,097	513	152	65	33	19	12	9	6
500	6.54E+07	1,25,001	8,001	1,001	297	126	65	38	24	16	11
1,000	5.24E+08	1,000,001	64,001	8,001	2,371	1,001	513	297	187	126	88

wastewater. For instance, much higher pressure may be required to dissolve air in water, in turn, to release pressure for bubble formation. Alternatively, special surface-active collectors may be used to overcome the problems of high dissolved solids and/or high water temperature (39).

Equations (17) and (18) illustrate the effects of dissolved solids and water temperature on the dissolved oxygen concentration (mg/L) in water (37, 40–42).

$$C_{\mathrm{DO.}} = (475 - 2.65\ \mathrm{S})/(33.5 + T), \tag{17}$$

$$C_{\mathrm{DO}} = (0.68 - 6 \times 10^{-4}\mathrm{T})(P' - p)(1 - 9 \times 10^{-6} S_{\mathrm{a}})/(T + 35), \tag{18}$$

where C_{DO} is the dissolved oxygen concentration in water at equilibrium with air above the water, mg/L; T is the water temperature, °C; S is the dissolved solids concentration, g/L; P' is the total pressure above the water, mm Hg; p is the water vapor pressure, mm Hg; and S_{a} is the salinity, mg/L.

Equation (17) was reported by Gameson and Robertson (40) for water at atmospheric pressure at equilibrium with air. The negative effects of high dissolved solids concentration and high water temperature on the solubility of dissolved oxygen in water are clearly illustrated by the equation.

Table 2.15
Bubble diameter, number, total surface area, silhouette area and total volume (22)

Volume of air	D μm →	Effective average diameter of air bubbles in micrometers										
		10	25	50	75	100	125	150	175	200	225	250
	V μm^3 →	524	8,180	65,400	2.21E+05	5.24E+05	1.02E+06	1.77E+06	2.81E+06	4.19E+06	5.96E+06	8.18E+06
mL/L	A μm^2 →	314	1,963	7,853	17,670	31,410	49,080	70,680	96,200	125,700	159,000	196,000
% v/v	S μm^2 →	79	491	1,963	4,417	7,853	12,270	17,700	24,100	31,400	39,800	49,100
	No./Liter	4.78E+09	3.06E+08	3.82E+07	1.13E+07	4.78E+06	2.44E+06	1.41E+06	8.91E+05	5.97E+05	4.19E+05	3.06E+05
2.5	Tot A cm^2	15,000	6,000	3,000	2,000	1,500	1,200	1,000	857	750	667	600
0.25%	% a/a/cm*	375	150	75	50	38	30	25	21	19	17	15
	No./Liter	9.55E+09	6.11E+08	7.64E+07	2.26E+07	9.55E+06	4.89E+06	2.83E+06	1.78E+06	1.19E+06	8.38E+05	6.11E+05
5.0	Tot A cm^2	30,000	12,000	6,000	4,000	3,000	2,400	2,000	1,714	1,500	1,333	1,200
0.50%	% a/a/cm	750	300	150	100	75	60	50	43	38	33	30
	No./Liter	1.43E+10	9.17E+08	1.15E+08	3.40E+07	1.43E+07	7.33E+06	4.24E+06	2.67E+06	1.79E+06	1.26E+06	9.17E+05
7.5	Tot A cm^2	45,000	18,000	9,000	6,000	4,500	3,600	3,000	2,571	2,250	2,000	1,800
0.75%	% a/a/cm	1,125	450	225	150	113	90	75	64	56	50	45
	No./Liter	1.91E+10	1.22E+09	1.53E+08	4.53E+07	1.91E+07	9.78E+06	5.66E+06	3.56E+06	2.39E+06	1.68E+06	1.22E+06
10.0	Tot A cm^2	60,000	24,000	12,000	8,000	6,000	4,800	4,000	3,429	3,000	2,667	2,400
1.0%	% a/a/cm	1,500	600	300	200	150	120	100	86	75	67	60
	No./Liter	2.39E+10	1.53E+09	1.91E+08	5.66E+07	2.39E+07	1.22E+07	7.07E+06	4.45E+06	2.98E+06	2.10E+06	1.53E+06
12.5	Tot A cm^2	75,000	30,000	15,000	10,000	7,500	6,000	5,000	4,286	3,750	3,333	3,000
1.25%	% a/a/cm	1,875	750	375	250	188	150	125	107	94	83	75
	No./Liter	2.87E+10	1.83E+09	2.29E+08	6.79E+07	2.87E+07	1.47E+07	8.49E+06	5.35E+06	3.58E+06	2.52E+06	1.83E+06
15.0	Tot A cm^2	90,000	36,000	18,000	12,000	9,000	7,200	6,000	5,143	4,500	4,000	3,600
1.5%	% a/a/cm	2,250	900	450	300	225	180	150	129	113	100	90
	No./Liter	3.34E+10	2.14E+09	2.67E+08	7.92E+07	3.34E+07	1.71E+07	9.90E+06	6.24E+06	4.18E+06	2.93E+06	2.14E+06
17.5	Tot A cm^2	105,000	42,000	21,000	14,000	10,500	8,400	7,000	6,000	5,250	4,667	4,200
1.75%	% a/a/cm	2,625	1,050	525	350	263	210	175	150	131	117	105
	No./Liter	3.82E+10	2.44E+09	3.06E+08	9.05E+07	3.82E+07	1.96E+07	1.13E+07	7.13E+06	4.78E+06	3.35E+06	2.44E+06
20.0	Tot A cm^2	120,000	48,000	24,000	16,000	12,000	9,600	8,000	6,857	6,000	5,333	4,800
2.0%	% a/a/cm	3,000	1,200	600	400	300	240	200	171	150	133	120

(*Continued*)

Table 2.15
(Continued)

Volume of air	*D* µm →	Effective average diameter of air bubbles in micrometers										
		10	25	50	75	100	125	150	175	200	225	250
	No./Liter	4.78E+10	3.06E+09	3.82E+08	1.13E+08	4.78E+07	2.44E+07	1.41E+07	8.91E+06	5.97E+06	4.19E+06	3.06E+06
25.0	Tot *A* cm^2	150,000	60,000	30,000	20,000	15,000	12,000	10,000	8,571	7,500	6,667	6,000
2.5%	% a/a/cm	3,750	1,500	750	500	375	300	250	214	188	167	150
	No./Liter	9.55E+10	6.11E+09	7.64E+08	2.26E+08	9.55E+07	4.89E+07	2.83E+07	1.78E+07	1.19E+07	8.38E+06	6.11E+06
50.0	Tot *A* cm^2	300,000	120,000	60,000	40,000	30,000	24,000	20,000	17,143	15,000	13,333	12,000
5.0%	% a/a/cm	7,500	3,000	1,500	1,000	750	600	500	429	375	333	300

*Looking down through one cm depth of the water, what % of the surface area is silhouetted by the projected area (S) of the bubbles in the water (% a/a/cm).

Table 2.16
Composition of sea water (22)

Component	g mol/L	g/kg	Equivalents/kg
Na^+	0.47015	10.5561	0.4590
Mg^{2+}	0.05357	1.2720	0.1046
Ca^{2+}	0.01024	0.4001	0.0200
K^+	0.00996	0.3800	0.0097
Sr^{2+}	0.00015	0.0133	0.0003
Total			0.5936
Cl^-	0.54830	18.9799	0.5353
SO_4^{2-}	0.03824	2.6486	0.0551
HCO_3^-	0.00234	0.1397	0.0023
Br^-	0.00083	0.0646	0.0008
F^-	0.00007	0.0013	0.0001
H_3BO_3	0.00043	0.0260	–
Total	1.13194	34.4816	0.5936
H_2O	54.89457	965.5184	
Total	56.02651	1,000.0000	

Density at 20°C = 1.0243 g/mL.
Dissolved solids = 35,320 mg/L.
Chloride concentration = 19,440 mg/L.

Equation (18) was reported by Fair, Geyer, and Okun (41), who considered the pressure above the water, and the water vapor partial pressure (Table 2.17). While the negative effects of high dissolved solids (in terms of high salinity) and high water temperature on dissolved oxygen concentration are similar, Eq. (18) further shows that the higher the total pressure above the water, the higher the dissolved oxygen concentration.

Wang (26) and Wang and Elmore (27) have developed more accurate dissolved oxygen concentration equations that are suitable for mathematical modeling and computer calculations. Wang and Elmore's equations (26, 27), shown in Table 2.18, can be applied to either fresh water or saline water, and cover all related parameters, such as water temperature, chloride concentration, barometric pressure, saturated water vapor pressure, etc.

4.6.3. *Example 1*

Predict the dissolved oxygen concentration in fresh water and sea water (Table 2.16) at 20°C.

Solution

For fresh pure water using Eq. (17):

$$\begin{aligned} C_{\mathrm{DO}} &= (475 - 2.65S)/(33.5 + T) \\ &= (475 - 2.65 \times 0)/(33.5 + 20) \qquad (17) \\ &= 8.88\ \mathrm{mg/L}. \end{aligned}$$

Table 2.17
Vapor pressure of pure water* (22, 43)

Temp., °C	*P*, mm Hg	Temp., °C	*P*, mm Hg
0	4.579	55	118.0
5	6.543	60	149.4
10	9.209	65	187.5
15	12.79	70	233.7
20	17.54	75	289.1
25	23.76	80	355.1
30	31.82	85	433.6
35	42.18	90	525.8
40	55.32	95	633.9
45	71.88	100	760.0
50	92.51		

*From "Handbook of Chemistry and Physics," 36th Edition, C. D. Hodgeman, Editor in Chief, Chemical Rubber Publishing Co. 1954–1955 (43).

Table 2.18 shows that the expected dissolved oxygen saturation concentration in fresh water at 1 atm and 20°C is 9 mg/L.

For sea water also using Eq. (17):

$$\begin{aligned} C_{\mathrm{DO}} &= (475 - 2.65\ \mathrm{S})/(33.5 + T) \\ &= (475 - 2.65 \times 35.32)/(33.5 + 20) \qquad (17) \\ &= 7.13\ \mathrm{mg/L}. \end{aligned}$$

Table 2.18 indicates that the expected dissolved oxygen saturation concentration in sea water (chloride concentration = 19,440 mg/L) at 1 atm and 20°C is about 7.3 mg/L.

4.6.4. Example 2

Calculate the dissolved oxygen concentration in sea water (Table 2.16) at 740 mm Hg pressure and 30°C.

Solution

From Table 2.17, the water vapor partial pressure is found to be 31.8 mm Hg.

The salinity is calculated using the data from Table 2.16 for the sea water.

$$S_{\mathrm{a}} = (0.5483\ \mathrm{g\,mole/L})(35{,}450\,\mathrm{mg/g\,mole}) = 19{,}440\ \mathrm{mg/L\ of\ chloride},$$

$$\begin{aligned} C_{\mathrm{DO}} &= (0.68 - 6 \times 10^{-4}\mathrm{T})(P' - p)(1 - 9 \times 10^{-6} S_{\mathrm{a}})/(T + 35) \\ &= (0.68 - 6 \times 10^{-4} \times 30)(740 - 31.8)(1 - 9 \times 10^{-6} \times 19{,}440)/(30 + 35) \qquad (18) \\ &= 5.95\ \mathrm{mg/L}. \end{aligned}$$

Table 2.18
Wang and Elmore's Equations* for Saturation Values of Dissolved Oxygen in Fresh and Sea Water Exposed to an Atmosphere Containing 20.9% Oxygen under a Pressure of 760 mm of Mercury (26, 27)

Water Temperature (T, °C)	Dissolved Oxygen (C_{DO}, mg/L) for Stated Concentrations of Chloride (CL, mg/L)					Difference per 1000 mg/L Chloride
	0	5000	10000	15000	20000	
0	14.7	13.8	13.0	12.1	11.3	0.165
1	14.3	13.5	12.7	11.9	11.1	0.160
2	13.9	13.1	12.3	11.6	10.8	0.154
3	13.5	12.8	12.0	11.3	10.5	0.149
4	13.1	12.4	11.7	11.0	10.3	0.144
5	12.8	12.1	11.4	10.7	10.0	0.140
6	12.5	11.8	11.0	10.4	9.8	0.135
7	12.1	11.5	10.8	10.2	9.6	0.130
8	11.8	11.2	10.6	10.0	9.4	0.125
9	11.6	11.0	10.4	9.7	9.1	0.121
10	11.3	10.7	10.1	9.5	8.9	0.118
11	11.0	10.4	9.9	9.3	8.7	0.114
12	10.8	10.2	9.7	9.1	8.6	0.110
13	10.5	10.0	9.4	8.9	8.4	0.107
14	10.3	9.7	9.2	8.7	8.2	0.104
15	10.0	9.5	9.0	8.5	8.0	0.100
16	9.8	9.3	8.8	8.4	7.9	0.098
17	9.6	9.1	8.7	8.2	7.7	0.095
18	9.4	9.0	8.5	8.0	7.6	0.092
19	9.2	8.8	8.3	7.9	7.4	0.089
20	9.0	8.6	8.1	7.7	7.3	0.088
21	8.8	8.4	8.0	7.6	7.1	0.086
22	8.7	8.3	7.8	7.4	7.0	0.084
23	8.5	8.1	7.7	7.3	6.8	0.083
24	8.3	7.9	7.5	7.1	6.7	0.083
25	8.2	7.8	7.4	7.0	6.5	0.082
26	8.0	7.6	7.2	6.8	6.4	0.080
27	7.9	7.5	7.1	6.7	6.3	0.079
28	7.7	7.3	6.9	6.6	6.2	0.078
29	7.6	7.2	6.8	6.5	6.1	0.076
30	7.4	7.1	6.7	6.3	6.0	0.075

$$^{*}C_{DO} = (14.53475 - 0.4024407T + 0.834117\times10^{-2}T^{2} - 0.1096844\times10^{-3}T^{3} + 0.6373492\times10^{-6}T^{4}) + CL\times10^{-3}(-0.1591768 + 0.5374137\times10^{-2}T - 0.1152163\times10^{-3}T^{2} + 0.1516847\times10^{-5}T^{3} - 0.8862202\times10^{-8}T^{4}).$$

Example 1: $C_{DO} = 7.6$ mg/L when $T = 29$ °C and $CL = 0$ mg/L.
Example 2: $C_{DO} = 7.2$ mg/L when $T = 29$ °C and $CL = 5000$ mg/L.
*$C'_{DO} = C_{DO}\,(P' - p)/(760 - p)$
*$p = 4.571512 + 0.352142T + 0.007386T^{2} + 0.000371T^{3}$

NOMENCLATURE

C_1 = Solubility of a gas in water (% v/v) under pressure P_1 (atm)
C_2 = Solubility of a gas in water (% v/v) under pressure P_2 (atm)
C_{air} = Concentration of air in water, % v/v (% air volume/water volume)
$C_{\mathrm{carbondioxide}}$ = Concentration of pure carbon dioxide in water, % v/v (% carbon dioxide volume/water volume)
$C_{\mathrm{carbondioxide\text{-}a}}$ = Actual concentration of carbon dioxide component in water, % v/v (% carbon dioxide volume/water volume)
C_{DO} = Dissolved oxygen concentration in water at equilibrium with air above the water, mg/L
C'_{DO} = Dissolved oxygen concentration in water at any barometric pressure, water temperature or chloride concentration, mg/L
C_{gas} = Concentration of a pure gas in water, % v/v (% gas volume/water volume = mL gas/100 mL water)
$C_{\mathrm{gas\text{-}a}}$ = Actual concentration of a gas component in water, % v/v (% gas volume/water volume)
C_{i} = Concentration of dissolved gas, mole/L
C_{nitrogen} = Concentration of pure nitrogen in water, % v/v (% nitrogen volume/water volume)
$C_{\mathrm{nitrogen\text{-}a}}$ = Concentration of nitrogen component in water, % v/v (% nitrogen volume/water volume)
C_{oxygen} = Concentration of pure oxygen in water, % v/v (% oxygen volume/water volume)
$C_{\mathrm{oxygen\text{-}a}}$ = Actual concentration of oxygen component in water, % v/v (% oxygen volume/water volume)
$C_{\mathrm{water}^{\cdot}}$ = Molar concentration of water
CL = Chloride concentration, mg/L
D = Bubble diameter, cm (or in) (or m)
d_{B} = Density of gas bubble, kg/m^3
D_{e} = Effective depth of air dispersion cylinder, cm
d_{W} = Density of water, kg/m^3
f = A constant
F_{internal} = Internal force, dyne
F_{surface} = Surface force, dyne
g = Gravitational acceleration = 9.8 m/s^2 = 32.174 ft/s^2
h = The elevation above sea level in thousands of meters (h = 1.0 when elevation = 1000 m)
H_{i} = Henry's law constant for the particular gas, i
i = A gas
p = Water vapor pressure, mm Hg
P = Internal bubble pressure, dyne/cm^2 (or psi)
P' = Total pressure above the water, mm Hg
P_1 = Normal atmospheric pressure = 1 atm (which may be corrected by elevation)
P_2 = Pressure of a gas above the water, atm
$\mathrm{PCT}_{\mathrm{gas}}$ = Actual percentage of a gas component, %
$\mathrm{PCT}_{\mathrm{nitrogen}}$ = Actual percentage of nitrogen component, %

PCT_{oxygen} = Actual percentage of oxygen component, %
$P_{i,0}$ = The partial pressure of the gas, i, at sea level where h is 0 m
$P_{i,h}$ = The partial pressure of the gas, i, at an elevation h
r = Surface tension, dyne/cm (or lb/in)
S = Dissolved solids concentration, g/L
S_a = Salinity, mg/L
T = Water temperature, °C
t = Bubbles traveling time to water surface, s or min
v = Water viscosity, Pa-s
V_{br} = Percent volume of gas bubble released from a previously pressurized water, %
V_T = Bubbles vertical rising velocity = terminal velocity of a spherical gas bubble, cm/s, or cm/min, or m/s
X_i = Dissolved gas mole fraction of any gas

REFERENCES

1. Wang LK, Wang MHS, Yaksich SM, Granstrom ML (1978) Water treatment with multiphase flow reactor and cationic surfactants. J Am Water Works Assoc 70(9):522–528
2. Krofta M, Wang LK (1982) Potable water treatment by dissolved air flotation and filtration. J Am Water Works Assoc 74(6):304–310
3. Krofta M, Wang LK (1985) Application of dissolved air flotation to the Lenox, Massachusetts water supply: water purification by flotation. J N Engl Water Works Assoc 99(3):249–264, Sept
4. Krofta M, Wang LK (1985) Application of dissolved air flotation to the Lenox, Massachusetts water supply: sludge thickening by flotation or lagoon. J N Engl Water Works Assoc 99(3): 265–284, Sept
5. Zabel T (1985) The advantages of dissolved-air flotation for water treatment. J Am Water Works Assoc 77(5):37–41
6. Hyde RA, Miller DG, Packham RF, Richards WN (1977) Water clarification by flotation. J Am Water Works Assoc 69(7):369–374
7. Krofta M, Guss D, Wang LK (1983) Improved biological treatment with a secondary flotation clarifier. Civil Eng Practicing Des Engineers 2:307–324
8. Krofta M, Wang LK (1984) Development of innovative Sandfloat systems for water purification and pollution control. ASPE J Eng Plumbing 0(1):1–16
9. Krofta M, Wang LK (1984) Tertiary treatment of secondary effluent by dissolved air flotation and filtration. Civil Eng Practicing Des Engineers 3:253–272
10. Krofta M, Wang LK (1986) Wastewater treatment by biological-physicochemical two-stage process System. Proceedings of the 41st industrial waste conference, Lewis Publishers Inc., Chelsea, MI, May 1986, pp 67–72
11. Krofta M, Wang LK (1987) Flotation technology and secondary clarification. TAPPI J 70(4):92–96
12. Krofta M, Guss D, Wang LK (1987) Development of low-cost flotation technology and systems for wastewater treatment. Proceedings of the 42nd industrial waste conference, Lewis Publishers Inc., Chelsea, MI, May 1987, pp 185–195
13. Wang LK, Dahm DB, Baier RE, Ziegler RC (1975) Treatment of tannery effluents by surface adsorption. J Appl Chem Biotechnol 25:475–490

14. Krofta M, Wang LK (1989) The world's largest potable flotation–filtration plant. OCEESA J 6(1): 7–10
15. Wang LK (2007) Emerging flotation technologies. In: Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical treatment processes. Humana Press, Totowa, NJ, pp 449–484
16. Wang LK, Shammas NK (2007) Pressurized ozonation. In: Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical treatment processes. Humana Press, Totowa, NJ, pp 1–56
17. Wang LK, Wang MHS (1995) Bubble dynamics and material balances of dissolved gas flotation process. Water Treat 10:41–54
18. Krofta M, Wang LK (1999) Flotation and related adsorptive bubble separation processes, 4th edn. Lenox Institute of Water Technology, Lenox, MA. Technical Manual No. Lenox/7–25–1999/348, 212p
19. Wang LK, Kurylko L, Wang MHS (1992) Gas dissolving and releasing liquid treatment system. US Patent No. 5167806, US Patent & Trademark Office, Washington, DC, Dec.
20. Wang LK, Kurylko L, Wang MHS (1993) Water and wastewater treatment. US Patent No. 5240600. US Patent & Trademark Office, Washington, DC, Aug.
21. Wang LK, Kurylko L, Wang MHS (1996) Sequencing batch liquid treatment. US Patent No. 5354458. U.S. Patent & Trademark Office, Washington, DC
22. Krofta M, Wang LK (2000) Flotation engineering. Lenox Institute of Water Technology, Lenox, MA, Technical Manaual No. Lenox/01–05–2000/368, first edition, Jan 2000, 255p
23. SWBIC (2010) Gas transfer. Southwest Biotechnology and Informatics Center, Washington, DC. http://www.swbic.org
24. Wang LK, Fahey EM, Wu Z (2005) Dissolved air flotation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ, pp 431–500
25. Nave CR (2010) Hyperphysics. Department of Physics and Astronomy, Georgia State University, GA. http://www.gsu.edu
26. Wang LK (1986) Dredging operations and waste disposal. In: Wang LK, Pereira NC (eds) Water resources and natural control processes, 1st edn. Humana Press, Totowa, NJ, pp 447–496
27. Wang LK, Elmore DC (1981) Computer-aided modeling of water vapor pressure, gas adsorption coefficient and oxygen solubility. Technical Report PB82–118787. U.S. Dept. of Commerce, National Technical Information Service, Springfield, VA, p 137
28. KSV (2010) Bubble pressure tensiometer. KSV Instruments Ltd., Helsinki, Finland. http://www.ksvltd.com
29. Maiken E (1995) Bubble decompression strategies. http://www.cisatlantic.com
30. Lage PLC (1999) Conservation of bubble size distribution during gas reactive absorption in bubble column reactors. Braz J Chem Eng 16(4):18
31. Chahine GL, Kalumuch KM, Cheng JY, Frederick GS (2010) Validation of bubble distribution measurements of the ABS acoustic bubble spectrometer with high speed video photography. Technical Report No. CAV2001. Jessup, MD. http://www.dynaflow-inc.com
32. Wienke BR (1991) Basic decompression theory and application. Technical Report. Best Publishing Company, Flagstaff, AZ
33. Sonoyama ZN, Iguchi M (2002) Bubble formation and detachment on nonwetted surfaces. Metall Mater Trans 33B:155–159
34. Data Physics (2009) Surface chemistry glossary. Data Physics Instruments GmbH. Filderstadt, DE. http://www.dataphysics.de
35. Editor (2010) Bubble rise in single capillaries – experimental set-up and procedure. Universteit Amsterdam, Kruislaaan, Amsterdam, Netherlands. http://www.science.uva.nl

36. Cargille-Sacher Labs (2005) Procedure for rising bubble rise testing using viscosity tubes. Technical Report. Gargille-Sacher Laboratories Inc., Cedar Grove, NJ, Sept
37. Wang LK, Wang MHS (2007) Bubble dynamics of adsorptive bubble separation processes. 2007 National engineers week conference, Albany Marriott, Albany, NY, 15–16 Feb 2007
38. Wang LK, Shammas NK, Guss DB (2010) Flotation biological systems. In: Wang LK, Ivanov V, Tay JH, Hung YT (eds) Environmental biotechnology. Humana Press, Totowa, NJ
39. Univ. of Pittsburg (2001) Froth flotation. College of Engineering, University of Pittsburg, PA. http://www.engr.pitt.edu/chemical/undergrad/lab_manuals/flotation.pdf
40. Gameson AH, Robertson HH (1955) Dissolved oxygen concentration. J Appl Chem 5:503
41. Fair GM, Geyer JC, Okun DA (1968) Water and wastewater engineering, vol 2. Wiley, NYC, NY
42. Humenick MJ (1977) Water and wastewater treatment. Marcel Dekker, Inc., NYC, NY
43. Hodgeman CD (1955) Handbook of chemistry and physics. Chemical Rubber Publishing Co., NYC, NY, 36th Ed.

3

Separation of Oil from Wastewater by Air Flotation

Gary F. Bennett and Nazih K. Shammas

CONTENTS

Abstract Air flotation, in all its variations, is an efficient way to extract oil from wastewater. If the wastewater is chemically pretreated to break the oil emulsions, air flotation units are capable of removing most of the emulsified oil in addition to the free oil. This chapter covers various flotation techniques to achieve oil/water separation. Flotation processes include electroflotation, dissolved air flotation (DAF), induced air flotation (IAF), and nozzle air flotation (NAF). Flotation system performance, air pollution aspects, product recovery from sludge (float), and costs of oil/water separation by flotation are covered.

Key Words Oil/water separation • DAF • IAF • electroflotation (EF) • nozzle air flotation (NAF) • performance • costs.

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1. INTRODUCTION

1.1. Background

For many years, industries that discharge their wastewaters directly to streams, rivers, and lakes have had to comply with limits imposed by the US Environmental Protection Agency (U.S. EPA) on the oil and grease content of their effluents. Currently, the NPDES new source performance standard for oil and grease is 10 mg/L for most industry groups with the added stipulation that none be floating or visible. i.e., no oil sheen will be visible. This standard represents that level of control achievable by the Best Available Technology (BAT) for removal of oil and grease (1). Even discharges to sewers are controlled under U.S. EPA regulations. Most municipalities have standards for the pretreatment of industrial wastewaters discharged to sewers. Generally, oil concentrations allowed in wastewater discharges to sewers are in the range of 50–100 mg/L (2). Current and proposed European Union (EU) standards and regulatory developments can be found in the literature (3).

A partial listing of facilities and activities that are likely sources of oil contamination of wastewaters and stormwater includes (1,4):

1. Asphalt materials production
2. Parking lots and Airports
3. Railroad yards
4. Vehicle fueling and maintenance areas
5. Cooling and heating blowdown
6. Compressor station blowdown
7. Car salvage facilities
8. Truck stops
9. Electric power generating facilities
10. Petroleum refineries and distribution centers
11. Metal working
12. Food processing
13. Vehicle washing

If a facility discharges wastewater or stormwater to the land surface or waters of the state, this discharge may be subject to federal, state, and local regulations governing surface water quality. Additionally, if the facility discharges directly to an aquifer, to the land surface, or to the vadose zone in such a manner that the pollutant will reach an aquifer, then the state's aquifer protection permit regulations may also apply,

Oils and grease are present in process wastewater and stormwater in five forms (1): free oil, physically emulsified, chemically emulsified, dissolved, and oil wet solids, as shown in Table 3.1.

To remove oil from wastewater, the wastewater is normally pumped to a gravity oil/water separator (5,6). There, with time and quiescence, most of the free oil droplets rise to the surface where they are skimmed off, but emulsified and dissolved oils remain. Normally, further oil removal is accomplished by chemically breaking the emulsion followed by treatment of the wastewater in an air flotation unit (7,8). The oil/water emulsion leaving the American Petroleum Institute (API) separator normally, according to Sylvester and Byseda (9), has oil droplets less than 30 μm in diameter and oil concentrations less than 200 mg/L.

Table 3.1
Oil and grease contamination in wastewater

Form of oil	Formation
Free oil	Oil present in wastewater or stormwater as droplets 20 µm or larger, having little or no water associated with it Floats to the surface because of its low specific gravity Oil dispersed in water in a stable form
Physically emulsified	Mechanical emulsions are formed by mixing through pumping, valves (especially globe valves), other restrictions in flow, vertical piping, and other means, and present as droplets 5–20 µm in size
Chemically emulsified	Chemical emulsions are usually intentionally formed using detergents, alkaline fluids, or other reagents, and having a droplet size less than 5 µm
Dissolved	Oil which is solubilized in the liquid solvent and must be detected using infrared analysis or other chemical means Oil/water separators do not remove dissolved oil
Oil wet solids	Oil that adheres to the surface of particulate materials

Air flotation has been used for many years in the beneficiation of ores. Its first application in the wastewater-treatment field was in the flotation of suspended solids, fibers, and other low-density solids (10,11). Flotation also was used for the thickening of activated sludge (12) and flocculated chemical sludges. More recently, air flotation has been utilized for the removal of oils and greases from wastewater because it is a practical, reliable, and efficient treatment process (13–16).

Air flotation is widely used to treat oil-bearing effluents from a wide variety of sources: refineries, ship's bilge and ballast waste, deinking operations, metal plating, meat processing, laundries, iron and steel plants, soap manufacturing, chemical processing and manufacturing plants, barrel and drum cleaning, washrack and equipment maintenance, glass plants, soybean processing, mill waste, and aluminum forming.

The process of flotation consists of four basic steps (17,18):

1. Bubble generation in the oily wastewater
2. Contact between the gas bubble and the oil droplet suspended in the water
3. Attachment of the oil droplet to the gas bubble
4. Rise of the air/oil combination to the surface where the oil (and normally attendant suspended solids) is skimmed off

Flotation utilizes the differential density between the bubbles to which the oil droplets and small solid particles become attached and the water to effect separation. Since the agglomerates have a lower density than the medium in which they are immersed, they rise to the surface where they are removed. The most commonly used flotation system for oil separation is the use of dissolved air in which air bubbles are formed when water supersaturated with air is released into the air/water mixture. A few systems are designed for dispersed or induced air in which the air is induced by rapid mechanical mixing.

Table 3.2
Typical ranges of oil and grease concentration in industrial wastewater

Wastewater type	Range of oil and grease concentrations, mg/L
Sewage	10–100
Food processing	100–1,000
Textile (wool processing)	10–50
Petroleum refining	100–1,000
Primary metals	
Rinse waters	10–1,000
Concentrate	10,000–50,000
Metal fabrication	10,000–150,000
Metal cleaning	
Rinse waters	10–1,000
Concentrate	100–5,000
Commercial laundries	100–2,000

Table 3.3
Typical refinery wastewater oil concentration

Oil phase	Oil concentration, mg/L
Free (floating)	220
Emulsified	75
Soluble	5
Total	300

Concentrations of oil and grease vary significantly from one industrial source to another and even between different plants in the same industries (Table 3.2). Concentrations are especially high in wastewater from the metals-related industries that use large quantities of oils for lubrication, cooling, and quenching in diverse processing operations, including rolling, casting, cutting, milling, and other metal-cleaning operations.

The old adage that oil and water do not mix is not true, especially in industrial wastewater. Oily wastes from these processes are frequently diverse mixtures of free floating, emulsified, and soluble substances that have varying stability. A typical analysis for refinery wastewater is given in Table 3.3.

1.2. Pretreatment

Since air flotation devices work best with feed streams having oil concentrations of 300 mg/L or less, air flotation units should be preceded by a primary treatment device such as an API (American Petroleum Institute) gravity separator to remove most of the free and floating oil. As a minimum, one can expect API effluent oil concentrations of approximately 25 mg/L, but this figure depends on how much oil is emulsified and how much is “free” oil (19).

Table 3.4
Estimated effluent quality from primary oil/water separation processes

Separators commercially available	Effluent oil concentration (mg/L)
Fram Akers Plate Separator	50–100
API rectangular	50–75
Circular	50–75
Inland Steel-Hydrogard	50–75
Shell parallel plate interceptor	35–50
Shell corrugated plate interceptor	35–50
Finger plate separator	35–50
Keene-GraviPak	20

Table 3.5
Performance of oil/water separation systems

System	Residence time (min)	Average effluent concentration (mg/L)
Gravity tank	600	40–50
API separator	30	40–115
Parallel plate	30	25–70
	5	40–100
Corrugated plate	5	10–50
Gas flotation	5	15–50
Gas flotation, with chemicals and recycle	5	5–50
Biological treatment	60–1,200	1

Table 3.6
Efficiencies of different oil separation processes in the treatment of refinery wastewater

Unit operation	Oil removal (%)	
	Free oil	Emulsified oil
API separator	60–99	–
Air flotation, no chemicals	70–95	10–40
Air flotation, chemicals	75–95	50–90
Chemical coagulation and sedimentation	60–95	50–90

Osamore and Ahlert (20), who surveyed the operability of various types of gravity separators, report gravity separator oil effluent concentrations in the 50 mg/L range (Table 3.4), while others reported equally variable results (Tables 3.5 and 3.6).

1.3. *Equalization*

Within a plant, industrial wastewaters fluctuate in quality and quantity with time depending on the process and the production cycle. Most wastewater-treatment systems are affected by changes in flow rate, contaminant concentration, pH, and temperature. Fluctuations in these parameters can be reduced by the use of an equalization system (21), which may be the most important feature in a wastewater-treatment facility (22). If significant quantities of oil are present, however, equalization may be preceded by an API separator.

Adams et al. (23) have demonstrated the need for smoothing out the variations in flow and concentration as well as the need for removal of free oil. A study of dissolved air flotation (DAF) treatment of wastewater from an edible oil plant indicated that there were very low levels of oil removal in the air flotation system and treatment system. This was attributed to a high concentration of free oil. Installation of a preliminary API oil separator removed these free oils. Installing an equalization tank after the separator reduced fluctuations in loading and allowed operation at a constant polymer dosage.

2. ALTERNATIVES TO FLOTATION

Alternatives for oil and grease removal can be summarized by eight processes (1): (1) gravity separation, (2) air flotation, (3) chemical flocculation, (4) filtration, (5) coalescence, (6) membrane processes, (7) biological processes, and (8) carbon adsorption (see Table 3.7). U.S. EPA (5) did a survey of the various types of wastewater-treatment technologies that are currently in use in 20 US petroleum refineries. Table 3.8 shows the results of the survey.

In addition to oil flotation the most popular processes, chemical treatment and membrane processes, are briefly discussed below.

2.1. *Chemical Treatment*

Chemical treatment is applicable especially for small flows. At Caterpillar Tractor in Leandro, CA, the flow is only 22,000 gal/d. A study of this plant by Lee and Schwab (24) resulted in the following proposed system design:

1. Equalization, acid treatment, heat, and surface oil skimming
2. Addition of lime and polyelectrolyte
3. Sedimentation
4. Sludge dewatering

Bench-scale testing at pH 2, heating to 50°C, adding lime to raise the pH to 9.0–9.5, and adding 3 mg/L Dow A-23 (a polymeric flocculant) resulted in 96% oil removal from a wastewater initially containing 5,493 mg/L of oil plus good removal of heavy metals, zinc, lead, and nickel (24).

2.2. *Membrane Processes*

Emulsified oils may be separated from wastewater utilizing membranes (25) that are permeable to water but impermeable to macroscopic molecules such as oil and suspended solids. Ultrafiltration (UF) and reverse osmosis (RO) are two such processes, differing from

Table 3.7
Processes for oil and grease removal

Process	Description	Advantages	Disadvantages
Gravity separation	API, CPI, TPS, PPI	Removal of suspended solids, and free and dispersed oils; simple and economical operation	No removal of oil droplets <20 µm or soluble oil; limited removal of emulsified oil Requires relatively low flow or large tank
Air flotation	DAF, IAF	Removal of suspended solids; can remove emulsified and dispersed oils with chemical addition; effectively treats shock loads	Chemical sludge handling required when chemical coagulants used
Chemical flocculation	Used with gravity separation and air flotation	Treatment/removal of high levels of suspended solids	Chemical sludge produced
Filtration	Sand, anthracite, multimedia, crushed graphite, oleophicically coated ceramic, hollow fiber membrane cartride (ultrafiltration)	Removal of suspended solids; separation of free, dispersed, and emulsified oil	Backwashing, which requires subsequent treatment
Coalescence	Fibrous membrane	Effective removal of all oil components, except soluble oils	Extensive pretreatment; high potential for fouling; not practical for full-scale operation
Membrane processes	Reverse osmosis; ultrafiltration; hyperfiltration	Removal of soluble oil	Membrane fouling and limited life; extensive pretreatment; low flux rate; not practical for full-scale operation
Biological processes	Activated sludge	Effective soluble oil removal	Extensive pretreatment required to reduce influent oil levels to <40 mg/L
Carbon adsorption	GAC used for filtration and coalescing separator; PAC used for removal of soluble oils only	Effective removal of all oil components including soluble oils	Expensive; extensive pretreatment; carbon must be regenerated or replaced; not practical for full-scale operation

Table 3.8
Wastewater-treatment technologies used in 20 petroleum refineries

Summary of current wastewater-treatment technologies			
	Treatment type	Direct discharge refineries (total 20)	Indirect discharge refineries (total 7)
In-plant controls	Oil–water separator	15	4
	Stripper	16	5
	Oxidizer	2	0
	Activated carbon	1	1
Primary treatment	API separator	9	5
	Air flotation	5	1
	Coagulation	1	0
	Chemical precipitation	1	0
	Dissolved air flotation	10	1
	Equalization	16	4
	Flocculation	1	1
	Grit chamber	0	1
	Gas flotation	0	1
	Induced air flotation	4	2
	Settling and skimming	0	1
Secondary treatment	Activated sludge unit	11	0
	Bio treatment ponds	6	2
	PAC bio-treatment	1	0
	RBCs	1	1
	Secondary clarifier	12	0
	Lagoons	3	0
	Filtration (media and sand)	3	1
	Aeration and other biological treatment	5	0

each other mainly in the permeability of the membrane to dissolved solids and the pressure needed to force water through it.

RO membranes provide a barrier to the transfer of contaminants such as dissolved solids (chlorides, phosphates, etc.) to remove those contaminants from the wastewater (26). However, RO membranes are easily fouled: hence, the feed must be relatively free of suspended solids and oil.

UF membranes are less discriminatory than RO membranes, allowing dissolved solids to pass through them, but rejecting oil and grease: moreover, the required pressure to effect the separation is generally less than 100 psi. Extremes of pH, temperature, and dirtiness can be tolerated within reason (although membrane life decreases as conditions become more severe), although flux (flow rate), frequency of cleaning, and membrane life are all affected.

UF systems have been effective in treating metals forming wastewater (27). The data shown in Table 3.9 are representative of what can be expected. Note that there is excellent removal of oil and grease and suspended solids, but some oil does pass through the membrane.

Table 3.9
Results from ultrafiltration treatment of aluminum-forming wastewater

Day	Concentration and removal					
	Oil and grease (mg/L)			Suspended solids (mg/L)		
	Influent	Effluent[a]	Removal (%)	Influent	Effluent[a]	Removal (%)
1	95	22	76	1,262	26	98
2	1,540	52	97	791	19	98
3	13,180	267	98	5,676	267	99

[a] The effluent is the treated water that has permeated (i.e., flowed through) the membrane.

In a survey of major industries using UF systems to treat oily wastewater (28), 21 respondents gave data on UF applications in the following industries: (1) general metalworking, (2) primary metals, (3) waste collection, (4) food processing, (5) transportation, and (6) textile.

3. OIL/WATER ANALYSIS

An accurate method for determining the oil content of a wastewater is extremely important. However, like many other water-pollution tests, such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), etc., the term “oil and grease” really defines a broad category of chemicals rather than a single identifiable chemical species.

Oily matter may be of mineral, animal, or vegetable origin. Oil can be present as free (or floating) oil, as an emulsion (water in oil or oil in water), or even in dissolved form (Table 3.1); oil can, and does, represent a wide variety of organic compounds of different molecular weights.

A variety of tests can be used to determine oil concentrations in water (but most tests involve extraction of the oil from water with a preferential solvent), and a wide variety of solvents can be used in those tests: hexane, petroleum ether, benzene, ethyl ether, chloroform, n-hexane, carbon tetrachloride, etc. Analytical procedures used for oil and grease are shown in Table 3.10. The most notable aspect of the data presented in Table 3.10 is the wide variety of solvents used. Because most of these solvents are flammable, and benzene is now on the OSHA-restricted exposure list, most of the foregoing solvents have been replaced with Freon (trichlorotrifluoromethane) as specified by the U.S. EPA (29). However, all chlorofluorocarbons (CFCs) have proved to be the cause for the depletion of atmospheric ozone. Consequently, there may be a return to hexane as the recommended solvent (30).

All of these solvents, however, extract only a fraction of the oils present; for example, petroleum ether extracts everything but asphaltenes (19). It is therefore essential to standardize any analytical procedure for each source of oily water separately, because of the solvent-extraction technology (30) and as a result of the different compositions of various oils. Limitations of the various methods have been tabulated by the Department of the Environment of the UK (19).

The infrared technique is generally accepted as the most accurate and reproducible for measuring oil concentrations in water. The American Society for Testing Materials recommends Freon extraction followed by infrared analysis in its standards (31).

Table 3.10
Methods for the determination of oil in water and wastewater

Society or institute	Method name and designation	Solvent used	Solvent boiling point (°C)	Method description	Interference material
American Public Health Association	Oil and grease	Petroleum ether	35–60	Direct extraction	
American Water Works Association, and Water Pollution Control Federation	Grease	*n*-Hexane	69	Soxhlet extraction method	Elemental sulfur and organic dyes
American Society for Testing and Materials	Oily matter in industrial wastewater	Benzene, carbon tetrachloride, or chloroform	60–80	Distillation of volatile oils followed by direct extraction	Phenolic type material and colloidal sulfur
American Petroleum Institute	Volatile and nonvolatile oily material (method 731–53)	Benzene	80	Distillation of volatile oils followed by direct extraction	Alcohols, cresols, and organic acids
	Nonvolatile oil material (method 732–53)	Ethyl ether	35	Ferric hydroxide flocculation followed by direct extraction of oil from floc by solvent	Elemental sulfur and chlorophyll

4. ELECTROFLOTATION AND ELECTROCOAGULATION

When a voltage is applied between two electrodes immersed in a conductive liquid such as wastewater, coagulation of the charged particles can occur. Also, upon the electrolysis of water, hydrogen and oxygen are released in the form of small, uniform bubbles that rise, producing a blanket effect. The bubble swarm carries suspended solids and oil globules to the surface where a floating sludge layer forms and is mechanically removed. Chemical coagulants enhance the floc formation.

Roth and Ferguson (32) reported on the results of electroflotation (EF) treatment at an aircraft maintenance facility. Chemical additives included lime (to pH approximately 8.5), alum (200 mg/L), and anionic polymer (1.5 mg/L). Using 6–9 V, 15–25 A/m^3(described as low energy usage), and a retention time of 20–30 min reduced the oil and grease more than 99% from 60 to 0.3 mg/L, with a concomitant reduction of metals, achieving effluent concentrations of 0.8 mg/L Ni, 0.5 mg/L total Cr, and 0.07 mg/L Al.

Another application of electrolytic process is in the coagulation of oily wastewater prior to air flotation. The process described by Weintraub et al. (33–36) and shown in Fig. 1.9 is as follows: oily emulsion wastewater from which free oil has been removed enters the electrocoagulation (EC) cell where it permeates uniformly through a rectangular caged anode fitted with iron or steel machinery turnings and chips; the wastewater then flows through a perforated sheet-metal cathode; DC voltage is applied to the electrodes, dissolving the ferrous iron at the anode and forming hydrogen and hydrogen ions at the cathode. A few hundred mg/L of salt may be added to increase the ionic conductivity and prevent passivation of the iron electrode.

The ferrous ions are oxidized to the ferric state in a complex manner with chemical oil emulsifying agents and the air. The destabilized oil emulsion droplets adsorb onto the highly dispersed and reactive ferric hydroxide microfloc. The oil-rich sludge that is generated accumulates on the surface where it forms a blanket that is easily skimmed off.

The air for the oxidation and for the flotation of the sludge is supplied by a DAF system operated at 85 psi (23). Subsequently, the water is passed through a sand filter for final polishing. Results include a 99% reduction of oil and grease from 2,330 to 19 mg/L, using a voltage in the range of 5–26 V and amperage of 6–45 A. The sludge averages 30% oil.

Ramirez (37) worked with the commercial Lectro Clear system to treat rendering wastewater. The system used separate EC (38) at 12.5 V and 1,500 A followed by EF (39) at 12.8 V and 400 A. The retention time was 25 min (37). Chemicals added included 1,200 mg/L H_2S0_4(to pH 4.5), 100 mg/L alum, and 6 mg/L of an anionic polyelectrolyte. DAF was used to dewater the skimmings. Operational results showed reduction of the oil and grease from 810 to 19 mg/L (98% removal); major amounts of suspended solids were also removed (3,500–95 mg/L).

Chambers and Cottrell (40) reported on the treatment of carrier-truck washings effluent in the UK. A flow of 230 m^3/d was treated in a 1.8 × 1.2 × 5-m deep tank at a rate of 11.4 m^3/h; the retention time was approximately 1 h. Alum at a concentration of 60 mg/L was added. In two experiments, the ether extractables were reduced approximately 75% and the suspended solids were reduced approximately 50%. Power requirement was approximately 0.4 kwh/m^3.

5. DISSOLVED AIR FLOTATION

5.1. Process Description

In the DAF process (Fig. 1.10), very fine gas bubbles are generated by reducing the pressure on a stream of the wastewater that has been exposed to air at pressures greater than atmospheric. When the pressure is released into the flotation basin, small bubbles nucleate from the supersaturated solution, attach to, and become entrapped by oil and solid particles and rise to the surface where they are removed.

The DAF system (Fig. 1.10) consists of the following units (41–43):

1. Pressurizing pump
2. Air-injection system
3. Saturation vessel
4. Load (pressure) regulator (also called the pressure-relief valve)
5. Flotation vessel (including the influent distributor)
6. Chemical addition system

Chemicals are usually added to break emulsions or promote floc formation.

5.2. *Flow Schemes*

Pressurization is usually applied in one of three flow schemes (10,44) (Fig. 1.11 in Chapter 1):

1. In the full-flow system, all of the incoming raw wastewater is pressurized and saturated with air. This results in the most air being dissolved and (compared with the other two methods) yields the maximum probability of good particle–bubble contact. However, it requires a larger saturation system and may break up previously formed floc due to the shearing action of the pump and pressure-reduction process.
2. In the split-flow system, only part of the incoming wastewater is pressurized. This requires less space, reduces pumping costs, lessens the impact of flow variations, and reduces breakup of the flocs.
3. With recirculation, 20–50% of the treated wastewater is returned via the pressurization system, thus avoiding disruption of flocs or demulsification of the oil in the untreated influent. This requires a larger flotation basin to provide for the recirculation flow.

As early as 1954, Rohlich (45) concluded that the recycle system was best. That conclusion has not changed with time.

Boyd et al. (46) compared two pressurization systems: full vs. recycle treatment of refinery wastewater; these two processes achieved 72 and 92% removal of influent oil, respectively. Degregorio, in an interview published in *Chemical Week* in 1979, noted that 80–90% of industrial DAF units employed recycled pressurization (47). The literature review supports that viewpoint; most DAF systems are operated in the recycle mode according to the articles cited herein.

5.3. *Chemical Usage*

Most air flotation systems employ chemical addition. Early in the application of air flotation systems, the importance of chemicals for emulsion breaking and floc formation was recognized. Biesinger et al. (48) tested the efficiency of a recycle DAF system on beef-packing-plant wastewater with and without the use of chemicals. Without chemicals, 73% of the influent oil and grease (initial concentration 300 mg/L) was removed, whereas with the addition of 10 mg/L alum, the removal increased to 86%.

Hart (49, 50) also experimented with chemical additives on a rather dilute refinery wastewater. Without chemicals, 65% removal of oil was removed (from 18 reduced to 6 mg/L); with chemicals, 79% removal was achieved (11 down to 2 mg/L). There were concomitant removals of SS, BOD, and COD (Table 3.11). Using an induced air flotation

Table 3.11
Comparison of the treatment efficiency of refinery wastewater with and without chemicals

Treatment process	Removals (%)			
	Oil	SS	COD	BOD_5
DAF				
Without chemicals	65	55	30	33
With 2 mg/L polyelectrolyte	79	75	42	40
IAF				
Without chemicals	93			
With chemicals	96			

(IAF) system, McIntyre also found that chemicals enhanced oil removal slightly, increasing the removal from 93 to 96% (Table 3.11). Pearson (51) experimented with the effects of the addition of inorganic chemicals, specifically alum, on oil removal. The use of alum plus a polyelectrolyte increased the oil removal from 40 to 90% (Fig. 1.13). Weight for weight, the aluminum ions were more efficient than ferric ions; they gave optimum removals at 35 mg/L as opposed to 60 mg/L with iron. In addition, the effluent produced by aluminum ions contained one half the oil present in the ferric-treated waste, i.e., 10 vs. 20 mg/L oil.

5.4. *Ionic Strength*

The ionic strength of solvents can also have an effect. Sato et al. (52) found that in general, oil removal was improved at higher ionic strengths and higher cation valences.

5.5. *Design Variables*

The design variables for DAF are discussed fully in Chap. 1. Particular pressures and recycle ratios applicable to oil removal were reported by Sato et al. (52), Beychock (53), and Adams et al. (54). Sato et al. (52) measured the effect of dissolution pressure on the residual oil concentration over the range from 30 to 70 psi. Removal was maximal at 45 psi. They concluded that too high a pressure decreases efficiency probably because of excessive liquid disturbance in the flotation column.

A compilation of data for percent recycle is found in Table 3.12. Percent recycle ranged from 25 to 58%, with 37% being the average of the literature values vs. the 50% recommended by Beychock (53) and within the range of 10–60% given by Adams et al. (54).

5.6. *Oil Components Removal*

Gas chromatography has now allowed the engineer/chemist to go beyond simply reporting oil and grease as a mileu of chemicals. Now the chemist can analyze for the removal of each different chemical in that mixture. In the treatment of refinery wastewater in a batch DAF

Table 3.12
Recycle ratios used in industrial DAF systems

Author	Wastewater	Recycle (%)
Biesinger (55)	Poultry processing	44
Biesinger (55)	Poultry processing	58
Biesinger (55)	Beef packing	35
Barker et al. (56)	Steel-rolling mill	25
Woodward et al. (57,58)	Poultry processing	20
Hart (49)	Refinery	30
Quigley and Hoffman (59)	Refinery	50
Steiner (60)	Refinery, pilot plant	20 (opt)
Zimmerman and Jacquez (61)	Poultry processing	35–50
Cardile and Fronczak (45)	Railroad	50
Franzen et al. (62)	Refinery	25
Churchill and Tacchi (63)	Refinery	50
	Metal working	30
McIntyre (64)	Metal working	40
Grosz (65)	Refinery	36
	Average	37%

Table 3.13
Performance of DAF in the treatment of refinery wastewater

Parameter	Before treatment	After treatment	Removal (%)
pH	6.7	6.7	
Turbidity, NTU	–	1.0	94.4
COD (mg/L)	160	8.0	95.0
Total SS at 105°C (mg/L)	57	12	79.0
Fixed SS at 550°C (mg/L)	31	4	87.0
Volatile at 550°C (mg/L)	25	10	60.0
Total oil and grease (mg/L)	92	4.62	95.0
Phenols (mg/L)	147	22.0	85.0
Ethylbenzene (mg/L)	0.5	0.025	95
Paraffin (n-C_{12})	–	–	98

system, Moursy and El-Ela (66) did just this. The fate of each identified hydrocarbon, both aromatic and paraffin, was determined (Table 3.13).

Their results showed that some hydrocarbons were completely removed; others were removed with efficiencies between 79 (n-C_{13}) and 98% (n-C_{12}). They attributed the differences in removal to the differences in solubility and molecular weights of the hydrocarbons, especially as the water solubility of the compounds decreased, the degree of removal increased.

Table 3.14
Performance of bench-scale IAF in treatment of wastewater

Chemical additive	Concentration (mg/L)	pH	Influent COD (mg/L)	COD removal (%)	Influent oil (mg/L)	Oil removal (%)	Influent sulfides (mg/L)	Sulfides removal (%)
(Raw wastewater)	–	9.0	1,378	–	222	–	318	–
None	0	9.0	1,060	23	58	48	238	25
Polyelectrolyte	25	9.0	1,171	15	42	62	256	20
Polyelectrolyte	6	9.0	988	28	41	63	256	20
Polyelectrolyte	12.5	9.0	868	37	41	63	–	–
Polyelectrolyte	12.5	9.0	892	35	44	60	223	30

Based on one sample, 25% BOD removal was noted.

6. INDUCED AIR FLOTATION

6.1. Process Description

In induced gas (air) flotation (IAF), bubbles are generated and discharged into the liquid by high-speed rotating impellers, by diffusers, or by homogenization of a gas/liquid stream (11, 67, 68). The bubbles are an order of magnitude larger (about 1,000 μm in diameter) than DAF bubbles. Short detention times of 5 min or less allow smaller equipment size (69). Multicell treatment systems can result in greater overall removal of oils. For example, with four cells each achieving 60% removal, the total removal is 97.5%. Any needed chemicals may be added to the first aeration cell where rapid mixing, flocculation, and flotation occur.

6.2. Performance Data

Representative performance data for bench-scale IAF systems have been provided by Adams et al. (54) (Table 3.14). Oil removals ranged from 48% without the use of chemical additives to 63% with them.

7. NOZZLE AIR FLOTATION

7.1. Process Description

A patented design by Degner and Colbert is based on injection of air into the recycled effluent before releasing this two-phase air/water mixture into the flotation vessel (70). The injection device uses an eductor or an exhauster as a gas aspiration nozzle (Fig. 1.19) to draw air into the recycled treated wastewater. Multiple cells may be combined for greater treatment efficiency. Residence time in the flotation cell is about 1 min. A unique aspect of this system is the use of a back pressure that maintains a gas blanket between the liquid level and the gas-tight cover. This cover allows collection, and if necessary treatment, of any off-gases.

7.2. Equipment Development

WEMCO (an equipment manufacturer) developed the nozzle aeration flotation system shown in Fig. 1.21 in Chapter 1 (71). This is a single cell of the recommended 4-cell treatment system. The manufacturer claims that the advantages include lower power requirement, since one pump provides mixing and air; elimination of the need for a separate flocculation vessel, since mixing, flocculation, and flotation are accomplished in the first cell; and lower maintenance costs, since there are no high-speed parts to wear out.

7.3. Performance Data

Gotzy (48) reported on bench-scale (batch) treatment of aluminum-forming and refinery wastewaters; Steiner et al. (72) and Hobe (73) reported on pilot plant-scale tests on refinery and tuna-cannery wastewaters, respectively, while Cardile and Fronczak (74) provided data on an operating system. Davies and Vose (75) noted that Chevron prefers the IAF process and has a number of units in refinery service in North America, but provides no data.

Steiner (60) used both bench- and pilot-scale models to study the performance of the nozzle air flotation (NAF) unit in treating wastewater from an API separator. Parameters that varied were polymer concentration, percent recycle (which varied as a result of a variable air-induction rate), and overall residence time. The removal of oil and grease as a function of nozzle pressure is shown in Table 3.15.

Hobe (73) provided few experimental details other than the need for chemicals and a comparison of the degrees of removal with and without chemicals. The removal using 25 mg/L of polymer averaged 85% based on 1,045 mg/L of oil and grease in the influent; without

Table 3.15
Effect of nozzle pressure on the performance of IAF

	Nozzle pressure (psi)		
	10	7.5	5
Recycle flow (gal/min)	28	24	20
Air-induction rate (ft/min)	1.67	1.08	0.50
Residence time (min)	1.40	1.55	1.80
Oil (conc: mg/L)			
Influent	36	54	41
Effluent	9	12	8
Removal (%)	75	78	80
Suspended solids (conc: mg/L)			
Influent	64	60	57
Effluent	15	17	17
Removal (%)	77	72	70

Feed flow. 5.5 gal/min: chemical addition. 10 mg/L Calgon WT-2640.

chemicals, the removal averaged 67%; the supernatant oil and grease averaged 25–30% FOG (fat, oil, and grease), 30–35% total solids, and 3–8% total protein.

Pearson (51) showed that a plot of residual oil concentrations vs. chemical dose exhibited a minimum effluent value for the dose of approximately 80 mg/L alum (Fig. 3.4). Above and below this value, the oil content of the effluent increased. The improvement in oil removal with the addition of polymer is also shown.

NATCO (76) reported that its Tridair hydraulic induced gas flotation cell accomplished 90–98% removal of insoluble oil, organics, and suspended solids. Removal efficiency was influenced by physical characteristics of the incoming stream such as pH, total dissolved and suspended solids, temperature, presence of chemicals, mixtures of different streams, and zeta potential. The nozzle/educator design ensured uniform dispersion of the finely divided air/gas bubbles throughout the liquid. By controlling the volume and rate of air/gas induced, the development of the proper bubble size for the efficient lifting of oil/organic and suspended solids was achieved.

Table 3.16 summarizes the performance of NAF in removing oil and grease in the treatment of various industrial wastewaters.

7.4. *Multicell Units*

Extensive comparative testing of oil-field and refinery wastewaters convinced Ellis and Fischer (77) that multistage units are more versatile and reliable than single-stage units. Each stage of flotation improves the water quality of the effluent of the previous stage. Hence, less than optimum conditions can be tolerated in one or more stages without sacrificing a final effluent of high quality. Single-stage units have only one opportunity to reduce contaminants to an acceptable level.

Table 3.16
Performance of nozzle IAF in industrial wastewater treatment

Author	Wastewater	Chemicals	Flow (gal/min)	Influent (mg/L)	Effluent (mg/L)	Removal (%)
Cardile and Fronczak (74)	Railroad maintenance	Polyelectrolytes	2,150	450	7.0	98 O & G[a]
				116	7.6	96 TSS
Steiner et al. (72)	Refinery	Polyelectrolytes	28	31	6	81 O & G
		(10 mg/L)	(Pilot)	38	11	71 SS
Hobe (73)	Tuna cannery	Polyelectrolytes (25 mg/L)	(Pilot)	1,045	145	86 O & G
Gotzy (48)	Al-forming cast house cooling water	Variable	(Bench)	Improvement in percent transmittance noted		

[a] O & G, oil and grease.

A test comparing a full-stream pressurization single-cell system to a multicell impeller induction system yielded an effluent oil concentration of 10–21 mg/L for the single cell vs. 2–10 mg/L for the multicell system. The latter system cost 60% as much as the former.

8. FLOTATION SYSTEM PERFORMANCE

According to a UK study (19), removals of oil by flotation generally average 90% if the influent concentration is 150 mg/L or more. If the influent concentration to the air flotation system is reduced to 25 mg/L by pretreatment, removals in the range of 70–75% can be expected. This report recommends that the inlet concentration to an air flotation system should not exceed 200–300 mg/L for effective system operation, a level that can normally be obtained by pretreatment in a gravity (API) oil–water separator.

Beychock (53) predicted that with the use of alum and the equipment design (loading) figures he recommends, 85–95% removal of oil can be obtained in a DAF unit operated in the recycle mode (Table 3.17).

Volesky and Agathos (78) have assembled a great deal of operating data for refinery wastewater treatment from the literature, much of it from Russian sources. Removals ranged from a low of 30–99.6%.

Performance data compiled from the literature are found in Tables 3.18 through 3.23. Oil removals from several systems treating refinery wastewater are shown in Table 3.18. Oil removals from other wastewaters are shown in the succeeding tables: ballast water (Table 3.19), paint manufacturing, tannery, glass plant and chemical plant wastewaters (Table 3.20), vehicle-maintenance wastewater (Table 3.21), metal-bearing oily wastewater (Table 3.22), and food-processing wastewater (Table 3.23). Because of the numerous variables associated with the data/testing (especially the type and amount of chemical additives), it is essentially futile to try to construct correlations. However, recently, several models have been developed to describe the performance of air flotation systems (94–98). Such modeling techniques should help researchers to be able to construct dependable correlations in the future.

Thompson and Wolf (99) reported that in a survey of flotation units used in the petroleum industry, flotation system performance varied widely. Oil-removal efficiencies ranged from 50 to 100% and appeared to depend upon the use of chemical aids. SS removal ranged between 30 and 80% and also depended on the use of chemicals. Insufficient data were

Table 3.17
Expected DAF performance

Contaminant	Expected removal (%)
Oil and grease	85–95
Suspended solids	70–75
COD (total)	65–85
COD (dissolved)	30–35

Table 3.18
Oil refinery wastewater treatment by various air flotation systems

Author	Oil			Chemicals[a] (mg/L)	Hydraulic loading (gal/min/ft^2)	System
	Influent (mg/L)	Effluent (mg/L)	Removal (%)			
Boyd et al. (79)	94	10–15	84–89	75–100 Alum 105 Cationic polymer	0.9	DAF (full flow)
Biesinger et al. (55)	220	9.5	96	50 Alum, 4 poly	0.7	DAF/R
	460	37	92	75 Alum, 0.5 poly	1.5	DAF/R
Ellis and Fischer (77)	50	20	60	Poly		IAF (multicell)
Hart (49)	11	2	79	2 Poly		DAF/R
Quigley and Hoffman (59)			85–95	30–70 Alum		DAF (full flow)
Smith and Robe (80)	2,000	10	95	2–3 Poly	2.0	DAF/R
Steiner (60)	50	15	80	10 Poly	2.8–7.5	DAF/R
	50	10	80	10 Poly		Nozzle air
Finkler et al. (81)	135	30	78			DAF
Franzen et al. (62)			75–85		3.8	DAF (full flow)
Churchill and Tacchi (63)	220	25	89	Alum + poly, 10 + 2	1.5–2.0	DAF/R
	150	10	93	10 Poly Median values		IAF (four-cell)
Eckenfelder (82)	125	35	72	None		
	100	10	92	100 Alum		
Ecodyne[b]	107	10	91	Alum + poly		DAF
	383	36	91			DAF
	680	6	90	Alum		
Kirkup (83)	76	3	96	Yes		IAF
	201	14	93	No		IAF
Moursy and El-Ela (66)	86.8	4.6	93	4.3 Alum, pH 5.9–6.2		DAF (batch)
Berne (84)	100	12	88	1.5 and 1.0 poly of two different types		DAF

[a] Poly = polyelectrolyte of unspecified source.
[b] Manufacturer's literature.

obtained on which to base any firm conclusion as to which equipment provided the best performance or to make performance predictions, mathematical or otherwise.

Galil et al. (100) treated an industrial effluent that contained hydrocarbons in the range of 20–77 mg/L. Less than 10% were found in "free" form, 70–80% were emulsified, and

Table 3.19
Ballast wastewater treatment by various air flotation systems

Author	Oil			Chemicals[a] utilized (mg/L)	Hydraulic loading (gal/min/ft^2)	System
	Influent (mg/L)	Effluent (mg/L)	Removal (%)			
Boyd and Shell (87)	100–200	5–10	90–97.5	70–100 Alum, 1 calionic poly	1.25	DAF
Ellis and Fischer (77)	50–5,000	10	80–99.8			IAF (multicell)
Envirex (86)	1,000	10–40	94–96		2.5	DAF
Eckenfelder (82)	133	15	89	100 Alum, 1 poly		DAF
Sport (oilfield brine) (88)			$\sim$95		1.2–6.0	DAF/R
Ellis and Fischer (oil-field brine) (77)	200–700	20	90–97	Poly		IAF (multicell)
	100–200	110	90–95	Poly		
	200–500	10–12	94–98	Poly		

[a] Poly = Polyelectrolyte.

Table 3.20
Removal of oil in treatment of four industrial wastewaters by air flotation systems

Wastewater	Oil in influent (mg/L)	Oil in effluent (mg/L)	Removal (%)	Chemicals utilized (mg/L)	Hydraulic loading (gal/min/ft^2)	System
Paint manufacturing (79)	1,000–2,000	0	100	150 Alum 5 Cationic polymer	–	DAF
Tannery (89)	370	70	81	270 $FeCl_3$, pH 4–5 10–20 polymer	–	DAF/R pilot
Glass plant (90)	100	0	100	75 High mol wt polymer	–	DAF/R
Chemical plant (55)	450	250	44	None	1.6	DAF full-stream

10–20% were dissolved. The DAF process enabled a reduction in the general hydrocarbon content by 50–90%. The results indicated that the chemical flocculation followed by DAF efficiently removed the emulsified phase, which could be aggregated and separated to the surface. It was found that the process could also remove substantial amounts of dissolved

Table 3.21
Treatment of vehicle-maintenance wastewater by air flotation systems

Author	Oil			Chemicals[a] utilized (mg/L)	Hydraulic loading (gal/min/ft^2)	System
	Influent (mg/L)	Effluent (mg/L)	Removal (%)			
Katnik and Pavilcus (90)	490	5	99	150 Anionic poly		DAF
Envirex (86)	400	10–52	87–97		2–3.5	DAF
Lynes (91)	166	13	92			IAF (pilot)
Cardile and Fronczak (74)	226	9	96	Poly and alum	1.26	DAF
	450	8	98			IAF (nozzle)
Eckenfelder (82)	250–700	20–50	90+	30 Alum, 10 activated silica		DAF

[a] Poly = Polyelectrolyte.

Table 3.22
Treatment of metal-bearing wastewater by various air flotation systems

Author	Oil			Chemicals[a] utilized (mg/L)	Hydraulic loading (gal/min/ft^2)	System
	Influent (mg/L)	Effluent (mg/L)	Removal (%)			
Katnik and Pavilcus[b] (90)	7,200	80	99			Air Sparger (batch)
Barker et al. (65)	1,482	84	92	Alum, clay, poly	1.70	1/3 design flow rate DAF/R
Ettelt[c] (92)	819	14	98	2,700 Alum, 20 Dow® A-23		DAF/R
Kreye et al.[d] (93)	100			Alum, poly (Percol® 727)		DAF
Envirex[e,f]	587	5	99	100 Alum, 1 poly		DAF/R (bench scale)
				0.5–0.75 Alum and poly		DAF/R
Ecodyne[f]	1,170	75	94	1,500 Alum and poly		DAF/R
	1,620	8	99	Alum and poly		

[a] Poly = Polyelectrolyte.
[b] Steel rolling.
[c] Can forming.
[d] Zinc plating.
[e] Machine shop.
[f] Manufacturer's literature.

Table 3.23
Treatment of food-processing wastewater by various air flotation systems

Author	Oil			Chemicals[a] utilized (mg/L)	Hydraulic loading (gal/min/ft^2)	System	Specific waste source
	Influent (mg/L)	Effluent (mg/L)	Removal (%)				
Biesinger et al. (55)	45	25	44		1.3	DAF/R	Poultry
	620	130	79		1.2	DAF/R	Poultry
	280	40	86	10 Alum	1.8	DAF/R	Beef
	300	80	73		1.1	DAF/R	Beef
	1,160	360	69	30 Alum, 0.5 poly	0.57	DAF/R (full flow)	Soybean oil
Adams et al. (54)	2,515			Alum, poly		DAF/R (full flow)	Edible oil
Woodward et al. (57)	3,140	18	99	75 Alum, 75 soda ash, 2 poly	2.8	DAF/R	
Murakami and Robe (85)	5,181	155	97	Alum, poly		DAF	
Envirex (86)							
(1981)	200	15–50	75–92		1.7–2.5	DAF	Poultry
(1982)	700	35–100	86–95		2–3	DAF	Rendering
Zimmerman and Jacquez (61)	4,000	140	96	250 Lime, 1 poly		DAF/R (bench scale)	Poultry
Ecodyne[b]	3,000	80	97	0.75 Poly		DAF	Meat packing
	600	80	87			DAF/R	

[a] Poly = Polyelectrolyte.
[b] Manufacturer's literature.

organic matter. The researchers explained this removal mechanism by the hydrophobic characteristics of some of the substances, which could bind to the solid surfaces. It was found that aggregates created by the flocculation with the cationic polyelectrolyte (C-577) could remove up to 40% of the dissolved hydrocarbon.

Al-Shamrani et al. (101) considered the effects of coagulant dose, pH, and the duration and intensity of both slow and fast mixing. Oil removals up to 99.3% at pH 8 and 99.94% at pH 7 were reported for aluminum sulfate and ferric sulfate, respectively. Rapid mixing times of approximately 2 min and flocculation times ranging from 15 to 20 min were found to be optimal for the DAF separation. The significant factors affecting the process were the recycle ratio, influent solids concentration, water quality such as salinity, surface tension, and temperature, residence time and the addition of coagulant or surfactants.

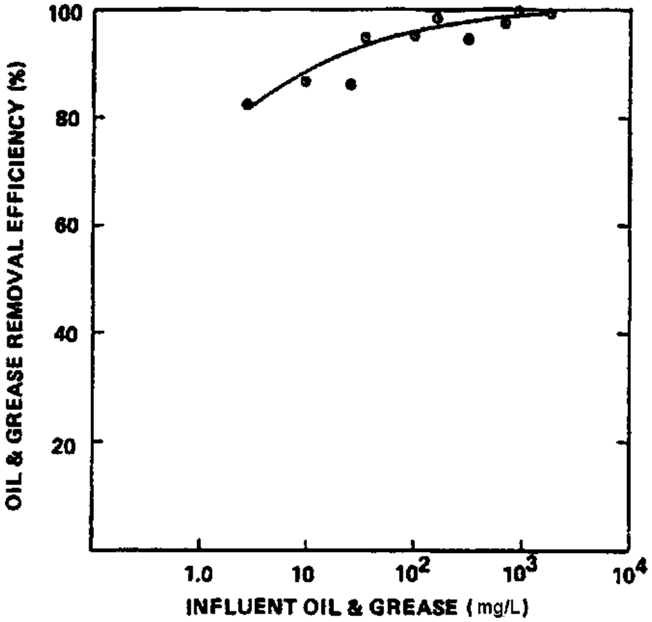

Fig. 3.1. Oil removal efficiency as a function of influent oil and grease concentration in a DAF system.

Abed Baig et al. (102) reported on the treatment of wastewaters from a variety of industries including oil refineries, petrochemical works, steel mills, metal finishing plants, cooking oil, and ghee factories. Their study was undertaken to investigate the removal of oil and grease from industrial and domestic wastewaters. Tests were carried out to find the removal efficiencies for oil and grease at retention times varying from 10 min to 2 h and for different concentrations varying from 50 to 500 mg/L. A retention time of 1 h was found to be sufficient for the separation of all oil concentrations. The samples were treated chemically prior to floatation by the addition of alum and polymer and then were treated in a DAF unit at pressures varying from 25 to 55 psi. A removal efficiency of 85% was achieved at 55 psi.

Percent removal can be a misleading term. Removal efficiency clearly varies as the influent oil concentrations vary, with higher efficiencies being attained at higher influent concentrations (Fig. 3.1). The critical factor is the residual concentration of the substance of concern in the final effluent.

9. AIR POLLUTION ASPECTS

A very early DAF paper on the treatment of refinery wastewater by Vrablik (103) contains an analysis of the DAF off-gas (Table 3.24). The unit was covered and the off-gas was directed to an air pollution abatement system. The treatment flow sheet shows that the off-gases go to a vapor-recovery system. In concept the author in 1959 was well ahead of the

Table 3.24
Analysis of DAF off-gas from the treatment of refinery wastewater

Contaminant	Contaminant concentration in air (mol %)
Isobutane	0.44
n-Butane	0.18
Butane	0.87
Isopentane	1.65
n-Pentane	0.82
Pentene	1.57
C_6 Plus	0.82
Benzene	0.02
Toluene	0.02
Oxygen	9.96
Nitrogen	83.65

time. Only recently have air-pollution control authorities attempted to limit ambient releases of hydrocarbons that are precursors for ozone formation.

10. PRODUCT RECOVERY FROM FLOAT

The role of the flotation system is to remove suspended materials by conveying them to the surface of the flotation vessel. The removed material then itself must be managed. If it is good oil (as recovered in refinery API separators) it may be recycled directly to the refinery. In other cases, for lesser quality oil, oil/water emulsions, or oily-contaminated solids, further treatment steps must be taken.

A common processing step for oil/water emulsions is to acidify with sulfuric acid to a low pH, heat to 150–160°F, and hold at that temperature 16–24 h. During that time, more oil that can be recycled can separate out. The rag layer is neutralized and sent back to the wastewater-treatment system.

Another possible technique for the separation of oil from dissolved-air-flotation (DAF) oily sludge (float) is by freezing and thawing (104).

Clearly, then the quality and concentration of materials in the sludge (surface-removed product or float) are of importance. A compilation of data is found in Table 3.25.

11. COSTS

All data dealing with capital and/or operating cost are given as reported and have not been updated; the year of the cost analysis is given at the end of each discussion. To allow the reader to adjust the cost data to current prices, the US Army Corps of Engineers Civil Works Construction Yearly Average Cost Index for Utilities is given in the Appendix (106).

Table 3.25
Quantity of floats recovered from various air flotation systems

Author	System influent				Recovered flotate			Waste type	Flotation system
	Flow rate (gal/min)	Recovered (%)	SS (mg/L)	Oil (mg/L)	Flow rate (gal/min)	SS (%)	Concentration O & G (%)		
Biesinger et al. (55)	825	28	900	45	3	0.92	0.65	Poultry	DAF/R
	690	46	1,300	620	2	24.5	10	Poultry	DAF/R
	600	40	2,000	280	12	2.1	12	Beef packing	DAF/R
	110	32	10,000	–	10	3.8	–	Cosmetic	DAF/R
Barker et al. (56)	500	–	80	1,482	83–500	–	–	Steel mill	DAF/R
Woodward et al. (57)	900	20	870	3,140	0.4	–	–	Poultry	DAF/R
Steiner (60)	1,000	~80	~60	70	0.3–0.4	–	30–40	Refinery	Pilot DAF
Envirex (86)	Bench scale	25	1,287	587	25 gal/1,000 gal	–	–	Machine shop	IAF
Lynes (91)	32	–	170	166	3.2	–	–	Railroad	IAF
Peters (105)	–	–	–	–	–	–	40–60	Machine shop	DAF
Woodward et al. (57)	1,200	~650	~160	~130	30	–	–	Poultry	DAF/R
Oblinger et al. (33)	–	–	–	2,336	–	–	30	Metal working	DAF/R
Berne (84)	–	–	–	–	–	8	18	Refinery	DAF
Grosz (65)	2,650	36	–	–	27	0.1	–	Refinery	DAF/R

11.1. Railyard Wastes

Lynes (91) has determined the results of a pilot-plant investigation of successful treatment of alkaline emulsified locomotive wastewater with IAF (WEMCO Depurator). He then compared costs of this continuous-treatment system to batch chemical treatment – $1.10/1,000 gal by air flotation vs. $0.41/1,000 gal by batch treatment (1986).

11.2. Barrel and Drum Wastewater

For the pretreatment of wastewater from a barrel and drum cleaning operation prior to discharge to a sewer, a Midwest firm installed a collection/pumping system, emulsion breaking chemical addition, a WEMCO Hydrocleaner (IAF), a neutralization system, an oil storage tank, a complete data-acquisition system, and a laboratory control building to handle 250 gpm at a 1981 capital cost of $681,000 (the IAF unit cost $57,000, 1981) (68).

11.3. Refinery Wastewater

Air Flotation has been tested and proven to be economical in treating refinery wastewater. After installing an air flotation system in Kansas, chemical costs were reduced threefold compared with the previous sedimentation system employed (107).

Thompson et al. (99) have compared several refinery oily wastewater-treatment systems. Table 3.26 shows the costs for gravity separators, air flotation, activated sludge, and carbon

Table 3.26
Yearly costs for treatment of 1,000 gal of oily wastewater

	Oily-water gravity separator	Gas flotation	Activated sludge	Carbon adsorption	Total
Investment costs (excluding land)	$300,000	$330,000	$1,600,000	$925,000	$2,175,000
Operating costs					
Power ($0.01/hp)	1,750	2,630	9,640	21,550	35,570
Maintenance at 4% plant cost	12,000	13,200	46,400	37,000	108,600
Direct labor and overhead	20,000	20,000	40,000	40,000	120,000
Depreciation at 10% plant cost	30,000	33,000	116,000	92,500	271,500
Insurance and taxes at 3% plant cost	9,000	9,900	34,800	27,750	81,450
Chemicals					
$/1,000 gal	0.14	0.15	0.47	0.42	1.18

[a] Included in investment.

Table 3.27
Cost of rectangular, dissolved-gas, recycle pressurization flotation system

Capacity		Power requirements (hp)	Costs[a]	
gal/min	bbl/d		Total ($)	Unit ($/bbl/d)
50	1,715	8.0	23,500	13.70
100	3,430	8.0	24,600	7.20
300	10,390	15.5	34,400	3.30
500	17,150	15.5	38,050	2.20
1,000	34,300	30.8	48,500	1.40

[a] Open top design – closed top and vapor recovery optional (extra cost).

Table 3.28
Cost of cylindrical, dissolved-gas, full-stream pressurization flotation system

Capacity		Power requirements (hp)	Costs[a]	
gal/min	bbl/d		Total ($)	Unit ($/bbl/d)
50	1,715	2.5	8,000	4.66
100	3,430	5.0	10,500	3.06
250	8,575	12.5	14,000	1.63
350	12,000	17.5	15,500	1.29
500	17,150	25.0	16,500	0.96
750	25,725	37.5	19,900	0.77
1,000	34,300	50.0	21,500	0.63
1,250	42,875	62.5	25,500	0.59
1,500	51,450	75.0	28,000	0.54
2,000	68,600	100.0	31,800	0.46
3,000	102,900	150.0	35,700	0.41

[a] Open top design – closed top and vapor recovery optional (extra cost).

Table 3.29
Cost of rectangular, froth-type flotation system

Capacity		Power requirements (hp)	Costs[a]	
gal/min	bbl/d		Total ($)	Unit ($/bbl/d)
150	5,150	13.0	15,600	3.03
300	10,300	21.0	19,800	1.92
450	15,450	31.0	21,500	1.39
750	25,725	41.0	24,750	0.96
1,125	38,585	61.0	35,100	0.91
2,250	77,175	61.0	47,600	0.62
3,000	102,900	81.0	49,000	0.48

[a] Open top design – closed top and vapor recovery optional (extra cost).

Table 3.30
Treatment cost of industrial wastewaters by DAF

Wastewater	Treatment cost ($/1,000 gal)
Poultry processing	0.14–0.17
Beef packing	0.16
Food processing	0.36
Deinking mill	0.08
Oil refining	0.09–0.12

Table 3.31
Detailed costs of three industrial wastewaters' treatment by DAF

Case number	Poultry		Beef	Chemical		Food	Drinking	Oil refinery	
	I	II		I	II			I	II
Flow rate (gal/min)	825	690	600	110	3,000	160	1,300	1,400	850
Equipment cost ($); includes, piping erection, and tankage	56,170	56,170	40,150	40,930	112,300	60,592	125,500	89,200	109,900
50% contingency	28,085	28,085	20,075	20,465	56,150	30,296	62,750	44,600	54,950
Amortization: 20 years at 6% interest ($/year)	6,590	6,590	4,711	4,802	13,176	7,109	14,725	10,466	12,895
Utilities ($/year); $0.015/kwh	872	872	872	2,940	9.798	2,000	12,248	5,880	17,760
Maintenance ($/year); 1% of equipment and contingency	842	842	602	614	1,684	910	1,882	1,338	1,648
Operation cost ($/year)	10,000	10,000	10,000	20,000	20,000	20,000	20,000	20,000	20,000
Chemical cost ($/year)[a]	–	–	–	–	–	790	9,120	47,560	25,150
Cost ($/1,000 gal)	0.14	0.17	0.16	0.49	0.03	0.36	0.08	0.12	0.09

[a] $1.50/lb polymer; $0.05/lb $FeCl_3$.

adsorption. For a flow of 1,000 gpm, the 1972 capital cost for a flotation system was $330,000; the operating cost (including fixed costs) was $0.15/1,000 gal.

11.4. Comparative Costs

Thompson et al. (99) tabulated costs for the three basic air flotation systems: (1) rectangular DAF (Table 3.27), (2) circular DAF (Table 3.28), and (3) rectangular IAF (Table 3.29). Cylindrical systems were the most economical, and require less steel in their construction and less space for installation, 1972.

Biesinger et al. (55) compared several different DAF systems. Flow rates ranged from 100 to 300 gpm. Construction costs did not vary widely ($40,000–$125,000). Operational costs varied significantly from $0.03 to $0.49/1,000 gal (Tables 3.30 and 3.31, 1974).

APPENDIX

U.S. Army Corps of Engineers Civil Works Construction Yearly Average Cost Index for Utilities (106)

Year	Index	Year	Index
1967	100	1989	383.14
1968	104.83	1990	386.75
1969	112.17	1991	392.35
1970	119.75	1992	399.07
1971	131.73	1993	410.63
1972	141.94	1994	424.91
1973	149.36	1995	439.72
1974	170.45	1996	445.58
1975	190.49	1997	454.99
1976	202.61	1998	459.4
1977	215.84	1999	460.16
1978	235.78	2000	468.05
1979	257.2	2001	472.18
1980	277.6	2002	484.41
1981	302.25	2003	495.72
1982	320.13	2004	506.13
1983	330.82	2005	516.75
1984	341.06	2006	528.12
1985	346.12	2007	539.74
1986	347.33	2008	552.16
1987	353.35	2009	570.38
1988	369.45		

REFERENCES

1. ADEQ (1996) Pretreatment with oil/water separators. Arizona Department of Environmental Quality, Water Quality Division, Aquifer Protection Program, OFR 96–15, July

2. Metcalf and Eddy (2003) Wastewater engineering treatment and reuse, 4th edn. McGraw Hill, New York, NY
3. Twardowska I (1999) Oily waste: current and upcoming EU standarization and regulatory development. Environmental technology for oil pollution 2nd international conference, analysis and utilization of oily wastes, AUZO'99, Jurata, Poland, 29 Aug–3 Sept 1999
4. Pan America Environmental (2009) Dissolved air flotation applications.Pan America Environmental, Inc., 2, 5, 2003,http://www.panamenv.com/dissolved-air-flotation-applications.htm
5. U.S. EPA (1997) Petroleum refining process waste listing determination, supplemental background document, listing support analyses.U.S. Environmental Protection Agency, Office of Solid Waste, Washington, DC, Mar
6. Bishop J (1992) Oil–water separators and skimmers: simple tools help solve complex problems. Hazmat World 5:56–60, Sept
7. Wang LK, Hung YT, Shammas NK (eds) (2005) Physicochemical treatment processes. Humana Press, Totowa, NJ, p 723
8. Wang LK, Hung YT, Shammas NK (eds) (2006) Advanced physicochemical treatment processes. Humana Press, Inc., Totowa, NJ, p 690
9. Sylvester ND, Byeseda JJ (1980) Oil/water separation by induced-air flotation. Soc Pet Eng J 20:579
10. Wang LK, Fahey EM, Wu Z (2005) Dissolved air flotation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Inc., Totowa, NJ, pp 431–500
11. Wang LK (2006) Adsorptive bubble separation and dispersed air flotation. In: Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical treatment processes. Humana Press, Inc., Totowa, NJ, pp 81–122
12. Wang LK, Shammas NK, Selke WA, Aulenbach DB (2007) Flotation thickening. In: Wang LK, Shammas NK, Hung YT (eds) Biosolids treatment processes. Humana Press, Totowa, NJ, pp 71–100
13. Alkhatib EA, Thiem LT (1991) Wastewater oil removal evaluated. Hydrocarbon Process 70:77–80
14. Melo MV, de Pereira OA, de Jesus RF, Duarte dos Santos LA (2006) Advances in non-conventional flotation for oily water treatment. J. Filtration 6:1. Also available at:http://www.lboro.ac.uk/departments/cg/research/filtration/journal_papers_volume_6.htm (2009)
15. PEC (1999) Treatment and utilization of oil-containing produced-water in oman. Petroleum Energy Center, Oman
16. Peters RW, Bennett GF (1989) The simultaneous removal of oil and heavy metals from industrial wastewaters using hydroxide or sulfide precipitation coupled with air flotation. Hazard Waste Hazard Mater 6(4):327–345
17. Shammas NK, Wang LK, Hahn HH (2010) Fundamentals of wastewater flotation. In: Wang LK, Shammas NK, Selke WA, Aulenbach DB (eds) Flotation technology. Humana Press, Totowa, NJ
18. Wang LK (1985) Theory and applications of flotation processes. US Department of Commerce, National Technical Information Service, Springfield, VA. PB 86–194198/AS, 15p, Nov
19. Dep. of the Environment (1976) The separation of oil from water for north sea operations, pollution paper no. 6. Department of the Environment, Central Unit on Environmental Pollution, UK Her Majesty's Stationary Office
20. Osamore FA, Ahiert RC (1978) Oil water separation, state-of-the-art. U.S. EPA Report, NTIS, PB-280–758. 96, Apr

21. Goel RK, Flora JR, Chen JP (2005) Flow equalization and neutralization. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Inc., Totowa, NJ
22. Paulson EG (1972) Water pollution control programs and systems. In: Lund HF (ed) Industrial pollution control handbook. McGraw-Hill, New York, NY
23. Adams CE Jr, Stein RM, Joseph JJ, Walsh T (1975) Design and performance of physical-chemical and activated sludge treatment for an edible oil plant. Proceedings of Purdue industrial waste conference, vol 30. Purdue University, West Lafayette, IN, p 457
24. Lee EL, Schwab RF (1978) Treatment of oily machinery waste. Proceedings of Purdue industrial waste conference, vol 33. Purdue University, West Lafayette, IN, p 624
25. Chen JP, Mou H, Wang LK, Matsuura T (2006) Membrane filtration. In: Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical treatment processes. Humana Press, Inc., Totowa, NJ, pp 203–260
26. Chian ESK, Chen JP, Sheng P-X, Ting Y-P, Wang LK (2007) Reverse osmosis technology for desalination. In: Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical treatment technologies. Humana Press, Inc., Totowa, NJ, pp 329–366
27. Carlton JC, Aronberg GR, Washington DR, Goodwin JK, Hall EP (1982) Handling of aluminum forming wastewater. Proceedings of Purdue industrial waste conference, vol 37. Purdue University, West Lafayette, IN, p 105
28. Wahl JR, Hayes TC, Kieper MH, Pinto SD (1979) Ultrafiltration for today's oily wastewaters, a survey of current ultrafiltration systems. Proceedings of Purdue industrial waste conference, vol 34. Purdue University, West Lafayette, IN, p 719
29. U.S. EPA (1974) Methods for chemical analysis of water and waste. US Environmental Protection Agency, Washington, DC
30. Scovarzzo P, Chen WY, Wang LK, Shammas NK (2007) Solvent extraction, leaching and supercritical extraction. In: Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical treatment processes. Humana Press, Inc., Totowa, NJ
31. ASTM (2003) Standard test method for oil and grease and petroleum hydrocarbons in water. Standard D-3921, American Society for Testing Materials, West Conshohocken, PA,http://www.astm.org/cgi-bin/SoftCart.exe/DATABASE.CART/REDLINE_PAGES/D3921.htm?L+mystore+rubs8597+1139311761, 2009
32. Roth HP, Ferguson PV (1977) An integrated industrial waste water treatment using electroflotation and reverse osmosis. Desalination 23:49
33. Oblinger FG, Weintraub MH, Gealer RL, Blais EJ (1984) In-plant operation of electrolytic cell for oily wastewater treatment. Environ Prog 3:1
34. Oblinger FG, Weintraub MH, Blais EJ, Gealer RL (1986) Automation of the electrolytic cell for the treatment of oily wastewater. Environ Prog 5:283
35. Weintraub MH, Dzieciuch MA, Gealer RL (1980) Method for breaking an oil-in-water emulsion. U.S. Patent 4,194,972, 25 Mar 1980
36. Weintraub MH, Gealer RL, Golovoy A, Dzieciuch MA (1983) Development of electrolytic treatment of oily wastewater. Environ Prog 2:32
37. Ramirez ER (1981) Physicochemical treatment of rendering wastewater by electrocoagulation. Proceedings of Purdue industrial waste conference, vol 36. Purdue University, West Lafayette, IN, p 437
38. Shammas NK, Pouet M-L, Grasmick A (2010) Wastewater treatment by electrocoagulation-filtration. In: Wang LK, Shammas NK, Selke WA, Aulenbach DB (eds) Flotation technology. Humana Press, Totowa, NJ

39. Krofta M, Wang LK (1984) Development of innovative flotation-filtration systems for water treatment, part C: an electroflotation plant for single families and institutions. Proceedings of American water works association, water reuse symposium II, vol 3. San Diego, CA, pp 1251–1264
40. Chambers DB, Cottrell WRT (1976) Flotation: two fresh ways to treat effluents. Chem Eng 83:95
41. Wang LK, Mahoney WJ (1994) Treatment of storm run-off by oil water separation, flotation, filtration and adsorption. Water Treat 9:223–233
42. Wang LK, Wang MHS, Mahoney WJ (1990) Treatment of storm run-off by oil water separation, flotation, filtration and adsorption, Part B: waste sludge management. Proceedings of the 44th industrial waste conference, Purdue University, West Lafayette, IN, pp 667–673
43. Cheremisinoff PN (1993) Oil/water separation. Natl Environ J 3:32–36
44. Krofta M, Wang LK (2000) Flotation engineering, 1st edn. Technical Manual No. Lenox/1–06–2000/368. Lenox Institute of Water Technology, Lenox, MA
45. Rohlich GA (1954) Application of air flotation to refinery waste waters. Ind Eng Chem 46:304
46. Ata S, Jameson GJ (2005) The formation of bubble clusters in flotation cells. Int J Miner Process 76:1–2
47. Anonymous (1979) Electrical process removes solids from waste streams. Chem Week 128:39
48. Gotzy E (undated) Evaluation of chemicals and their cleaning ability on oil and suspended solids in cast house cooling water using induced-air flotation. National-Southwire Aluminum Co., Hawesville, KY
49. Hart JA (1970) Air flotation treatment and reuse of refinery waste water. Proceedings of Purdue industrial waste conference, vol 25. Purdue University, West Lafayette, IN, p 406
50. Hart JA (1970) On improving wastewater quality. WaterSew Works 117:20–26, Sept–Oct
51. Pearson SC (1976) Factors influencing oil removal efficiency in dissolved air flotation units. Proceedings of 4th annual industrial pollution conference, WWEMA, Philadelphia, PA
52. Sato Y, Murakami V, Hirose T, Yamamoto H, Uryu Y (1979) Removal of emulsified air particles by dissolved air flotation. J Chem Eng Jpn 12:454
53. Beychock MR (1967) Aqueous wastes from petroleum and petrochemical plants. Wiley, New York, NY
54. Adams CE Jr, Ford DL, Eckenfelder WW (1981) Development of design and operational criteria for wastewater treatment. Enviro Press, Nashville, TN
55. Biesinger MG, Vining TS, Shell GL (1974) Industrial experience with dissolved air flotation. Proceedings of Purdue industrial waste conference, vol 29. Purdue University, West Lafayette, IN, p 290
56. Barker JE, Foltz VW, Thompson RJ (1971) Treatment of waste oil: wastewater mixture. In: Cecil LK (ed) Water – 1970, AIChE symposium series, vol 67. New York, NY, p 107
57. Woodward FE, Sproul OJ, Hall MW, Ghosh MM (1972) Abatement of pollution from a poultry processing plant. J Water Pollut Control Fed 44:1909
58. Woodward FE, Hall MW, Sproul OJ, Ghosh MM (1977) New concepts in treatment of poultry processing wastes. Water Res 11:873
59. Quigley RF, Hoffman EL (1966) Flotation of oily waste. Proceedings of Purdue industrial waste conference, vol 21. Purdue University, West Lafayette, IN, p 527
60. Steiner JL (1977) A study of dissolved and induced air flotation to remove oil and suspended solids from petroleum refinery wastewater. MS thesis, University of Toledo, Toledo, OH

61. Zimmerman MH, Jacquez RB (1981) Poultry waste pretreatment through dissolved air flotation coupled with lime-polymer conditioning. Proceedings of industrial waste conference, vol 35. Purdue University, West Lafayette, IN, p 586
62. Franzen AE, Skogan VG, Grutsch JF (1972) Chem Eng Prog 68:65
63. Churchill RJ, Tacchi KJ (1978) A critical analysis of flotation performance. In: Bennett GF (ed) Water – 1977, AIChE symposium series, AIChE, New York, NY, p 74
64. McIntyre JP (1983) Dualsystems best for dual wastes. Pollut Eng 46, Sept
65. Grosz RB (1979) Upgrading biological systems to improve performance and reliably meet effluent standards. 53rd Annual Ohio water pollution control conference, Toledo, OH, June
66. Moursy AS, El-Ela SEA (1982) Treatment of oily refinery wastes using a dissolved air flotation process. Environ Int 7:267
67. Krofta M, Wang LK (1999) Flotation and related adsorptive bubble separation processes, 4th edn. Technical Manual No. Lenox 7–25–1999/348. Lenox Institute of Water Technology, Lenox, MA
68. Bennett GF (1988) The removal of oil from wastewater by air flotation: a review. Crit Rev Environ Control 18:189–253
69. Degner VR (1976) Dispersed air flotation cell design and operation. In: Bennett GF (ed) Water – 1975, AIChE symposium series, vol 71. New York, NY, p 151
70. Degner VR, Colbert WV (1978) Dispersed gas flotation process. U.S. Patent 4,110,210, 29 Aug 1978; Degner VR, Colbert WV (1980) Dispersed air flotation machine. U.S. Patent, 4,226,706, 7 Aug 1980
71. Nipper RD (1978) A study of induced air flotation and removal of emulsified oil from a drum recycling plant wastewater. MS thesis, University of Toledo, Toledo, OH
72. Steiner JL, Bennett GF, Mohler EF, Clere LT (1978) Air flotation of refinery waste water. Chem Eng Prog 74:39
73. Hobe D (1978) Tuna cannery waste treatment. Pacific Northwest Pollution Control Association, 1978 annual conference, Victoria, BC, Oct 1978
74. Cardile RP, Fronczak R (1981) Resolution of an industry's oil waste problem. Proceedings of Purdue industrial waste conference, vol 36. Purdue University, West Lafayette, IN, p 395
75. David BT, Vose RW (1977) Custom designs cut effluent treating costs: case histories at Chevron, U.S.A. Inc. Proceedings of Purdue industrial waste conference, vol 32. Purdue University, West Lafayette, IN, p 1035
76. NATCO (2009) Tridair hydraulic Induced Gas Flotation System, NATCO Group. http://www.natcogroup.com/TRIDAIR%20HYDRAULIC%20Induced%20Gas%20Flotation%20System.htm
77. Ellis MM, Fischer PW (1973) Clarifying oil field and refinery waste waters by gas flotation. J Pet Technol 25(4):426–430
78. Volesky B, Agathos S (1974) Oil removed from refinery wastes by air flotation. Water Pollut Res Can 9:328
79. Boyd JL, Shell GL, Dahlstrom DA (1972) Treatment of oily wastewaters to meet regulatory standards. In: Cecil LK (ed) Water – 1971, AIChE symposium series, vol 68. New York, NY, p 124
80. Smith AW, Robe K (1976) Heavy-emulsion oil waste reduced from 2,000 to 10 ppm. Chem Process 22, Nov
81. Finkler ML, Olds SD, Applegate CS (1976) Pilot plant testing develops treatment for petroleum refinery. Proceedings of Purdue industrial waste conference, vol 31. Purdue University, West Lafayette, IN, p 26

82. Eckenfelder WW Jr (1980) Principles of water quality management. CBI Publishing, Boston, MA
83. Kirkup WM (1977) Refinery oil/water separation equipment and its applications. Filtr Sep vol 14, May/June p 259
84. Berne F (1982) Physical-chemical methods of treatment for oil-containing effluents. Water Sci Technol 14:1195
85. Murakami ES, Robe K (1975) Before: sewage changes $55,660/yr, now: $4,340. Food Process, Aug vol 36, p 80
86. Envirex (1982) Dissolved air flotation, product brochure. U.S. Filter/Envirex, Waukesha, WI
87. Boyd JL, Shell GL (1972) Dissolved air flotation application to industrial wastewater treatment. Proceedings of Purdue industrial waste conference, vol 27. Purdue University, West Lafayette, IN, p 705
88. Sport MC (1970) Design and operation of dissolved gas-flotation equipment and the treatment of oil field produced brine. J Pet Technol 22(8):918–920
89. Arnoldi HW, Corning DP, Sykes RL (1980) The application of flotation techniques to the treatment of tannery waste waters. J Soc Leather Technol Chem 64:69
90. Katnik KE, Pavilcius AM (1979) A simplified approval and purifying oily wastewater. Plant Eng vol 33, 18 Oct, p 81
91. Lynes PF (1980) Evaluation of induced air flotation for railyard wastewater. Proceedings of 8th annual WWEMA conference
92. Ettelt GA (1977) Control of flotation separator equipment including integrating with chemical pretreatment processes. Prog Water Technol 9:363
93. Kreye WC, Oliver JW, Sutton HC, Voreh FR (1978) Treatment of zinc plating and oil bearing wastewater. Proceedings of Purdue industrial waste conference, vol 33. Purdue University, West Lafayette, IN, p 155
94. Ciribeni DV, Gutierrez LV (2005) Froth collapse in column flotation: a prevention method using froth density estimation and fuzzy expert systems. Miner Eng 18:5
95. Rigas F, Panteleos P, Laoudis C (2000) Chemical composite design in a refinery's wastewater treatment by air flotation. Global Nest Int J 2(3):245–253
96. Liers S, Baeyens J, Mochtar I (1996) Modeling dissolved air flotation. Water Environ Res 68:1061–1075
97. Beckley CT, Eades AA (2001) A multiphase CFD model of DAF process. Water Sci Technol 43 (8):145–152
98. Leppinen DM (2000) A kinetic model of dissolved air flotation including the effects of interparticle forces. J Water Supply: Res Technol – Aqua 49(5):258–259
99. Thompson CS, Stock J, Mehta PL (1972) Cost and operating factors for treatment of oily waste water. Oil Gas J 70:53
100. Galil NI, Wolf D (2001) Removal of hydrocarbons from petrochemical wastewater by dissolved air flotation. Water Sci Technol 43(8):107–113
101. Al-Shamrani AA, James A, Xiao H (2002) Destabilization of oil-water emulsions and separation by dissolved air flotation. Water Res 36(6):1503–1512
102. Abed Baig M, Mir M, Bhatti I, Baig MA (2005) Removal of oil and grease from industrial effluents. Electron J Environ Agric Food Chem
103. Vrablik ER (1959) Fundamental principles of dissolved air flotation of industrial wastes. Proceedings of Purdue industrial waste conference, vol 14. Purdue University, West Lafayette, IN, p 743

104. Wu RM, Chu CP, Jean DS, Lee DJ (1999) Separation of oil from dissolved-air-flotation (DAF) oily sludge by freezing and thawing. In: Advances in filtration and separation technology, vol 13b. Advances in filtration & separation solutions for the Millennium '99, AFS Publications pp 756–761
105. Peters HG (1980) Mixing technology reduces energy use. Ind Waste 26, May/June
106. US ACE (2009) Civil works construction cost index system manual. 110–2–1304, Yearly Average Cost Index for Utilities, US Army Corps of Engineers, Tables, Washington, DC, p 44. PDF file is available on the Internet at http://www.nww.usace.army.mil/cost
107. PTTC (2009) Air flotation found to be economic in Kansas. PTTC newsletter, Petroleum Technology Transfer Council.www.pttc.org/tech_sum/ts_001.htm
108. Sawyer CN, McCarty PL, Parkin GF (1994) Chemistry for environmental engineering, 4th edn. McGraw-Hill, New York, NY

4
Fundamentals of Wastewater Flotation

Nazih K. Shammas, Lawrence K. Wang, and Hermann H. Hahn

Contents

Abstract The main focus of this chapter is the scientific analysis of flotation for wastewater treatment. The analysis includes a brief description of where and why flotation is used and with what intent. The physical and chemical theories of flotation as they pertain to wastewater flotation, such as characteristic bubble size and its modification, specific contact angles and their control, reactor flow-through pattern, etc. are discussed. Some more frequently encountered versions of flotation reactors are given, together with some illustrating data on the actual plant performance. Furthermore, a rational method to obtain optimum designs of flotation plants and to operate given plants under optimal conditions is described. Here, preparatory investigations and laboratory studies parallel with large-scale operation can be valuable. The design engineer will also be interested in a survey of data on process efficiency as found in the literature along with first estimates on the costs of this flotation process.

Key Words Flotation • wastewater treatment • theory of flotation • optimum design • process efficiency • costs • DAF • wastewater flotation.

1. INTRODUCTION

The main focus of this chapter is the application of scientific analysis of flotation to the treatment of wastewater. The analysis includes a brief description of where and why flotation is used and with what intent. The physical and chemical theories of flotation as they pertain to

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wastewater flotation, such as characteristic bubble size and its modification, specific contact angles and their control, reactor flow-through pattern, etc. are discussed. Some more frequently encountered versions of flotation reactors are given, together with some illustrating data on actual plant performance. Furthermore, a rational method to obtain optimum designs of flotation plants and to operate given plants under optimal conditions is described. Here, preparatory investigations and laboratory studies parallel with large-scale operation can be valuable. The design engineer will also be interested in a survey of data on process efficiency as found in the literature along with first estimates on the costs of this flotation process.

Flotation in a physical sense is the upward motion of particles, flocs, or other aggregates due to a net buoyancy force. This concept has been applied directly in wastewater treatment in removing substances that are specifically lighter than water. Predominantly, these have been oily and fatty materials.

Ore refining represents a very early and very successful application of the flotation process. Here, the buoyancy has been increased by attaching air bubbles onto the ore particles that are specifically heavier than water. The use of air bubbles to separate solids from a liquid phase has logically also been referred to as flotation; this is the narrow technical meaning of the term used in treatment technology. In wastewater treatment this process has not been very successful until recently, for reasons to be discussed below. Possible exceptions are the aforementioned oil removal either without additional air or by using compressed air.

2. WASTEWATER FLOTATION

Flotation in this discussion is understood to be primarily dissolved air flotation (DAF) (see Fig. 4.1). Flotation in this sense is not confined to substances with a specific gravity lower than that of water, and it does not include ion flotation. As will be discussed later, gas bubbles are produced in the reactor and attached to discrete particles or to particle aggregates after aggregation or during aggregation.

Flotation is used as a liquid–solid separation process similar to the function of the sedimentation process or the filtration process (1–3). This is one means of true removal of solids from wastewater. In addition, all those substances that are associated with solids through adsorption phenomena are also removed.

Flotation will be employed to separate solids that are present or that are “created” in the reactor as is the case in phosphate precipitation. A few possible and largely tested applications are flotation in the phase of primary clarification (4–6), flotation as secondary clarification with or without chemical addition (4–7), flotation in tertiary treatment (8, 9), and flotation in biosolids thickening (10–12) – the treatment of stormwater overflows has been proposed and investigated (13).

The removal of total suspended solids also affects the BOD/COD load since some fractions of the suspended phase are organic. The BOD/COD load is also reduced because dissolved organic substances, included in these global parameters, may be adsorbed onto solids that are removed by flotation (14–16).

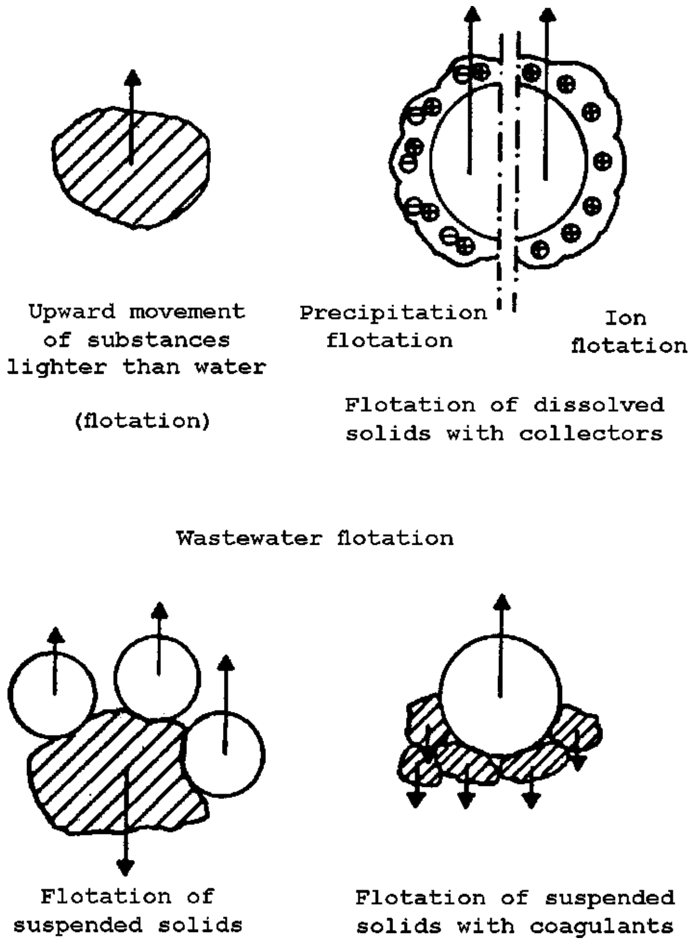


Fig. 4.1. Definition of the flotation process (13).

Processes for effective liquid–solid separation, in particular for smaller, close-to-colloidal particles will become important with increased use of chemicals in wastewater treatment. Such chemicals are applied for the removal of phosphorous components, for the improvement of solids retention in treatment plants, or for control of heavy metals. The need for liquid–solid separation will therefore also increase with increasing chemical usage (13).

Wastewater flotation – as indicated, above – requires the generation of small air bubbles, smaller than 100 μm. The reasons for this will be discussed later. This size of air bubble requirement excludes compressed air flotation as a technical process in wastewater treatment. Conceptually, electroflotation and DAF (by pressurizing fresh water or recycled water and introducing it at lower pressure into the reactor or by applying a vacuum to the air-saturated wastewater stream as it enters the reactor) may be used. From a point of view of feasible and successful operation, DAF appears to be the most efficient for the treatment of municipal

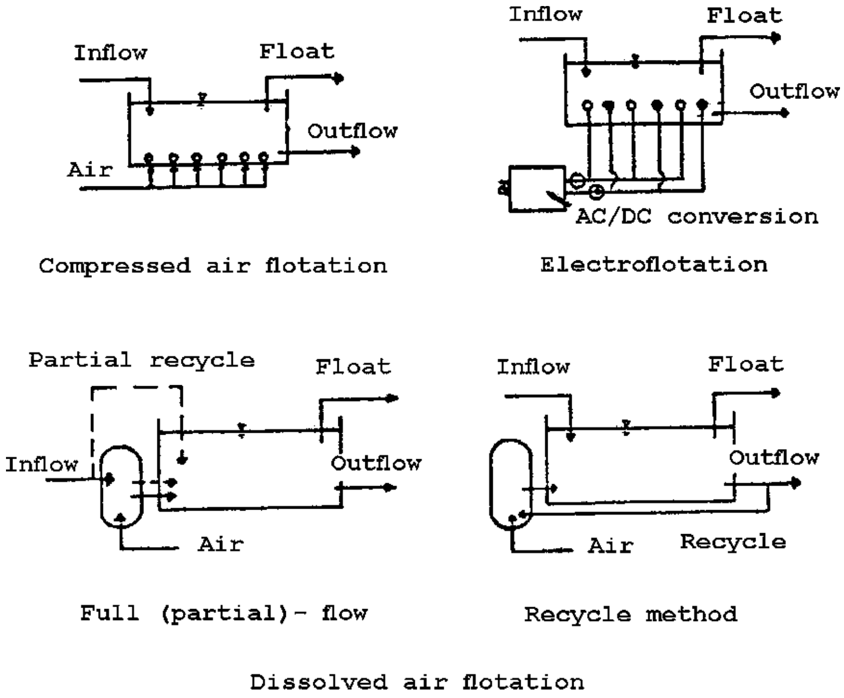


Fig. 4.2. Flotation processes (17).

wastewater. In specific industrial processes, electroflotation or even vacuum flotation might be applied. Figure 4.2 shows schematic sketches of DAF, both with and without recycling, electroflotation, and compressed air flotation (17).

The general theme of all contributions is the "scientific basis" of flotation. Previous discussions have shown several surface chemical principles that should be applicable to a description of wastewater flotation. Similarly fluid mechanical aspects or experiences in reactor design should be considered when designing a wastewater flotation unit. Complications in wastewater flotation will most likely arise from unknown and changing composition of the liquid and solid phases and also from the deviation of real-world reactors from laboratory or conceptual reactors.

In this discussion therefore the application and limits of concepts developed in the area of surface chemistry and within the field of reactor design are to be described. Consequences for planning, design, and operation of wastewater flotation units under the auspices of scientific analysis are to be elaborated. A typical example is the difficulty in defining in detail the colloidal chemical aspects of wastewater.

3. APPLICATION OF PHYSICOCHEMICAL PRINCIPLES

The physicochemical principles discussed in the following paragraphs will be applied in such way as to optimize the sequence of steps in designing and operating wastewater flotation units. In this way it should be possible to arrive at a good optimal design that allows for corrections (through operation) when wastewater characteristics change. From this analysis it should be possible to develop recommendations for a set of analyses to parallel operation and to optimize the actual performance of a real-world plant.

In the following paragraphs the most significant reaction steps are described. Knowing these, the parameters controlling each reaction step will be identified. And finally, one has to ask which physical or physicochemical principle can be applied to describe and even control parameters a priori, or where and in what way site-specific analyses must be performed in order to quantify phenomena that are specific to wastewater and that cannot yet readily be explained by physicochemical principles.

3.1. *Reaction Steps in Wastewater Flotation*

Depending upon the point of view, one can identify a very large number of reaction steps of more physical or more chemical nature, or one will find that only relatively few significantly differing steps are of importance for the technical operation of a flotation unit.

In wastewater flotation, i.e., the liquid–solid separation due to the upward movement of particle–bubble complexes, the most significant steps are (13, 14) as follows:

1. Air-bubble formation/generation/introduction into the system
2. Contact between solid particles or aggregates and air bubbles (or enclosure of bubbles into aggregates while those are forming)
3. The actual rise of the air bubble–solids complex as it is enhanced or hindered by the continuous flow through the reactor.

Additional reaction steps that might be of interest from a more basic point of view include the air/gas solution (under pressure) in water, the addition of chemicals to stabilize gas bubbles, the aggregation of solid particles in themselves prior to flotation or in conjunction with the flotation process, the modification of aggregation between gas bubbles and solid particles by means of chemicals, and the various movements of a gas bubble–solid particle complex in an actual reaction chamber as controlled by inflow, outflow, baffles, short-circuiting and not complete mixing. However, for this more technical discussion the three reaction steps as shown schematically in Fig. 4.3 are to be focused on. It will be these three steps that might become process/rate controlling (e.g., too large bubbles will not guarantee the formation of a stable bubble–solid complex under certain conditions characteristic for a wastewater system). It is these three steps that can be modified or controlled by physical and chemical means accessible to a designing or operating engineer.

3.2. *Step 1: Generation of Gas Bubbles*

Air bubble formation is accomplished in flotation reactors for wastewater treatment by saturating the wastewater stream or a part thereof or the treated recycle wastewater. This will take place with air under pressure in a pressure tank. Subsequently, the pressure is reduced to (as a rule) normal atmospheric pressure. As the Henry–Dalton law predicts, the higher

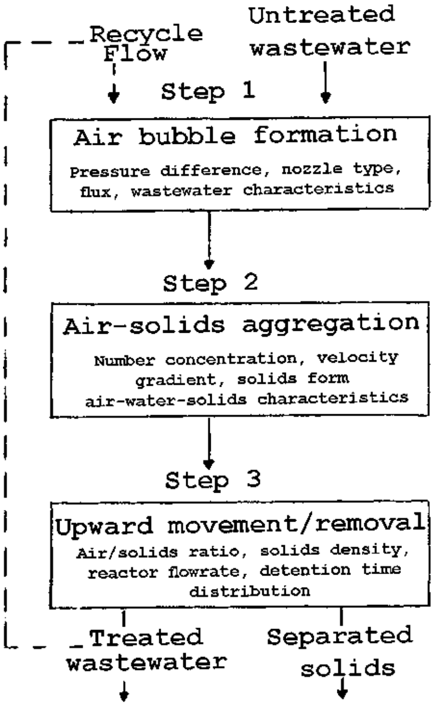


Fig. 4.3. Reaction steps in wastewater flotation indicating design and operation parameters (13).

amount of air/gas dissolution at higher (partial) pressures will be released to reach the new equilibrium. This new equilibrium is controlled by the new (atmospheric) partial pressure.

Thus, the most significant factors in the generation of gas bubbles are pressure in the air saturation chamber or pressure difference between compressor and atmosphere and flux of wastewater or recycled water through the system relative to the wastewater stream. Furthermore, the wastewater characteristics (in particular the characteristics of the dissolved phase) described, for instance, in terms of surface tension at the gas–water interface will be of importance since these describe the maximum size of stable bubbles or indicate when coalescence of bubbles will occur. Last but not the least, the type of nozzle or aerator or air injector may affect average bubble size and the size distribution of bubbles. Figure 4.4 illustrates how with a change in pressure difference the average bubble size can be modified (18). As the optimal bubble size for typical wastewater systems is in the order of 100 μm or below (as will be described later) pressure differences of 4–5 bar are usually selected (19, 20). This represents a higher limit for air pressurization from an operational point of view. Since it is also somewhat of a lower limit from the efficiency point of view, there is relatively little advantage in experimenting with this significant parameter. Similarly, the type of injector used will affect average bubble size and size distribution of bubbles as seen in Fig. 4.4. The form or type of injector device should therefore also be a design objective. However, here other aspects come into consideration as well. Possible clogging due to wastewater-specific constituents must be avoided. Commercial or competitive aspects

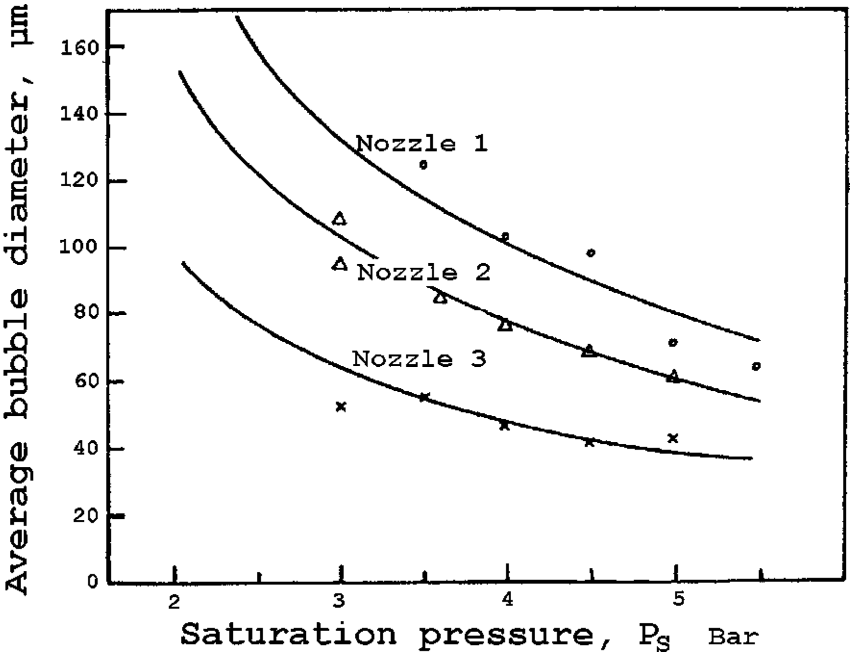


Fig. 4.4. Bubble size as function of saturation pressure for different nozzles (13). (To convert pressure to psi multiply bars by 14.5).

(i.e., the inaccessibility of specific types of information or types of devices) will also play a significant role. Thus, even though the correct choice of injector type may affect the overall process efficiency, one frequently only convinces oneself of the suitability of the device that is offered by the designing or consulting engineering firm (21). The reaction step “bubble formation” can largely be described by physical and physicochemical principles. Since the physical aspects, as explained, are mostly predetermined, specific physicochemical characteristics that describe the wastewater will have to be identified, quantified, and optimized.

3.3. *Step 2: Air–Solids Aggregation*

The formation of a stable aggregate between one or more gas bubbles and a solid particle or floc requires the collision or encounter between both partners and subsequently, a permanent adherence between these two different phases.

Encounters or soft collisions are facilitated by velocity gradients in the reactor. Those velocity gradients may result from the continuous flow in the reactor, the upward motion of the gas bubbles, and the downward motion of the solid particles or flocs. This means that predominantly, physical parameters control the reaction step. Bubble and floc (number) concentration affect the frequency of encounter. However, under usual wastewater conditions, both solid particles in the aqueous phase and gas bubbles (at air/solid ratios used for wastewater flotation) are present in number concentrations that are high enough not to be rate-limiting. Thus, rarely must there be an increase in gas bubble number concentration or in particle concentration or in the intensity of shear flow in order to attain a critical encounter frequency.

Adherence or permanent contact between particles/flocs and gas bubbles depends upon the resulting forces at the gas–water–solid interface deriving from physical attraction forces and physicochemical repulsion forces. This is a predominantly physicochemically controlled reaction step. This can be expressed conveniently (3) by considering the surface tension of the gas–solid interface and the solid–liquid interface as well as the liquid–gas interface as indicated in Fig. 4.5 (22). It becomes apparent from the pertinent Eqs. (1) and (2) that the adhesive energy increases with increasing surface tension at the solid–liquid and the liquid–gas interfaces and decreasing surface tension at the gas–solid interface. Rewriting this equation, one can define a characteristic angle, A_e, the so-called contact angle, which reflects those properties of the three-phase system that are decisive for a permanent aggregation between gas bubbles and solid surfaces. This contact angle therefore represents the most significant parameter in determining the optimal bubble size that leads to a stable gas–solid aggregate. Decreasing contact angle (i.e., for more hydrophilic flocs or particles), and generating smaller bubbles are needed to obtain a stable gas bubble–floc complex (23). Typical wastewater conditions lead to contact angles in the order of 40–50° requiring very small bubbles, possibly less than 100 μm in size (Fig. 4.6).

$$E_{\text{solid-gas}} = F(r_{\text{SL}} + r_{\text{LG}} - r_{\text{SG}}) \tag{1}$$

$$r_{\text{SG}} = r_{\text{SL}} + r_{\text{LG}} \cos A_e, \tag{2}$$

where $E_{\text{Solid-gas}}$ is the surface adsorption energy at the solid–gas interface, kcal; F is surface adsorption factor, kcal-cm/dyne; r_{SL} is surface tension at solid–liquid interface, dyne/cm; r_{LG} is surface tension at liquid–gas interface, dyne/cm; r_{SG} is surface tension at solid–gas interface, dyne/cm; and A_e is equilibrium contact angle, degree.

As indicated, the characteristics of all three phases contribute to the chemical adherence. It is possible to manipulate the surface tension at the gas–liquid interface, affecting bubble size

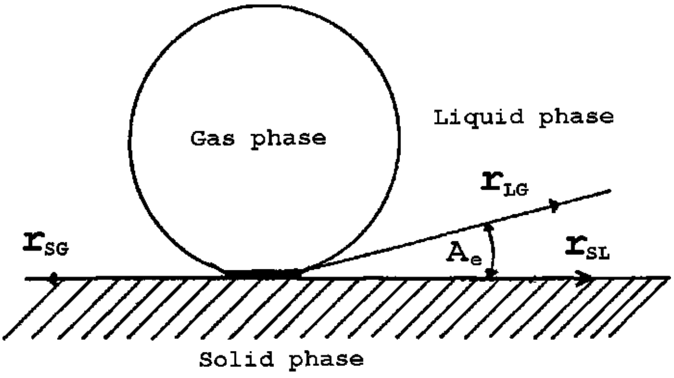


Fig. 4.5. Characterization of the three-phase system (22).

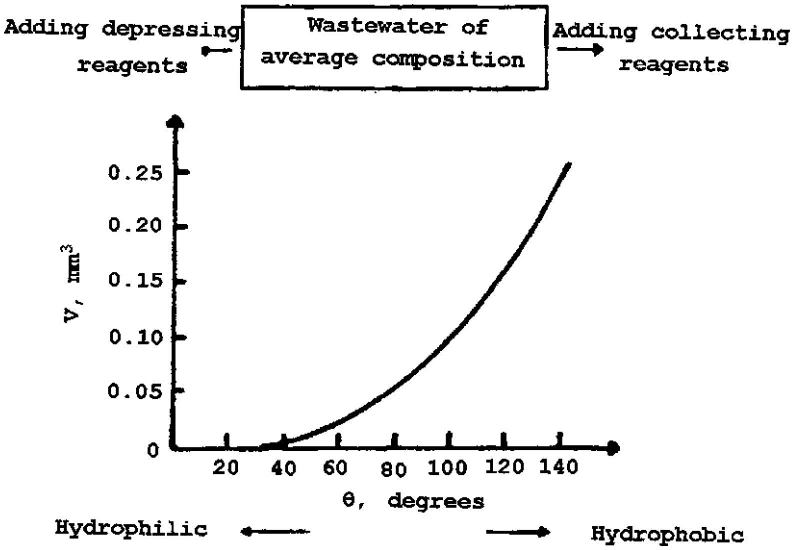


Fig. 4.6. Maximum permissible volume of air bubbles as function of contact angle at 20°C (13).

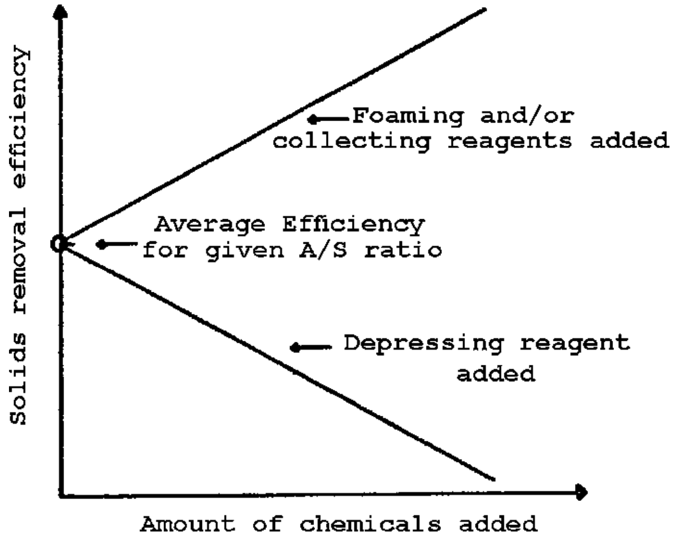


Fig. 4.7. The role of supportive and inhibitory chemicals added to control the flotation process (13).

and bubble stability (foaming agents – see schematic illustration in Fig. 4.7). It is also possible to change the surface tension at the gas–solid interface, changing the specific attachment of bubble and solids (i.e., increasing or decreasing the affinity by adding collectors or so-called depressing reagents). This is frequently done in ore treatment. Similarly it must be expected that predominantly dissolved wastewater constituents may affect or control

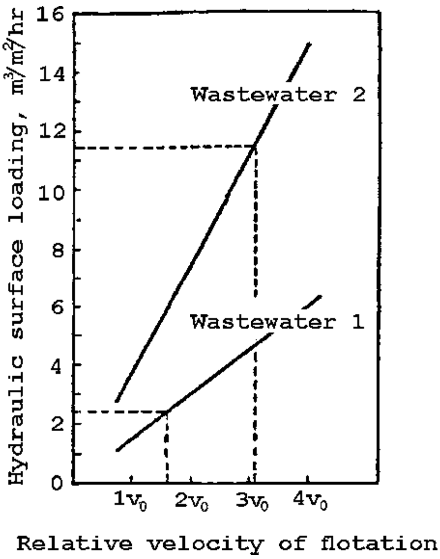


Fig. 4.8. Flotation characteristics of wastewaters quantified as different flotation velocity (13).

these interface phenomena. This means that some wastewaters are more easily floated with a given air/water injection device than others (24). This is illustrated in Fig. 4.8 where relative flotation velocities, leading to different maximum hydraulic surface loadings, have been observed under identical physical conditions for two different wastewaters.

3.4. *Step 3: Upward Movement of Bubble–Solid Complex*

Having formed a stable complex, the resulting force of gravity and buoyancy will be directed upward and lead to an upward motion. The velocity of this motion is such that the fluid resistance (drag resistance) equals the resultant net (static) buoyancy component. In this sense flotation can be looked at as the analogous reverse of sedimentation.

While there are many additional complications, for instance due to the introduction of recycled water or the introduction of a third phase or the even less complete mixing or less perfect flow through the reactor, the analogy between sedimentation and flotation still can be used to relate hydraulic surface loading and flotation velocity as illustrated in Fig. 4.9. This relationship is generally corroborated by actual plant data. In a similar fashion a relationship between maximum permissible solids loading and flotation characteristics can be derived (25–27).

From this mechanistic model of the flotation process one would derive that an increase in the number of gas bubbles attached to one solid particle or floc, provided the crucial surface tension parameters allow this, will lead to an increase in the flotation velocity. And with this the degree of liquid–solid separation in a given reactor improves. If the efficiency of the liquid–solid separation is expressed, for instance, by the concentration of remaining solids and the amount of gas bubbles attached to a solid particle by the so-called air/solid ratio, then with increasing air/solids ratio the remaining concentration of floating particles should decrease (28). Observations confirming these phenomena are shown in Fig. 4.10.

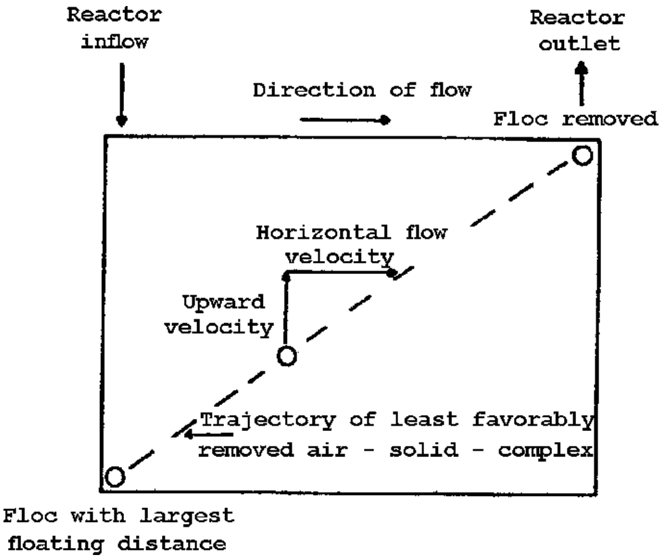
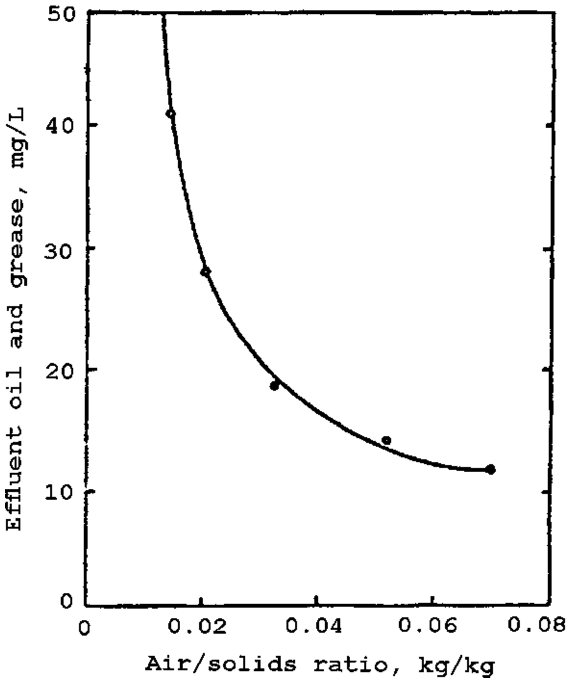


Fig. 4.9. Boundary trajectory of a bubble–solids aggregate that is still removed (13).

Fig. 4.10. Process efficiency as function of *A*/*S* ratio (13).



This argumentation has led to the formulation of one of the most important flotation parameters, the air/solids ratio (i.e., the *A*/*S* ratio). However, in order to achieve a higher *A*/*S* ratio one has to increase either both the pressure difference and the amount of water recycled or one of those two parameters separately, introducing in all instances additional turbulence and possibly a disturbance of the flow-through pattern. This, in turn, may mean a reduction in overall process efficiency. Thus, only within certain boundaries, the increase of *A*/*S* ratios will lead to a direct increase in the process efficiency.

It has been mentioned before that the flow-through pattern within the continuous flow reactor is of great importance for the net upward motion of the bubble–solid complex. Hence, it will affect the overall process efficiency. The flow pattern is controlled or determined by the geometry of the reactor (depth, width, length) and by the location of input and output relative to each other and relative to the reactor geometry. Baffles and similar devices built into the reactor will also affect in their way the flow-through pattern. Even the flow rate or flux relative to reactor volume and reactor geometry will control to some degree the flow-through pattern and therefore the upward motion of the bubble–solid complex. The schematic drawings of two flotation reactors in Fig. 4.11 show how the effective flotation zone differs from the overall reactor geometry (24). In addition, short-circuiting and dead space phenomena identified, for instance, through the measurement of local flow rates will show further deviation from the ideal of a completely mixed continuous flow rector. This leads to different relationships between, for instance, the flotation velocity and the maximum permissible hydraulic surface loading as is shown in Fig. 4.11 for the two reactor types. Apparently the differently conceived reactor "one" allows higher hydraulic surface loading and is therefore

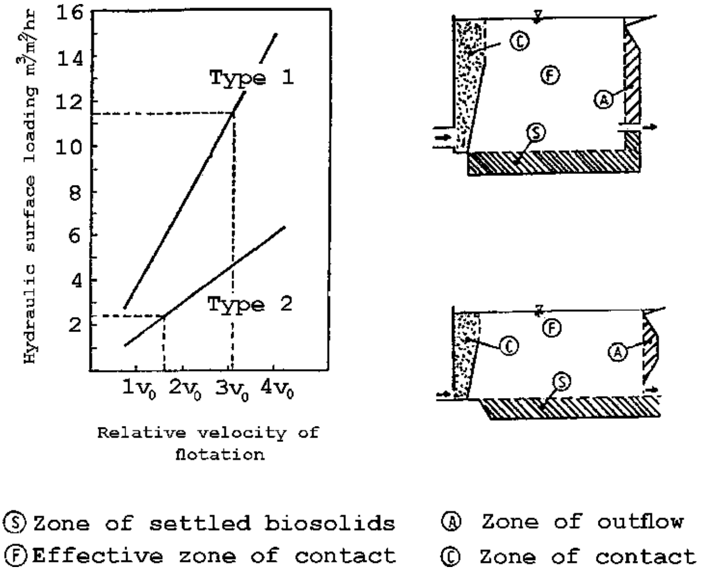


Fig. 4.11. Hydraulic surface loading vs. relative flotation velocity for two types of tanks (13).

more efficient than reactor “two”. In this field, there is little experience on the application of hydromechanic and chemical engineering principles to the description and prediction of flotation reactor behavior. Thus, the technique of model scale experiments might be exploited to investigate this reaction step (13, 14, 29, 30). With more data on these phenomena it should be possible to describe and predict plant performance or even to optimize iteratively reactor geometry and reactor appurtenances.

4. WASTEWATER FLOTATION DESIGN

In deciding for or against the use of a flotation device in wastewater treatment it is necessary to have information on the general efficiency of the process (representative data for average wastewater characteristics) and on the specific site-dependent/wastewater-dependent modifications of such efficiency data, which can only be obtained through experiments. Furthermore cost data, both, absolute and in relation to other comparable liquid–solid separation processes must be provided. If then, the decision is made in favor of a flotation reactor, design criteria, sequences of fixing design parameters, and the interrelationship with pilot plant experiments must be identified. Thus, the following sections deal with the necessary steps in the design, the identification of expected efficiency, and the projected cost of a flotation device. Prior to this a brief introduction to typical flotation devices will be given along with case studies illustrating the application.

4.1. Typical Large-Scale Flotation Reactors

Flotation reactors are even more the domain of the mechanical engineer than other wastewater treatment units. The mechanical engineer will tailor the design in part specifically for the encountered wastewater treatment problem. In part this will be (competition-oriented) specific know-how of special firms. Thus, it is difficult to find sample designs that might be called “standard”.

In Figs. 4.12 and 4.13 two types of more frequently encountered flotation reactors of differing characteristics are shown in order to point out various important and generally encountered features. Figure 4.12 shows a rectangular (35) longitudinally oriented reactor while Fig. 4.13 shows a cylindrical radially operated reactor (31). Similar arguments as for or against rectangular and cylindrical sedimentation basins are employed in outlining the relative merits of one or the other form. Both types have been used in technical plants for the flotation of municipal wastewater, with good success.

Both figures show that, independent of the different flow-through pattern, various devices and/or appurtenances needed for the flotation of municipal wastewater appear similarly in both designs (13, 14):

1. The inflow is mixed with the air-saturated and pressurized recycle water at atmospheric pressure and enters the reactor relatively deep (through baffles).
2. The outflow is separated from the reactor by another baffle, protecting the floating biosolids blanket.

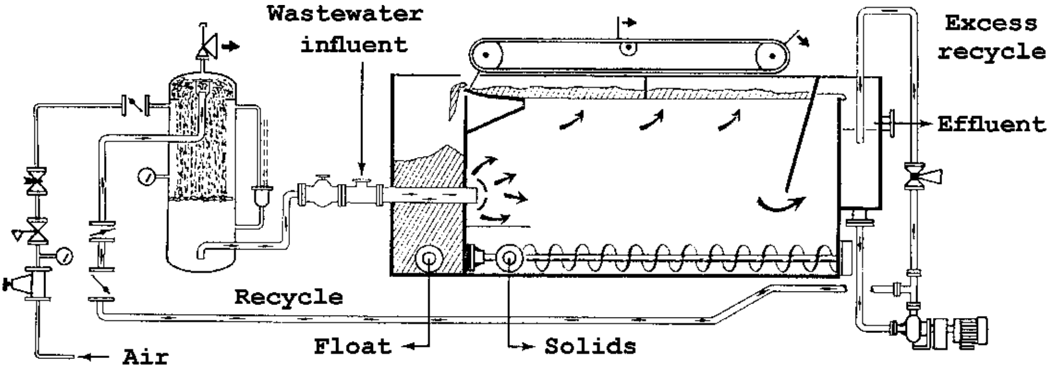


Fig. 4.12. Longitudinal flotation reactor (35).

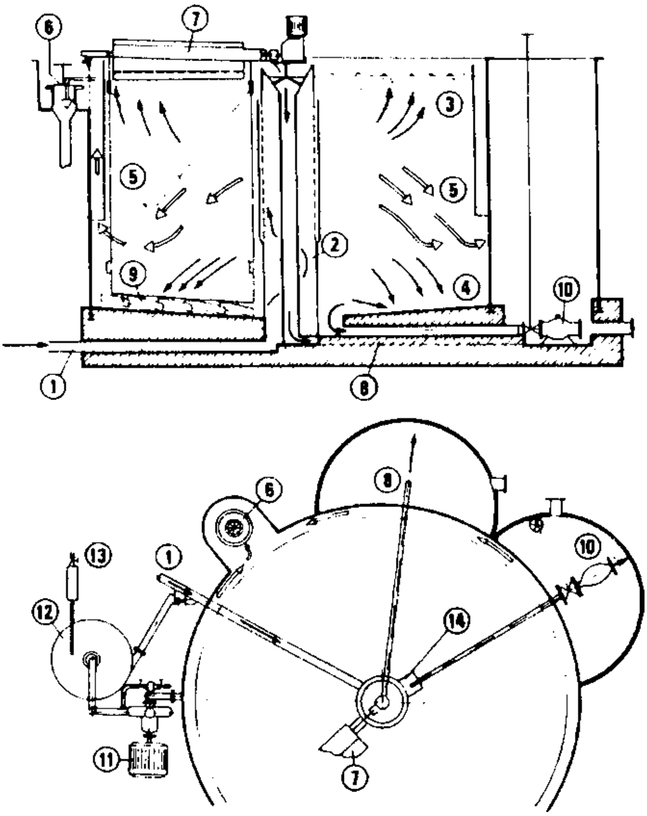


Fig. 4.13. Cylindrical flotation reactor (15, 31).

3. In the treatment of municipal wastewater both types of solids removal should be provided, for the floating biosolids on top of the reactor (by an endless belt mechanism as shown in Fig. 4.12 or a rotating scoop as shown in Fig. 4.13) and a bottom residue removal device (scraper in the case of Fig. 4.12 and rotary plow in the case of Fig. 4.13) moving the sediment into a central sump.

Injector and nozzle design; form, size, and location of pressure tanks; and pumps and fixtures vary from manufacturer to manufacturer. This can also be deduced by comparing Fig. 4.12 with Fig. 4.13.

4.2. Flotation–Filtration Reactor

The recently developed flotation–filtration reactor consists of two unit processes: DAF and filtration with built-in chemical flocculation in one single tank. It is an excellent package plant for tertiary treatment of secondary effluents (32).

The influent enters the inlet at the center near bottom, and it flows through a hydraulic rotary joint and an inlet distributor into the rapid mixing section of a slowly moving carriage. The entire moving carriage consists of rapid mixer, flocculator, air dissolving tube, backwash pump, biosolids discharge scoop, and biosolids recycle scoop. From the rapid mixing section, the water enters the hydraulic flocculator for gradually building up the flocs by gentle mixing. The flocculated water moves from the flocculator into the flotation compartment clockwise with the same velocity as the entire carriage including the flocculator moving counterclockwise simultaneously. The outgoing flocculator effluent velocity is compensated by the opposite velocity of the moving carriage, resulting in a “zero” horizontal velocity of the flotation chamber influent. The flocculated water thus stands still in the flotation tank for optimum clarification. At the outlet of the flocculator, clean water with microscopic air bubbles is added to the flotation tank in order to float the insoluble flocs and suspended matter to the water surface. The float accumulated on the water surface is scooped off by biosolids discharge scoop and discharged into the center biosolids collector where there is a biosolids outlet to an appropriate treatment facility. The bottom of the unit is composed of multiple sections of sand filter and clear well. The clarified flotation effluent passes through the sand filter downward and enters the clear well. The filters are backwashed periodically.

The pressurized feed stream is held at this high pressure for about 0.2–3.0 min in a retention tank (i.e., a pressure vessel) designed to provide sufficient time for dissolution of air into the stream to be treated. From the retention tank, the stream is released back to atmospheric pressure in the flotation chamber. Most of the pressure drop occurs after a pressure reducing valve and in the transfer line between the retention tank and flotation chamber, so that the turbulent effects of depressurization can be minimized. The sudden reduction in pressure in the flotation chamber results in the release of microscopic air bubbles (average diameter 80 μm or smaller), which attach themselves to suspended or colloidal particles in the process water in the flotation chamber. This results in agglomeration that, due to the entrained air, gives a net combined specific gravity less than that of water that causes the flotation phenomenon. The vertical rising rate of air bubbles ranges between 0.5 and 2.0 ft/min (32). The floated materials rise to the surface of the flotation chamber to form a floated layer. Specially designed flight scrapers, scoops, or other skimming devices continuously remove the floated material. The float can in certain cases attain a thickness of many inches and can be relatively stable for a short period. The layer thickens with time, but undue delays in removal will cause a release of particulates back to the liquid.

The flotation–filtration plant uses granular media filtration, which involves the passage of water through a filter bed of filter media with resulting deposition of solids. Eventually the hydraulic pressure drop across the filter bed becomes excessive, or the efficiency of the filter bed to remove suspended solids is impaired. Cleaning the bed by backwashing is then necessary to restore operating head and filter effluent quality. The time in service between backwashings is called the filter run time. The head loss at which filtration is interrupted for cleaning is termed the terminal head loss. Either sand alone or both anthracite and sand can be used as the filter media. When both anthracite and sand are used as the filter media, with anthracite being placed on top of the sand, the filtration operation is termed dual-media filtration. Gravity granular media filters in the flotation–filtration plant operate by using the available head in the DAF chamber. The filter system includes multiple filter compartments. This allows for the filtration system to continue operating while one compartment is being backwashed by automatic backwash mechanism. Each filter compartment is, in effect, a single filter. Filter flow rate is based on declining rate, as there are no flow rate controllers. An attractive feature of the automatic backwash filter is that operating head losses are generally less than 1 ft of water (provided that the filter bed consists of either 11 in. of sand, or 2 in. of anthracite plus 9 in. of sand.) A motor-driven moving carriage assembly is equipped with a backwash (clean water) pump and a washwater collection pump and it backwashes each filter compartment sequentially as it rotates to the top of the compartment. The backwash unit also includes a hood that covers the filter compartment during backwashing. The collection pump automatically draws backwash wastewater from the filter and discharges the wastewater to a sewer or recycling unit for reuse.

The advantages of this high-rate flotation–filtration system include (32, 34) the following:

1. *High efficiency of pollutants removal*: The flotation–filtration reactor can remove not only classical pollutants, but also toxic heavy metals, toxic inorganics, and toxic organics.
2. *Removal of troubling pollutants*: Fungi, floating algae, trace oil, soluble phosphate, asbestos, etc., in secondary effluent or industrial effluent can be easily separated by the flotation–filtration reactor, while such pollutants cannot be cost-effectively removed by conventional processes.
3. *Cost saving*: Tertiary treatment processes, such as ultrafiltration, reverse osmosis, granular carbon adsorption, ion exchange, and chemical oxidation, all require pretreatment systems. The flotation–filtration reactor can be used as an alternative tertiary treatment or used as a pretreatment unit. In either case, a significant cost saving is expected.
4. *Unique Construction*: A flotation–filtration reactor can be delivered fully prefabricated. Larger units are delivered in parts that are flanged together. Generally, no heavy foundation or support structure is needed as the total load factor when filled with water weighs less than 250 lb/ft^2, which is less than the load for a parking lot. A flat concrete ground pad is usually sufficient.
5. *Complete automation* (including influent flow control, water level control, proportional chemical feed, and timer-controlled or headloss-controlled filter backwash) significantly simplifies the plant's operation and maintenance. Only one operator is required if manual operation is preferred.

6. *Energy saving*: The flotation–filtration system uses a static rapid mixer and a hydraulic baffled flocculator both having no moving parts. These static units not only do not break down, but also conserve energy.
7. *Water conservation and environmental impact*: The flotation–filtration reactor plant recycles all filter backwash water to the head of the plant for reprocessing; thus it conserves water and produces no wastewater. The amount of biosolids produced is very small in comparison with conventional processes.

4.3. Applications of the DAF Process

Wastewaters can be classified into domestic wastewater, industrial wastewater, and a mixture of both wastewaters. Either the domestic or the mixture of wastewaters is also called municipal wastewater. Since the characteristics of industrial wastewater vary significantly from industry to industry, only the characteristics of domestic wastewater are presented in Table 4.1 (32).

Wastewater treatment processes are classified as pretreatment, primary treatment, secondary treatment, tertiary treatment, and biosolids management.

Pretreatment processes include grinding for solids size reduction, screening for solids removal, flow equalization, and/or oil separation.

4.3.1. Primary Treatment

Primary treatment can be chemical and/or physical. Chemical primary treatment includes pH adjustment by neutralization and nutrients and metals removal by coagulation/flocculation. Physical primary treatment usually refers to suspended solids removal by sedimentation or DAF (see Fig. 4.14) (33). The effluent from a primary treatment process system is called primary effluent. A wastewater treatment plant having only pretreatment, primary treatment, and biosolids treatment facilities is classified as primary treatment plant although biosolids handling elements are not part of primary treatment.

For municipal wastewater treatment, primary treatment is considered to be the absolute minimum. Table 4.1 indicates that a primary treatment plant can remove about 90% of settleable solids, 10–30% of organic carbon, up to 10% of organic nitrogen, and less than 15% of total phosphorus (32).

4.3.2. Secondary Treatment

Secondary treatment generally involves a biological process for removal of organic substances through biochemical adsorption and subsequent oxidation either in the reactor or in other elements. The biological process can be activated sludge, trickling filter, rotating biological contactor, activated biofilter, aquaculture, lagoons, oxidation ditch, or an anaerobic biological treatment process. The effluent from a secondary treatment process is called secondary effluent. A wastewater treatment plant having pretreatment, primary treatment, secondary treatment, and biosolids treatment facilities is classified as secondary treatment plant. An example for the application of DAF in secondary treatment is shown in Fig. 4.15 (35).

Table 4.1
Constituents of municipal wastewater and their removal in primary and secondary treatment (32)

Parameter	Concentration (mg/L except as noted)		Removal (%)	
	Range	Typical	Primary	Secondary
Physical				
Total Solids	350–1,250	750		
Settleable solids	50–200	100	90	
Total suspended solids	100–400	250		50–90
Volatile suspended solids	70–300	150		60–90
Total dissolved solids	250–850	500		5
Volatile dissolved solids	100–300	150		30
Chemical				
pH, unit	7–7.5	7.0		
Calcium	30–50	40		
Chlorides	30–85	50		
Sulphate	20–60	15		
Organic carbon				
BOD_5	100–400	250	10–30	>90
COD	200–1,000	500	10–30	70–80
TOD	200–1,100	500	10–30	70–80
TOC	100–400	250	10–30	60–80
Nitrogen				
Total (as N)	15–90	40		35
Organic	5–40	25	10	50–80
Ammonia	10–50	25		0–20
Nitrites			Produced	
Nitrates			Produced	
Phosphorus				
Total (as P)	5–20	12	0–15	20–40
Organic	1–5	2		
Inorganic	5–15	10		

Secondary treatment of municipal wastewater as is seen in Table 4.1 can remove up to 90% of suspended solids, 30% of volatile dissolved solids, over 90% of BOD, up to 80% of COD, TOC and organic nitrogen, up to 20% of ammonia nitrogen, and up to 40% of total phosphorus (32).

4.3.3. *Tertiary Treatment*

In many instances, secondary treatment is no longer sufficient for protection of lakes, streams, estuaries, or ground water supply. Tertiary treatment (or advanced treatment) is necessary when particular contaminants must be removed to meet effluent standards, or to prepare the water for reuse (see Fig. 4.16) (35). Common tertiary treatment processes include

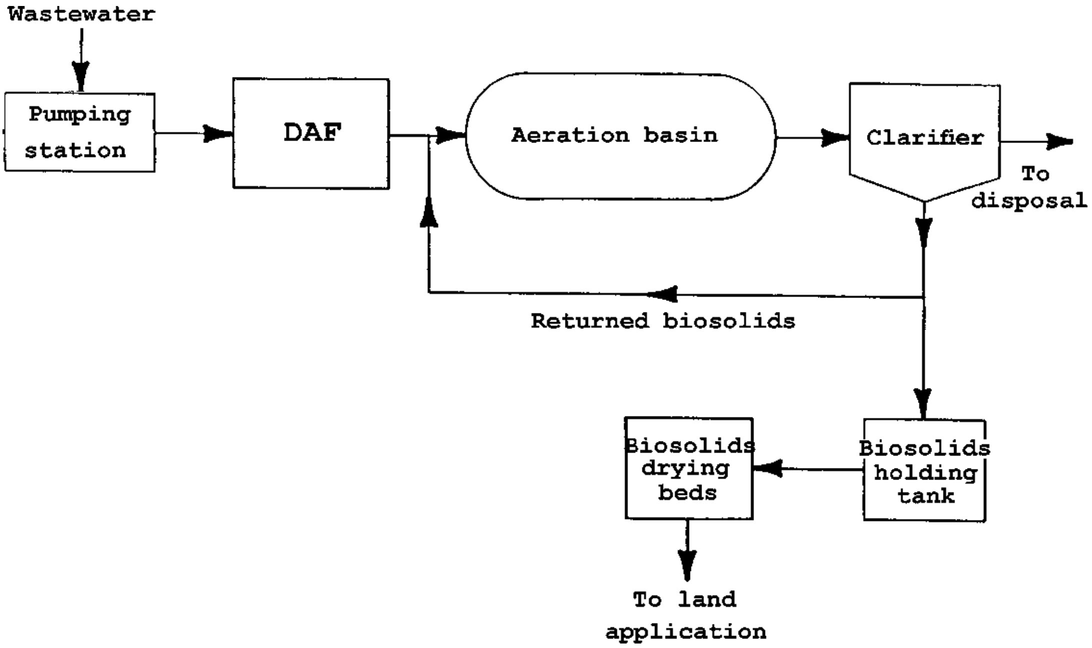


Fig. 4.14. Application of DAF as a primary clarification process (33).

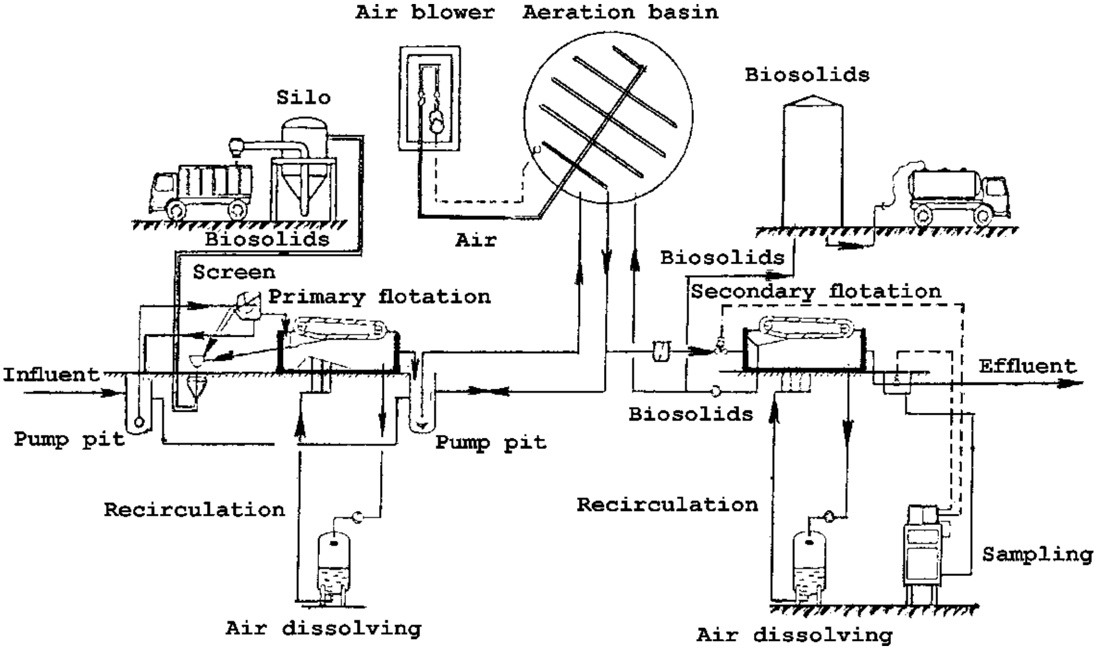


Fig. 4.15. Application of DAF as a secondary clarification process (35).

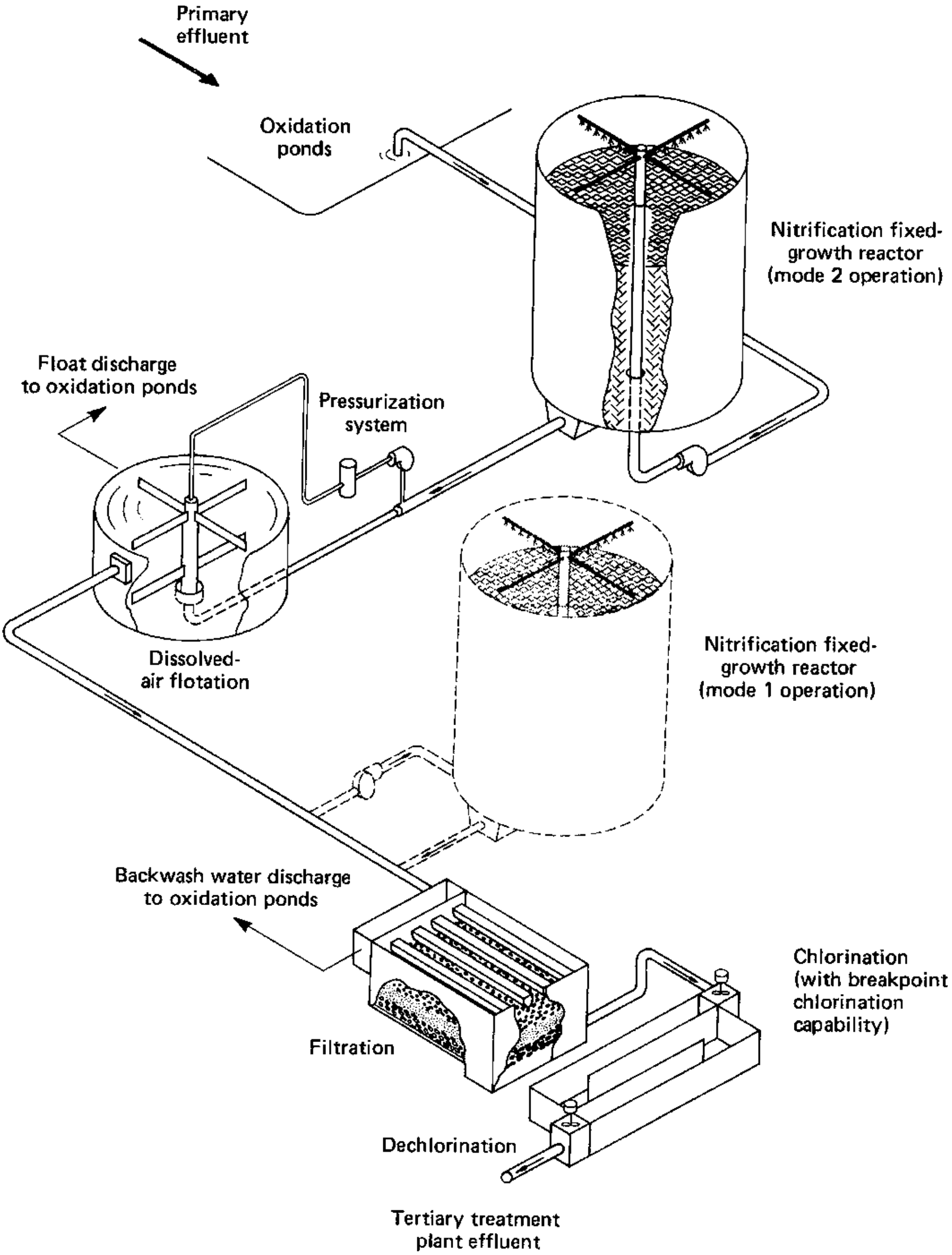


Fig. 4.16. Application of DAF as a tertiary clarification process (35).

ultrafiltration, reverse osmosis, carbon adsorption, ion exchange, sand filtration, denitrification, ammonia stripping, and coagulation/clarification. The objectives of tertiary treatment include removal of phosphorus, nitrogen, residual organics, residual color, residual suspended solids, or residual dissolved solids (32). The effluent from a tertiary treatment process is called tertiary effluent. A treatment plant having all stages of treatment and biosolids management facilities is classified as tertiary treatment plant.

The plant effluent from a primary treatment plant, a secondary treatment plant, or a tertiary treatment plant is often disinfected with chlorine, ozone, or UV light to destroy pathogenic microorganisms before discharge into the receiving waters (34).

4.3.4. Industrial-Wastes Treatment

For treatment of combined wastewater by municipalities or treatment of industrial wastewater by the industry many more water quality parameters must be added on the plant effluent monitoring list because industrial wastewaters often contain toxic or extremely undesirable contaminants. Table 4.2 indicates the parameters set by the US Environmental Protection Agency (US EPA) Effluent Discharge Standards for industrial wastewater or combined wastewater (32).

4.3.5. Biosolids Treatment

Biosolids treatment and management technologies include thickening by gravity or DAF (see Fig. 4.17) (36); stabilization by aerobic or anaerobic digestion; conditioning by chemical or heat treatment; dewatering by belt filter presses, centrifugation, sandbeds or heat drying; and ultimate reuse/disposal by landfill, land application, or incineration (conversion into energy).

4.4. Application Examples

In one instance, seasonal overloading (from wineries) caused repeated breakdown of a municipal activated sludge treatment plant. Therefore, the hydraulically overloaded primary clarifier was substituted by a flotation unit with a preceding chemical dosage step. The conclusions on the basis of a long-term investigation can be formulated as follows (13):

1. The solids retention is 20–30% higher than in a sedimentation clarifier (this leads to or is coupled with an increase of 20–40% in COD reduction).
2. The treated liquid phase has higher oxygen concentrations (3–9 mg/L) and therefore introduces a higher oxygen load into the activated sludge unit where such oxygen is needed.
3. The solids content of the float blanket is higher than in settled biosolids. This means that despite higher solids retention, i.e., higher biosolids production than in a sedimentation unit, no higher biosolids volume is to be handled.
4. The maximum hydraulic loading and solids loading is higher than for sedimentation basins with the added possibility of adjustment due to feed fluctuations (within certain ranges).

Table 4.2
Parameters setting the standards for the discharge of industrial and combined wastewater (US EPA, 32)

Parameter	Industry													
	Automobile	Beverage	Canning	Fertilizer	Inorganic chemicals	Organic chemicals	Meat products	Metal finishing	Plastic and synthetics	Pulp and paper	Petroleum refining	Steel	Textiles	Dairy
BOD_5	x	x	x		x	x	x		x	x	x		x	x
COD	x		x	x	x	x		x	x	x	x		x	x
TOC			x			x				x	x			x
TOD						x								
pH		x	x	x	x	x	x		x	x	x	x	x	x
Total solids	x				x									
Suspended solids	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Settleable solids		x					x							
Total dissolved solids		x	x	x	x	x	x		x	x	x		x	
Volatile suspended solids											x			
Oil and Grease	x	x		x		x	x	x	x	x	x	x	x	
Heavy metals, general						x		x		x			x	
Chromium	x			x	x						x	x	x	
Copper											x			
Nickel	x													
Iron	x			x	x						x	x		
Zinc	x			x					x		x	x		
Arsenic					x									
Mercury				x	x									
Lead	x				x						x			
Tin	x											x		
Cadmium	x													
Calcium				x										
Fluoride				x	x									

Cyanide					x	x		x	x		x	x		
Chloride	x			x	x	x					x	x		x
Sulfate	x			x	x				x		x	x		
Ammonia	x			x		x	x		x	x	x	x		
Sodium				x										
Silicates					x									
Sulfite										x				
Nitrate	x			x		x			x	x	x			x
Phosphorus			x	x	x	x	x		x	x	x			x
Urea or organic nitrogen				x										
Color		x	x				x			x	x		x	x
Total coliforms		x					x			x				
Fecal coliforms			x							x				
Toxic materials		x					x		x	x	x		x	x
Temperature		x	x	x	x						x	x	x	x
Turbidity		x					x			x	x			x
Foam		x												
Odor											x			
Phenols	x				x	x			x	x	x	x	x	
Chlorinated benezoids and polynuclear aromatics					x				x					
Mercaptans/ sulfide									x		x		x	

The overall picture of the effectiveness of this combination of coagulation and flotation with an activated sludge unit can be obtained from the following data (13):

Influent

BOD=375–600 mg/L
COD=600 mg/L

Effluent

Solids removal up to 95% over a range of solids loading rate from 1 kg/m^{2}/h to 5.5 kg/m^{2}/h
COD reduction=70–75% (in sedimentation 50–55%)
Oxygen concentration=30–80% of saturation value at 30–65% recycled water

Biosolids characteristics

Solids concentration=7–9% at recycle rates of 30–70% and A/S ratio of 0.02–0.20

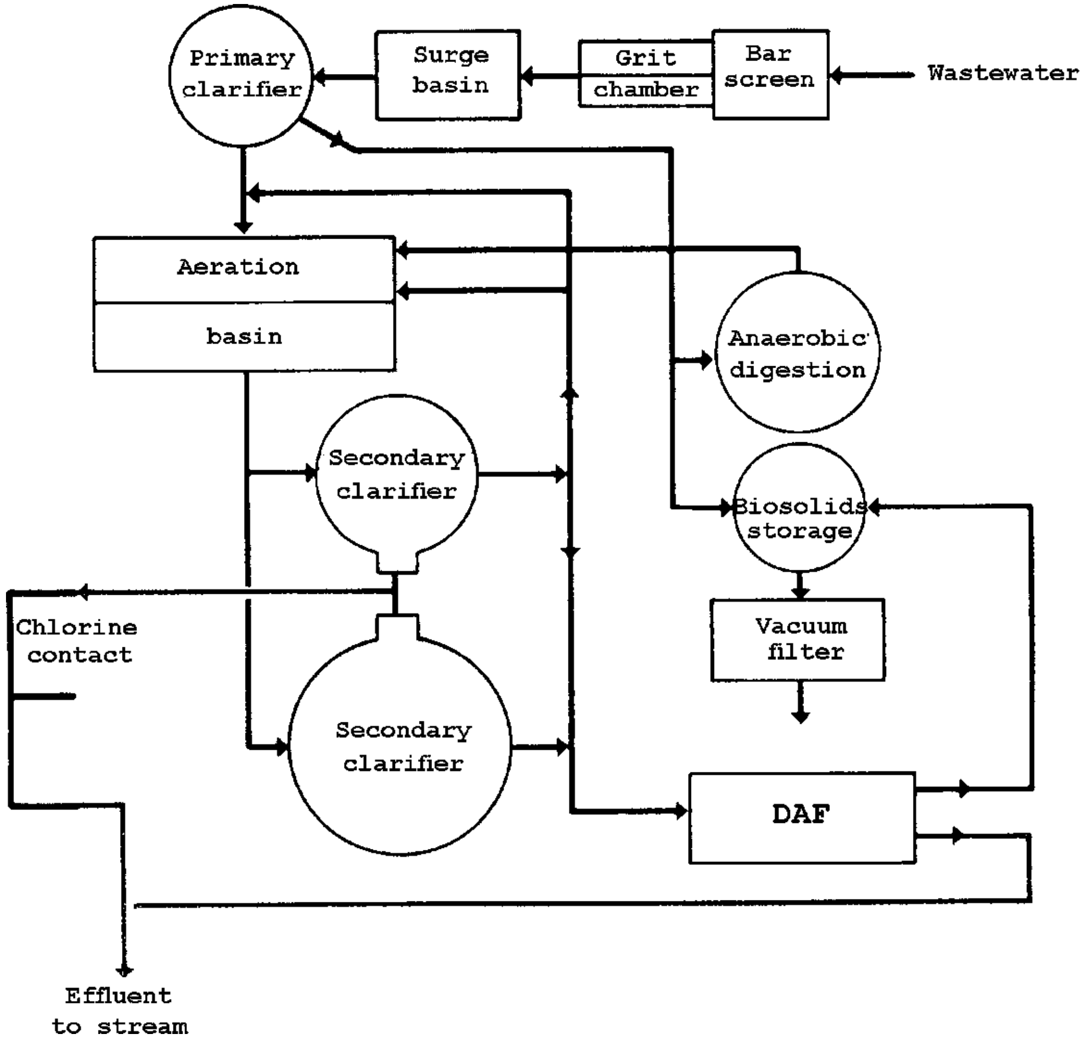


Fig. 4.17. Application of DAF as a biosolids thickening process (36).

In another instance, an overloaded or insufficiently operating secondary clarifier was to be aided by an additional flotation reactor placed between the activated sludge unit and the secondary clarifier. It was expected that not only liquid–solid separation would go to higher efficiencies but also that the recycled activated sludge would be more active due to higher oxygen concentration. Furthermore, flotation might affect a higher solids concentration of the separated activated sludge, allowing a better control of the biosolids loading parameters. Again the following positive statements may serve as a summary of the data obtained in a long-term large-scale investigation:

1. The volume of the return biosolids is reduced to about 1/10th of the original amount.
2. The oxygen concentration in the separated biosolids is of the same order as in the aerated effluent of the activated sludge reactor and presents a reservoir of few minutes.
3. The oxygen concentration of the effluent of the flotation reactor is higher by a factor of 2–3 than the inflow into the activated sludge plant and higher than the effluent of the supernatant from the secondary sedimentation basin.

The following characteristic data would describe the specific situation appropriately (13):

Influent to the flotation cell (effluent of the activated sludge reactor)
Flow = 6.5 m^3/h
DO = 4 mg/L
TSS = 2,200 mg/L
I_{sv} = 107 mL/mg

Effluent of the flotation cell
Flow = 6.0 m^3/h
DO = 6.8 mg/L
TSS = 5,500 mg/L

Biosolids
Flow = 0.5 m^3/h
DO = 1.9 mg/L
TSS = 27,800 mg/L
I_{sv} = 35.5 mL/mg

4.5. *Design Criteria*

The more basic interpretation of the different reaction steps of the flotation process, as well as observations from treatment plant operation, indicates that this particular unit process is controlled by a large number of design and operation parameters. Design parameters are understood to include (13, 14) the following:

1. Dimensions of the reactor
2. Arrangement of inflow and outflow
3. Capacities of ancillary equipment (pressure tank, pumps, etc.)
4. Provisions for variation in operation (amount of air introduced, amount and type of chemicals added, etc.)

Operational parameters include the following:

1. Amount of air introduced
2. Air to solid ratio, *A*/*S*
3. Hydraulic loading
4. Type and amount of chemicals
5. pH adjustments, etc.

The operational parameters may change with changing wastewater characteristics and can or must be controlled through appropriate adjustment in order to optimize the process. Thus, the setting of design parameters represents a sort of irreversible decision while operational parameters can be adjusted continuously to compensate for less than optimal design. This means that great care must be taken in deciding on the order of magnitude of such design parameters.

Figure 4.18 shows a list of pertinent process variables. Each variable is characterized as to whether it is primarily decided during the phase of design and construction or if it still can be adapted during the phase of operation. It is seen that a large number of variables fall into the category of design parameters, while other parameters, predominantly of chemical nature, are operational parameters. The variables to be fixed in a specific design in direct correspondence with the type of wastewater to be floated, the amount of wastewater, and the specific purification requirements are (13) as follows:

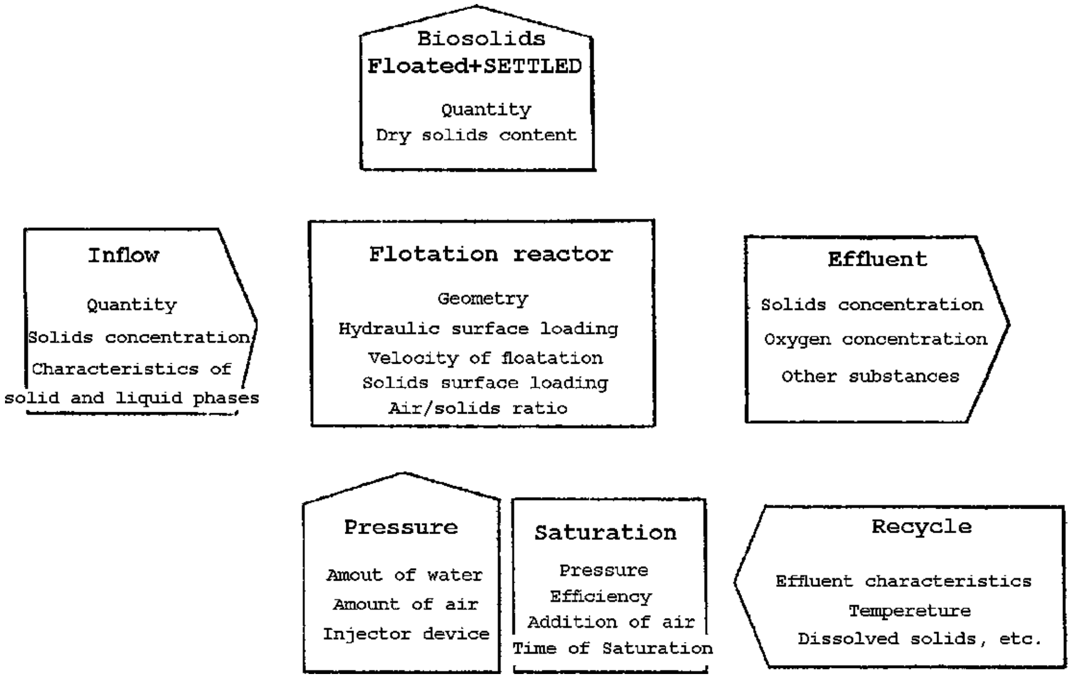


Fig. 4.18. Design parameters and operation variables of the flotation process (13).

1. For the purpose of bubble generation
    - Injector type and form
    - Recycle flow rate
    - Volume of pressure tank
    - Pressure
2. For the aggregation of bubbles and solids and for the transport of the bubble–solids complex
    - Effective surface area including baffle arrangement
    - Effective reactor depth, including biosolids handling and storing
    - Inflow and outflow arrangement, determining flow-through pattern

A conceptual understanding, description, and prediction of the effect of these parameters upon the flotation of wastewater do not yet exist (13). Therefore, it is not possible to describe and optimize such designs by mathematical models. It is advisable to use many bench or pilot scale model investigations to support intuition and experience in characterizing plant performance, with the goal of finding optimum plant dimensions.

Whenever possible, as mentioned above, design should be based on pilot flotation–filtration investigations of the actual wastewater to be treated. Such pilot plant investigations are the best way to assure (32) the following:

1. Selection of optimal parameters, such as chemical type and dosage, flocculation detention time and G value, flotation detention time, flotation overflow rate, air supply rate, pressure and detention time of air dissolving tube, clarifier recirculation ratio, filtration rate, terminal head loss, filter run time, backwash rate, etc.
2. Defining effluent quality performance for a given application
3. Determination of the effects of primary and/or secondary treatment variations
4. Representative cost comparisons between different flotation/filtration designs capable of equivalent performance (i.e., quantity treated and plant effluent quality).

In general, the retention time in the flocculation/flotation chambers is usually 3–5 min depending on the characteristics of the wastewater flow and the performance of the particular plant. Only the recycle flow flotation system is feasible for tertiary treatment of secondary effluent. The pressure and retention time of air dissolving tube are in the ranges of 25–70 psig and 0.2–3.0 min, respectively. A typical flotation overflow rate for tertiary treatment employing a flotation–filtration unit is 3.5 gpm/ft^2. Typical filtration rate and filter backwash rate are 3.0 gpm/ft^2 and 15.0 gpm/ft^2, respectively. Terminal head loss usually is less than 1 ft (32).

One procedure for a global assessment of the interaction between the reactor and wastewater of specific characteristics in terms of flotation efficiency is described in the following section.

4.6. Rational Design

A simplified flowsheet for the successive steps proposed to design a flotation plant is given in Fig. 4.19 (37). Assuming that a manufacturer-specific type of reactor with empirically optimized inflow, outflow, and baffle arrangement exists, one must then answer the most crucial question of what to use as the maximum permissible hydraulic or solids surface loading. This in turn will fix the reactor surface in direct correspondence with the wastewater

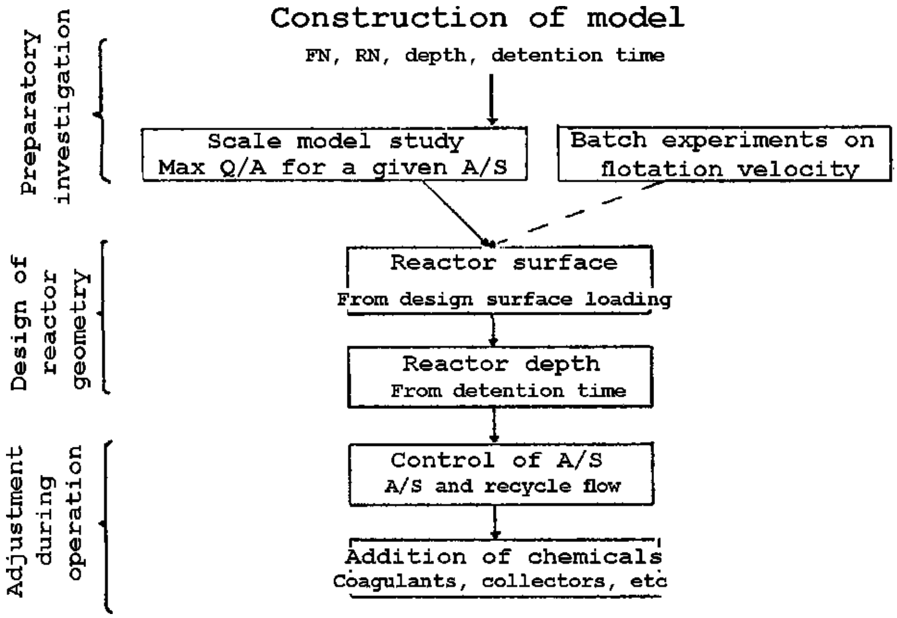


Fig. 4.19. Procedure for design and operation of flotation reactors (37).

flow rates and/or the wastewater solids load. Reactor depth, the only other design parameter to be determined, may be derived from average detention times or correlated directly with empirical evidence on optimum reactor depths. Consequently, all reactor dimensions can be determined.

As is seen in Fig. 4.19, the adjustment of the *A*/*S* ratio, and to some degree of the type and concentration of chemicals to be used, may correct somewhat the changes in the floatability, that is, the flotation velocity. With such changes the permissible surface loading will be different, thus allowing a limited compensation for unfavorable design parameters. Similarly the technical means of removing the floating biosolids blanket as well as the frequency of removing it must be and can be decided upon during operation after both biosolids and effluent characteristics are specified. Figure 4.19 furthermore indicates that the information necessary to identify a design surface loading may come from a batch reactor experiment or studies with a scaled-down continuous flow pilot model (37).

A schematic representation of the nature and intensity of such preparatory investigations is given in Fig. 4.20. In a scaled-down model of the intended large-scale reactor – scaling laws obeying Froude number (FN), Reynolds number (RN) or depth, detention time, and other parameters – various experiments with systematically increased hydraulic and surface loading at fixed *A*/*S* ratios are performed, and solids reduction rates or efficiency of the process is evaluated. This leads to a maximum surface loading (expressed either as *Q*/*A* or TSS/A) for a given *A*/*S* ratio. Parallel to this, the flotation velocity characteristics of that particular wastewater are determined in a batch flotation unit (24) as indicated in Fig. 4.20. When this is done for different types of wastewater, a reactor-specific monogram/relationship can be defined.

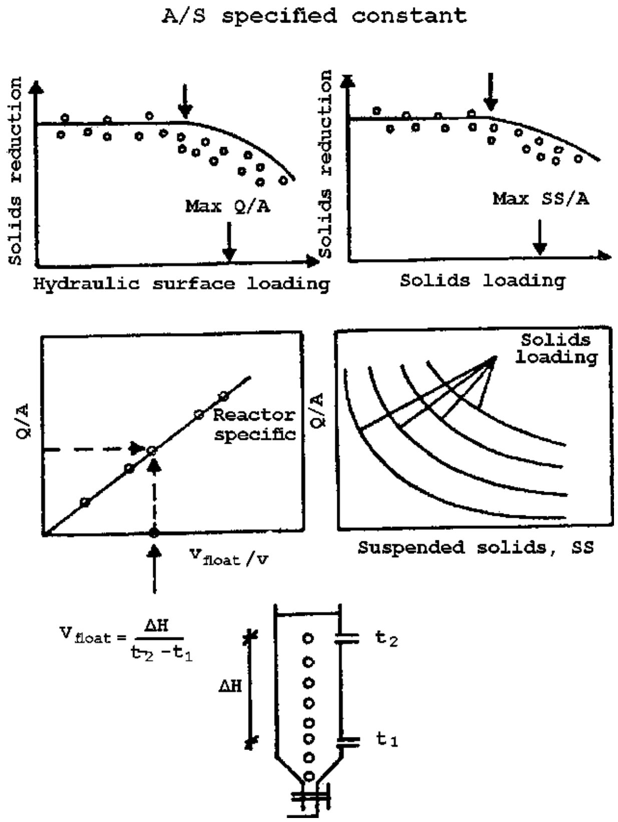


Fig. 4.20. Illustration of investigation to test the flotation characteristics of wastewater (V_{Float}) for a flotation reactor model (13).

This will establish a relationship of observed flotation velocity of a specific wastewater, which is easily determined in a batch experiment, to the maximum permissible surface loading.

Thus, if such monogram exists for the reactor type intended to be installed, then the preparatory investigation requires only the determination of the flotation velocity. If a new reactor type is to be used, continuous flow type investigations in a scaled-down model must be performed as indicated.

It should be mentioned here that there are specific differences not only in the flotation characteristic of specific wastewater (leading to a relative or absolute flotation velocity) but also in the reactor type as it is illustrated in Fig. 4.11 for two geometrically differing reactors. Therefore, a systematic investigation with differently designed model reactors might be used to optimize in an iterative manner the overall reactor design.

4.7. Process Efficiency

The possible applications of flotation for liquid–solid separation have been indicated in the introductory paragraphs. In many instances, flotation as one possible unit process will be compared with sedimentation, not only in terms of operational convenience and reliability or existing engineering know-how but also in terms of efficiency and cost. The projected process efficiency on one hand and the costs of this process on the other hand will be decisive in selecting this or another unit process. Cost aspects will be discussed in the following section, while the present discussion is devoted to a brief description of the overall process efficiency, as far as that is possible.

From the preceding, more detailed and conceptual description of the flotation process it has become apparent that it is not possible to describe the efficiency of this process, that is, the ratio of solids retention to solids inflow concentration (a technical efficiency parameter) in a global or general way. It is rather necessary to specify for each observed solids retention rate the decisive wastewater characteristics as well as the reactor particularities and the operational conditions (such as *A*/*S* ratio, amount of recycle water, pressure difference, chemicals used, etc.). This, however, is not done in most instances where such process efficiencies are given in the literature. Therefore, these data cannot be used as a direct indication of liquid–solid separation rate to be expected. They may only be used as a means of estimating orders of magnitude. The U.S. EPA average data presented in Table 4.3 is only used as a general guide when DAF is designed for wastewater treatment. In practical applications, the design engineers must obtain actual wastewater matrix and the representative inflow concentration for planning and designing a wastewater system.

Tables 4.3–4.6 show for illustration's sake such more generalized process removal and efficiency data for various types of wastewaters and biosolids (13, 23, 24, 32, 38–47). In using such summaries the following facts must be born in mind:

1. Efficiency values can at best be given as ranges and not as deterministic singular data.
2. One has to differentiate between points of application in wastewater and biosolids treatment, be it primary clarification or secondary clarification or in the context of tertiary treatment (predominantly for phosphate removal) or for biosolids thickening.
3. It is generally advisable to refer to experiments with wastewater systems that correspond to the one under consideration, i.e., if possible the type of wastewater should be listed.
4. Similarly, operational parameters of chemical nature (predominantly pH value and type and amount of coagulant used) should be known or listed.
5. In some instances it is not meaningful or not even desirable to list efficiency values as ratio of solids retention over inflow concentration; but rather an absolute value for the effluent solids concentration that can be attained with this process is of much more importance to the designing engineer.

With these precautions the summary of literature data on process efficiency may be used to make first estimates of an orientating nature on the technical suitability or competitiveness of this process.

5. COSTS OF FLOTATION

Analogous to the discussion on the representativity of efficiency data of the process as published in the literature, a word of caution is in order with respect to the limited usefulness of generalized cost data. As in describing the efficiency of individual plants, the

Table 4.3
Pollutants removal by flotation (US EPA, 32)

Pollutant	Effluent concentration		Removal efficiency (%)	
	Range	Median	Range	Median
Classical pollutants, mg/L				
BOD (5-day)	140–1,000	250	4–87	68
COD	18–3,200	1,200	8–96	66
TSS	18–740	82	6–98	88
Total phosphorus	<0.05–12	0.66	50–>99	98
Total phenols	>0.001–23	0.66	3–>94	12
Oil and grease	16–220	84	57–97	79
Toxic pollutants, μg/L				
Antimony	ND–2,300	20	4–95[a]	76
Arsenic	ND–18	<10	8–>99	45
Xylene	ND–1,000	200	95–>99	97
Cadmium	BDL–<72	3	0–>99	98[a]
Chromium	2–620	200	20–99	52
Copper	5–960	180	9–98	75
Cyanide	<10–2,300	54	0–<62	10
Lead	ND–1,000	70	9–>99	98
Mercury	BDL–2	BDL	33–88	75
Nickel	ND–270	41	29–>99	73
Selenium	BDL–8.5	2		NM
Silver	BDL–66	19		45
Thallium	BDL–50	14		NM
Zinc	ND–53,000	200	12–>99	89
Bis (2-ethylhexyl) phthalate	30–1,100	100	10–98	72
Butyl benzyl phthalate	ND–42	ND	97–>99	>99
Carbon tetrachloride	BDL–210	36		75
Chloroform	ND–24	9	20–>99	58
Dichlorobromomethane		ND		>99
2,4-Dichlorophenol		6		NM
Di-*n*-butyl phthalate	ND–300	20	0–>99	97
Diethyl phthalate		ND		>99
Di-*n*-octyl phthalate	ND–33	11	61–>99	78
N-nitrosodiphenylamine		620		66
N-nitroso-di-*n*-propylamine		84		NM
2-Chlorophenol		2		NM
2,4-Dimethylphenol	ND–28	14		>99
Pentachlorophenol	5–30	13		19
Phenol	9–2,400	71	0–80	57
2,4,6-trichlorophenol		3		NM
Benzene	5–200	120		NM
Chlorobenzene		57		NM

(*Continued*)

Table 4.3
(Continued)

Pollutant	Effluent concentration		Removal efficiency (%)	
	Range	Median	Range	Median
Dichlorobenzene	18–260	140		76
Ethylbenzene	ND–970	44	3–>99	65
Toluene	ND–2,100	580	10–>99	39
Fluoranthene	0.5–<10	5.2		NM
Fluorene		14		NM
Naphthalene	ND–840	96	33–>99	77
Pyrene	0.3–18	9.2		0
Anthracene/phenanthrene	0.2–600	10	45–>98	81
2-Chloronaphthalene		17		0

Blanks indicate data not available; BDL, below detection line; ND, not detected; NM, not meaningful.
[a] Approximate value.

Table 4.4
Flotation process efficiency in wastewater treatment (13)

Type of wastewater and type of treatment	Parameter	Reduction (%)	Effluent (mg/L)
Municipal preliminary clarification			
Without coagulants	Total solids	50–60	150
	Settleable solids	98	
With coagulants	Total solids	85–95	0–50
	Settleable solids	100	0
Municipal physicochemical treatment	Suspended solids	80–98	1–10
	Turbidity	65–85	
	Total phosphorus	85–95	0.2–1.0

quantification of costs of a specific plant depends upon the local situation, i.e., the place within the treatment process, the wastewater characteristics, the size of the plant, required efficiencies, ambient requirements as the control of noise, odor, etc. (13). Nevertheless, cost data of an orientating nature are needed in order to compare this process with others.

Cost data of the kind that are found in so-called "cost functions," which are meanwhile available for nearly all unit processes used in wastewater treatment and which are frequently reevaluated and corrected, may be derived from a postcalculation of executed projects.

The cost is a function of time. When cost information is given, the time and location for the cost must be specified. Knowing the cost, location, and the time, the cost data in the past can be adjusted to the present using appropriate cost indexes, such as the index shown in the Appendix. Different cost indexes are available; the locality factors (for transferring the costs from one region to another, or one country to another) and the detailed cost elements can be

Table 4.5
Flotation process efficiency in industrial wastewater treatment (13)

Type of industrial waste	Parameter	Reduction (%)
Slaughter house	BOD_5	76
	Permanganate value	57
Margarine factory	Suspended solids	92
	Ether extractable material	89
Car factory	Suspended solids	98
	Ether extractable material	97
Paper mill	Suspended solids	96
	Permanganate value	91
Cannery	Suspended solids	78
	BOD_5	58

Table 4.6
Flotation and sedimentation efficiency in biosolids treatment (13)

Type of biosolids	Chemical addition	Solids content (%)
Sedimentation		
Primary biosolids	None	0.4–4.5
	Polyelectrolyte	5–8
Activated sludge	None	0.2
	Polyelectrolyte	2.8
Flotation		
Activated sludge	None	4
	Polyelectrolyte	6–7
Primary + activated sludge	None	3.3
	Polyelectrolyte	4

found from the literature (48). Process costs, frequently given as annual total costs or as specific costs (i.e., relative to the unit of wastewater treated), must include construction and equipment costs, that is, investment costs, as well as operation and maintenance costs. Figure 4.21 shows the costs for construction and equipment for a DAF clarification plant (49). Figure 4.22 shows the plant operation and maintenance annual costs (49).

The calculations of the costs for DAF clarification are based on the following:

1. Service life of 40 years.
2. Costs are based on an overflow rate of 4,440 gpd/ft^2 of surface area.
3. Construction cost includes the basic unit, flow splitting device and an enclosed piping and equipment gallery for drive equipment, pumps, air tanks and miscellaneous equipment.
4. Largest practical size for an individual unit is currently 20 ft × 100 ft. for a rectangular unit. Larger sizes could be possible with technology advances.

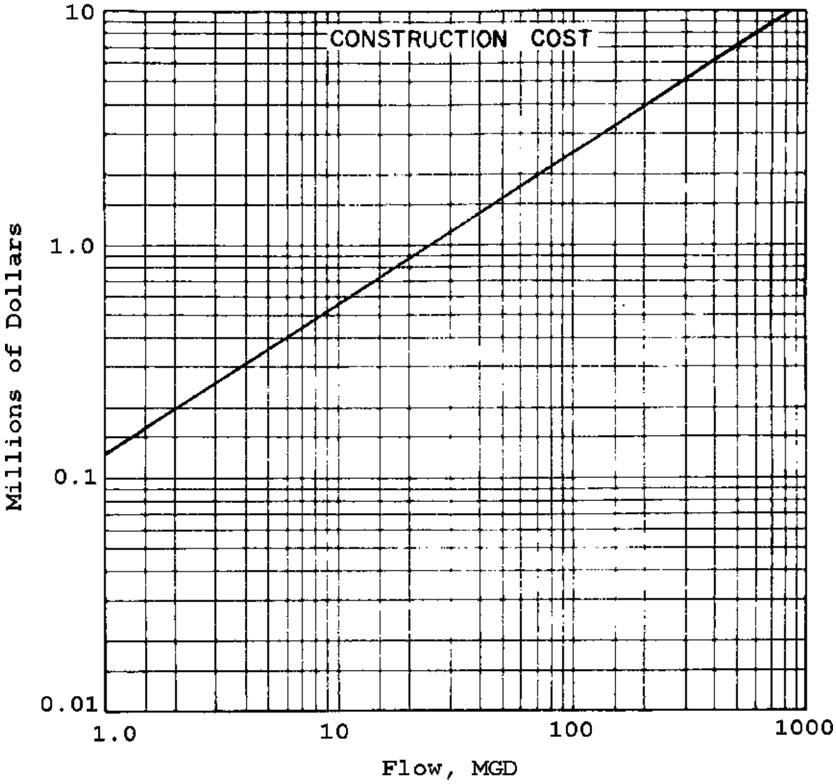


Fig. 4.21. Construction cost for DAF clarification (49).

5. Power cost is based on 0.10 kwh/ft^2.
6. No chemical costs are included.
7. Operations and maintenance costs include 48 h/year for routine checks and 0.009 h/ft^2 for maintenance. Also, for each overflow event: 1 h travel time, 1 h setup/shutdown time, 0.004 h/ft^2 for washdown, and 4 h/d operation.
8. Process Performance: (with chemicals)

BOD_5 removal, %	40–60
SS removal, %	50–70

The costs for DAF thickening are shown in Figs. 4.23 and 4.24 for construction and annual operation and maintenance, respectively (49). The cost calculations are based on the following:

1. Service life: 40 years
2. Construction costs include the following:
   (a) Flotation chamber (2-h detention based on biosolids flow)
   (b) Pressure tanks (60 psig)
   (c) Recycle pumps (100% recycle)

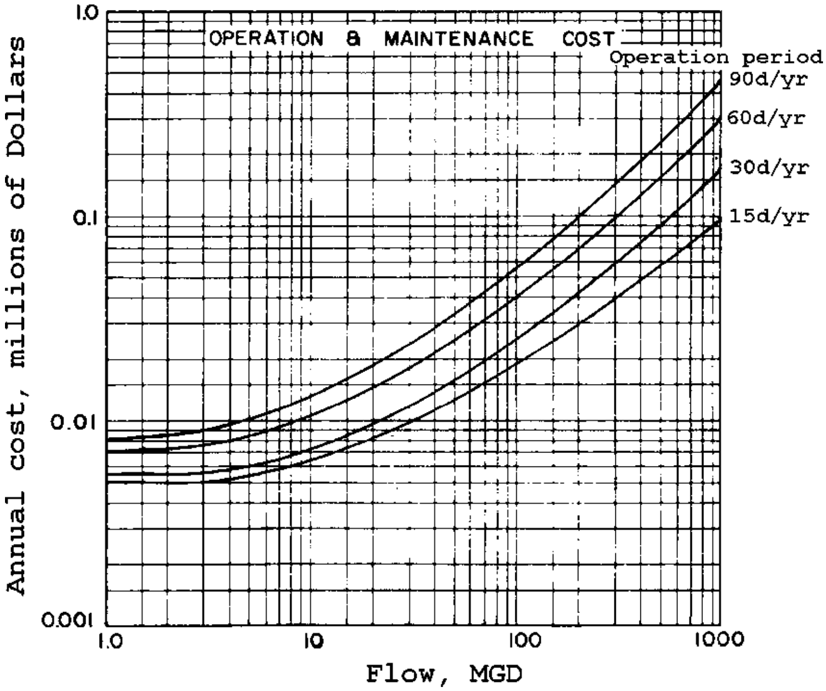


Fig. 4.22. Annual operation and maintenance costs for DAF clarification (49).

3. Costs for thickening of secondary biosolids only: 820 lb/MG
4. Loading rate = 2 lb/ft^2/h
5. Operating time for various flowrates:

0.1	40 h/week
1 MGD	40 h/week
10 MGD	100 h/week
100 MGD	168 h/week

Adjustment factor: To determine costs at loading rates or biosolids quantities other than the above, enter curve at effective flow, Q_{ADJUSTED}:

$$Q_{\mathrm{ADJUSTED}} = \mathrm{Q}_{\mathrm{DESIGN}} \times \frac{2\ \mathrm{lb/ft^2/h}}{\text{New design mass loading rate}} \times \frac{\text{New design biosolids mass}}{820\ \mathrm{lb/d/MG}} \quad (3)$$

Cost in terms of year 2005 dollars (as an example): It must be indicated that all these curves were calculated for the USA in the year 1976 using US dollar interest rates, energy costs, and labor costs. To obtain costs in terms of 2005 US dollar value, multiply the cost obtained from Figs. 4.21 to 4.24 by a factor of 2.55:

$$\mathrm{Cost}_{2005} = 2.55\ \mathrm{Cost}_{\mathrm{Figure}} \quad (4)$$

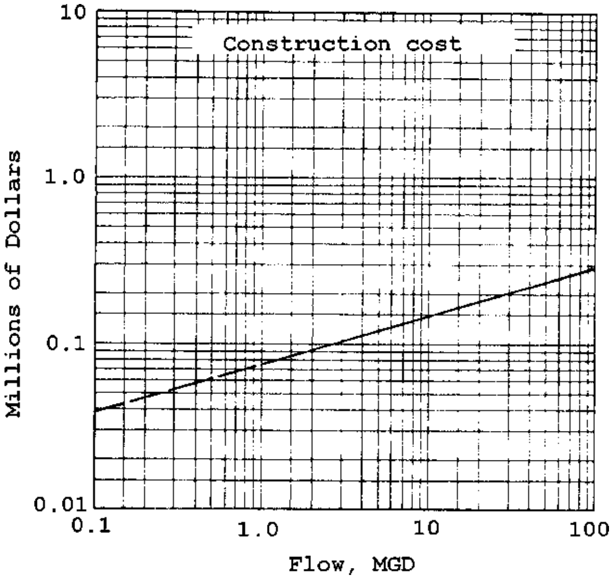


Fig. 4.23. Construction cost for DAF thickening (49).

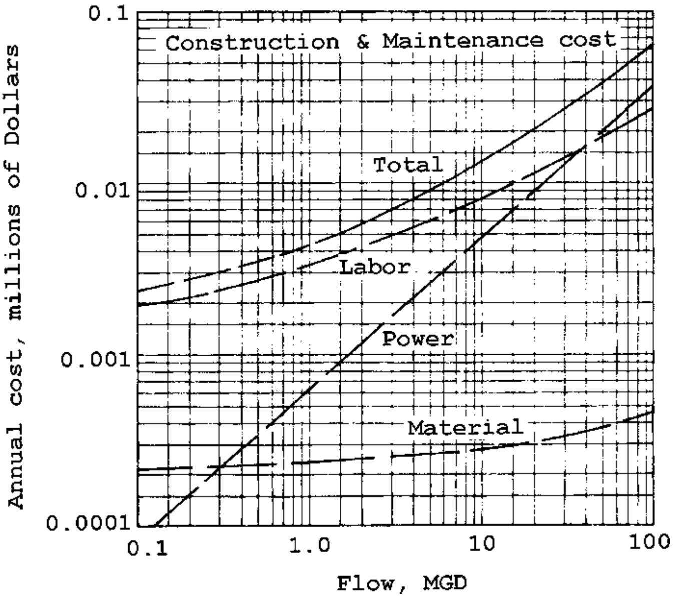


Fig. 4.24. Annual operation and maintenance costs for DAF thickening (49).

Table 4.7
Cost comparison of various treatment processes (13, 53–55)

Treatment process	Relative cost (100,000 population)	Relative cost (10,000 population)
Filtration	3.1	12
Flotation	1.7	3.5
Sedimentation	1[a]	2.0
Coagulation	1.8	2.1
Physical/biological treatment	20	35

[a] All costs were calculated relative to sedimentation cost for a population of 100,000.

This cost multiplication factor is obtained from the US Army Corps of Engineers, United States Cost Index for Utilities (50), by calculating the ratio of the dollar value in 2005 to its value in 1976, the year for which the costs in the figures were determined (refer to Appendix):

$$\text{Cost factor} = 516.75/202.61 = 2.55$$

Finally an overall comparison of specific costs of different unit processes, such as coagulation (chemicals only), sedimentation, flotation, and filtration is given in Table 4.7 (13, 51, 52). These unit processes are used today in wastewater treatment (3, 13, 53). A comparison with the specific cost of other biological wastewater treatment systems can be found elsewhere (54, 55).

Similarly the 2009 costs can be calculated if the 2009 Cost Index (570.38) shown in Appendix is used. The future costs can be calculated when the future Cost Index becomes available (50).

6. ENGINEERING CONSIDERATIONS

6.1. DAF for Primary/Secondary Clarification

DAF is used to remove suspended solids by flotation (rising) by decreasing their apparent density. DAF consists of saturating a portion or all of the wastewater feed, or a portion of recycled effluent with air at a pressure of 25–70 psig. The pressurized wastewater is held at this pressure for 0.5–3.0 min in a retention tank and then released to atmospheric pressure in the flotation chamber. The sudden reduction in pressure results in the release of microscopic air bubbles, which attach themselves to oil and suspended particles in the wastewater in the flotation chamber. This results in agglomerations, which, due to the entrained air, have greatly increased vertical rise rates of about 0.5–2.0 ft/min. The floated materials rise to the surface to form a biosolids layer called the float. Specially designed flight scrapers or other skimming devices continuously remove the float. The effectiveness of DAF depends upon the attachment of bubbles to the suspended oil and other particles that are to be removed from the waste stream. The attraction between the air bubble and particles is primarily a result of the particles' surface charges and bubble-size distribution (56).

The more uniform the distribution of water and microbubbles, the shallower the flotation unit can be. Generally, the depth of effective flotation units is between 4 and 9 ft. The surface float can in certain cases attain a thickness of many inches and can be relatively stable for a short period. The layer thickens with time, but undue delays in removal will cause a release of particulates back to the liquid.

Units can be round, square, or rectangular. In addition, gases other than air can be used. The petroleum industry has used nitrogen, with closed vessels, to reduce the possibilities of fire.

DAF has been used for many years to treat industrial wastewater. It has commonly been used to thicken biosolids generated by municipal wastewater; however, lately it has been put in use to treat all types of municipal wastewater.

Performance:

Removal (w/o chemicals), %	Suspended solids = 40–65 Oil and grease = 60–80
Removal (w. chemicals), %	Suspended solids = 80–93 Oil and grease = 85–99

Chemicals required: Alum $Al_2\ (SO_4)_3.14H_2O$, ferric chloride ($FeC1_3$), and polymers can be added to aid in the coagulation process prior to the actual flotation step.

Design criteria:

Pressure, psig	25–70
Air to solids ratio, lb/lb	0.01–0.1
Float detention, min	20–60
Surface Hydraulic Loading, gal/d/ft^2	500–8,000
Recycle, percent (where employed)	5–120

Process reliability: DAF systems have been found to be reliable. However, chemical pretreatment is essential, without which DAF units are subject to variable influent conditions, resulting in widely varying performance.

Environmental impact: Requires very small land area. The air released in the unit is unlikely to strip volatile organic material into the air. The air compressors will need silencers to control the noise generated. The biosolids generated will need methods for disposal. These biosolids will contain high levels of chemical coagulants used in the flotation process.

6.2. *DAF-Filtration for Industrial Wastewaters and for Tertiary Treatment of Municipal Wastewaters*

DAF is a widely used process in the following industries:

1. Municipal Biological Treatment Plants
2. Petroleum Refining
3. Pulp and Paper Mills

4. Rubber Processing
5. Metal Finishing

DAF is also used on a limited basis in the following industries: auto and other laundries, iron and steel manufacturing, aluminum forming, battery manufacturing, explosives manufacturing, gum and wood chemicals, pharmaceutical manufacturing, paint and ink formulation, soap and detergent manufacturing, textile mills and linen supply laundries.

The combined flotation–filtration units make an excellent wastewater treatment package plant. The flotation–filtration plant is applicable in the following cases:

1. In a biological wastewater treatment plant, flotation–filtration units can be used as a tertiary treatment unit for final polishing of plant effluent. It is a very efficient unit for the removal of phosphates as well as many toxic substances.
2. In industrial waste treatment, the flotation–filtration unit could constitute a total physicochemical treatment system for removal of toxic, nonbiodegradable, refractory, floating, and/or oily substances.
3. Flotation–filtration can also be an excellent pretreatment unit to other tertiary wastewater treatment processes, such as granular carbon adsorption, ultrafiltration, reverse osmosis, ion exchange, etc.

6.3. *DAF for Thickening*

In DAF systems, a recycled subnatant flow is pressurized from 30 to 70 psig and then saturated with air in a pressure tank. The pressurized effluent is then mixed with the influent biosolids and subsequently released into the flotation tank. The excess dissolved air then separates from solution, which is now under atmospheric pressure, and the minute (average diameter 80 μm) rising gas bubbles attach themselves to particles that form the floating biosolids blanket. The thickened blanket is skimmed off and pumped to the downstream biosolids handling facilities while the subnatant is returned to the plant. Polyelectrolytes are frequently used as flotation aids to enhance performance and create a thicker biosolids blanket (56–59).

Applications: DAF is the most common form of flotation thickening in use in the USA and has been used for many years to thicken biosolids generated by the waste activated sludge process and to a lesser degree to thicken combined biosolids. The use of air flotation is limited primarily to thickening of biosolids prior to dewatering or digestion. Used in this way, the efficiency of the subsequent dewatering units can be increased and the volume of supernatant from the subsequent digestion units can be decreased. Existing air flotation thickening units can be upgraded by the optimization of process variables and by the utilization of polyelectrolytes. Air flotation thickening is best applied to waste activated sludge. With this process, it is possible to thicken the biosolids to 6% solids, while the maximum concentration attainable by gravity thickening is 2–3% solids. The DAF process can also be applied to mixtures of primary and waste activated biosolids. DAF also maintains the biosolids in aerobic condition and potentially has a better solids capture than gravity thickening. There is some evidence that activated biosolids from pure oxygen systems are more amenable to flotation thickening than biosolids from conventional systems.

Performance: A summary of data from various air flotation units indicates that solids recovery ranges from 83 to 99% at solids loading rates of 7–48 lb/ft^2/d. Other operating data are as follows (56):

Influent suspended solids	3,000–20,000 mg/L (median 7,300)
Supernatant suspended solids	31–460 mg/L (median 144)
Suspended solids removal	94–99+% (median 98.7)
Float solids	2.8–12.4% (median 5.0)
Loading	1.3–7.7 lb/h/ft^2 (median 3.1)
Flow	0.4–1.8 gal/min/ft^2 (median 1.0)
Supernatant suspended solids	150 mg/L (returned to mainstream of the treatment plant)

Chemicals required: Flotation aids (generally polyelectrolytes) are usually used to enhance performance.

Some design criteria are as follows:

Pressure	30–70 psig
Effluent recycle ratio	30–150% of influent flow
Air to solids ratio	0.02 lb air/lb solids
Solids loading	5–55 lb/ft^2/d (depending on biosolids type and whether flotation aids are used)
Polyelectrolyte addition	5–10 lb/ton of dry solids
Solids capture	70–98+%
Total solids, unthickened	0.3–2.0%
Total solids, thickened	3–12%
Hydraulic loading	0.4–2.0 gal/min/ft^2

Reliability: DAF systems are reliable from a mechanical standpoint. Variations in biosolids characteristics can affect process (treatment) reliability and may require operator attention.

Environmental Impact: Requires less land than gravity thickeners. A subnatant stream is returned to the head of the treatment plant, although it should be compatible with other wastewaters. The air released to the atmosphere may strip volatile organic material from the biosolids. The volume of biosolids requiring ultimate disposal may be reduced, although its composition will be altered if chemical flotation aids are used. The air compressors will require shielding to control the generated noise.

NOMENCLATURE

A = horizontal reactor area, m^2 (ft^2)
A_e = equilibrium contact angle, degree
A/S = air to solids ratio, kg/kg (lb/lb)
DO = dissolved oxygen, mg/L
$E_{\text{Solid–gas}}$ = the surface adsorption energy at the solid–gas interface, kcal

F = surface adsorption factor, kcal-cm/dyne
I_{sv} = sludge (biosolids) volume index, mL/mg
Q = flowrate, m^3/d (MGD)
r_{SL} = surface tension at solid–liquid interface, dyne/cm
r_{LG} = surface tension at liquid–gas interface, dyne/cm
r_{SG} = surface tension at solid–gas interface, dyne/cm
S = weight of dry solids, kg (lb)
t = detention time, min
T = temperature, °C (°F)
TSS=total suspended solids, mg/L
v = flotation rising velocity, m/min (ft/min)

APPENDIX

United States Cost Index for Utilities: US Army Corps of Engineers (50)

Year	Index	Year	Index
1967	100	1989	383.14
1968	104.83	1990	386.75
1969	112.17	1991	392.35
1970	119.75	1992	399.07
1971	131.73	1993	410.63
1972	141.94	1994	424.91
1973	149.36	1995	439.72
1974	170.45	1996	445.58
1975	190.49	1997	454.99
1976	202.61	1998	459.4
1977	215.84	1999	460.16
1978	235.78	2000	468.05
1979	257.2	2001	472.18
1980	277.6	2002	484.41
1981	302.25	2003	495.72
1982	320.13	2004	506.13
1983	330.82	2005	516.75
1984	341.06	2006	528.12
1985	346.12	2007	539.74
1986	347.33	2008	552.16
1987	353.35	2009	570.38
1988	369.45		

REFERENCES

1. Shammas NK, DeWitt N (1992) Flotation: a viable alternative to sedimentation in wastewater treatment plants. Water Environment Federation 65th annual conference, proceedings of the liquid treatment process symposium, New Orleans, LA, 20–24 Sept 1992, pp 223–232

2. Krofta M (1990) Flotation replaces sedimentation in water and effluent clarification, Technical Report, Krofta Engineering Corp., Lenox, MA
3. Wang LK, Hung YT, Shammas NK (eds) (2005) Physicochemical treatment processes. The Humana Press, Inc., Totowa, NJ. p 723
4. Krofta M, Miskovic D, Shammas NK, Burgess D (1994) Pilot-scale applications of a primary-secondary flotation system on three municipal wastewaters. Specialist conference on flotation processes in water and sludge treatment, Orlando, Florida, 26–28 April 1994
5. Krofta M, Wang LK (1986) Wastewater treatment by a biological-physicochemical two-stage process system. Proceedings of the 41st industrial waste conference, 13–15 May1986
6. Shammas NK (1997) Physicochemically-enhanced pollutants separation in wastewater treatment. Proceedings of the international conference: rehabilitation and development of civil engineering infrastructure systems – upgrading of water and wastewater treatment facilities, organized by The American University of Beirut and University of Michigan, Beirut, Lebanon, 9–11 June 1997
7. Krofta M, Miskovic D, Shammas NK, Burgess D, Lampman L (1994) An innovative multiple stage flotation-filtration low cost municipal wastewater treatment system. IAWQ 17th biennial international conference, Budapest, Hungary, 24–30 July 1994
8. Krofta MM,, Wang LK (1984) Tertiary treatment of secondary effluent by dissolved air flotation and filtration. Civil Engineering for Practising and Design Engineers 3, pp 253—272 (National Technical Information Service, Springfield, VA. Tech. Report No. PB83-171165)
9. Kiuru HJ (1990) Tertiary wastewater treatment with flotation filters. Water Sci Technol 22:139
10. Wang LK, Shammas NK, Hung YT (eds) (2008) Biosolids treatment processes. The Humana Press, Inc., Totowa, NJ, 800 pp
11. Wang LK, Shammas NK, Selke WA, Aulenbach DB (2008) Flotation thickening. In: Wang LK, Shammas NK, Hung YT (eds) Biosolids treatment processes. The Humana Press, Inc., Totowa, NJ, pp 71–100
12. Cizinska S, Matejo V, Wase C, Kiasson Y, Krejci J, Daihainmar G (1992) Thickening of waste activated sludge by biological flotation. Water Res 26:139
13. Hahn HH (1982) Wastewater flotation, Lenox Institute of Water Technology, Report No. LIR/08-82/2, August
14. Wang LK, Fahey EM, Wu Z (2005) Dissolved air flotation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. The Humana Press, Inc., Totowa, NJ, pp 431–500
15. Krofta M, Wang LK (2000) Flotation engineering, Technical Manual No. Lenox/1-06-2000/368, Lenox Institute of Water Technology, Lenox, MA
16. Krofta M, Wang LK (1999) Flotation and related adsorptive bubble separation processes, Technical Manual No. Lenox 7-25-1999/348, 4th edn Lenox Institute of Water Technology, Lenox, MA
17. Hahn HH (1981) Kommunale Abwasserreinigung durch_Flotation – eine Einführung, in Fortschritte bei der Anwendung des Flotationsverfahrens in der kommunalen Abwasserreinigung, Hrsg. Hahn, H. H., Bd. 25 der Berichtsreihe des Institutes fur Siedlungswasserwirtschaft, Universität Karlsruhe
18. Schulz KD (1979) Entspannungsflotation – Charakterisierung der Luftblasen, die bei der Entspannung luftgesättigten Wassers entstehen, Vertieferarbeit am Institut fur Siedlungswasserwirtschaft der Universität Karlsruhe
19. Metcalf & Eddy, Inc., Metcalf and Eddy (2003) Wastewater engineering treatment and reuse, 4th edn. McGraw Hill, New York
20. Eckenfielder WW (1989) Industrial water pollution control, McGraw-Hill, New York, NY

21. Krofta M, Guss D, Wang LK (1988) Development of low-cost flotation technology and systems for wastewater treatment. Proceedings of the 42nd industrial waste conference, Lewis Publishers, Chelsea, MI, p 185
22. Hahn HH, Klute R (1974) Neuere physikalisch-chemische Aspekte bei der Abwasserreinigung – Teil II: Flotation und Filtration. In: Wasserkalender 1975, Seite 45–88, Erich Schmidt-Verlag Berlin
23. Hanisch B (1959) Die wirtschaftliche Anwendung der Flotation mit sehr kleinen Luftblasen zur Reinigung von Abwasser, Dissertation, Technische Hochschule Stuttgart
24. Kiefhaber KP (1981) Versuchsanlage zur Entspannungsflotation von Abwasser – Vergleich von Versuchsergebnissen, Dissertationsschrift, Universität Karlsruhe, Bd. 27 der Berichtsreihe des Institutes für Siedlungswasserwirtschaft, Universität Karlsruhe
25. Wang LK (1991) Water and wastewater treatment using advanced dissolved air flotation. The 1991 Annual conference of the Korea society of water pollution research and control, Seoul, Korea, 22–23 Feb 1991
26. Krofta M, Wang LK (1984) Development of innovative flotation-filtration systems for water treatment, Part A: first full-scale Sandfloat Plant in U.S. Proceedings of the water reuse symposium III, San Diego, CA, 26–31 Aug 1984, pp 1226–1237
27. Janssens JG (1992) Developments in coagulation, flocculation and dissolved air flotation. Water/Eng Manage 139:26
28. Adams J (1974) Air flotation, IAWPR Advanced Study Institute, Birmingham, England
29. Krofta M, Wang LK, Pollman CD (1989) Treatment of seafood processing wastewater by dissolved air flotation carbon adsorption and free chlorination. Proceedings of the 43rd industrial waste conference, Lewis Publishers, Chelsea, Michigan, p 535
30. Schneider IAH, Neto VM, Soares A, Rech RL, Rubio J (1995) Primary treatment of soybean protein bearing effluent by dissolved air flotation and by sedimentation. Water Res IAWQ 29(1):69–75
31. Krofta M (1977) Neue Anlagen zur Verbesserung der innerbetrieblichen Stoffrückgewinnung und Rückwasseraufbereitung, Arbeitstagung 1977 Gernsbacher Papiermacher, 17. Mai
32. Krofta M, Wang LK (1984) Tertiary treatment of secondary effluent by dissolved air flotation and filtration. Civil Engineering for Practising and Design Engineers, Pergamon Press Ltd., 3, 253–272
33. Shack PA, Blandford JR, Landley JL (1985) Control of filamentous growth in food processing activated sludge systems, Technical Report, Powell Valley Foods Company, Caryville, TN
34. Krofta M, Wang LK, Aulenbach DB, VanDyke JP (1989) Treatment of RBC effluent by dissolved air flotation. In: Advances in coal and mineral processing using flotation, Chapter 26, pp 233–240
35. Wang LK (2005) New technologies for water and wastewater treatment. In: Edwin C. Tiff, Jr. Water resources symposium, NY American Water Works Association and NY Water Environment Association, Liverpool, NY, 15–17 Nov 2005
36. U.S. EPA (1982) Pollution abatement in a brewing facility. U.S. Environment Protection Agency, Cincinnati, OH
37. Hahn HH, Kiefhaber KP (1982) Einsatz der Flotation in der weitergehenden Abwasserreinigung - Lleistungsfähigkeit und Möglichkeiten der Leistungsanpassung durch Vorversuche. In Abwasser und Schlammbehandlung – Fortschritte und Probleme, Bohnke HrsgB, 15. Essener Tagung
38. Muller-Neuhaus G (1955) Die Klärung von Abwasser mittels Flotation unter Verwendung handelssüblicher Waschmittel und Waschrohstoffe. Jahrbuch vom Wasser, vol. XXII, 340

39. Kohler R (1969) Versuche zur Behandlung von Schlachthofabwasser durch Überdruckflotation. Wasser, Luft und Betrieb 13:472
40. Beebe AH (1953) Soluble oil wastes treatment by pressure flotation. Sewage Ind Waste 25, 1314
41. Hess RW (1953) 1952 Industrial wastes forum. Sewage Ind Waste 25:709
42. Hilson MA (1971) Sludge conditioning by polyelectrolytes. J Inst Water Eng 25:402
43. Crow RD, Johnson EE (1965) Organic polyelectrolytes – a new approach to raw sewage flocculation. The 38th WPCF Conference
44. Mogelnicki S (1968) Experiences in polymer applications to several solids-liquids separation processes. Proceedings of the 10th sanitary engineering conference, University of Illinois, IL
45. Jordan VJ, Scherer CH (1970) Gravity thickening techniques at a water reclamation plant. J Water Pollut Control Fed 42:2
46. Braithwaite RL (1964) Polymers as aids to the pressure flotation of waste activated sludge. Water Sew Works 11:545
47. Ettelt GA (1964) Activated sludge thickening by dissolved air flotation. Proceedings of the 9th purdue industrial waste conference, p 210
48. Wang LK, Pereira NC, Hung YT (eds) (2005) Advanced air and noise pollution control. Humana Press, Inc., Totowa, NJ, 526 pp
49. U.S. EPA (1976) Areawide assessment procedures manual, Technical Report No. EPA-600/9/76-014, U.S. Environmental Protection Agency, Cincinnati, OH, July 1976
50. U.S. ACE (2008) Yearly average cost index for utilities. In: Civil works construction cost index system manual, 110-2-1304, U.S. Army Corps of Engineers, Washington, DC, p 44. PDF file is available on the Internet at http://www.nww.usace.army.mil/cost
51. Kiefhaber KP, Neis U, Hanz T, Hahn HH (1980) Kosten der Flotation in der Abwasserreinigung, Korrespondenz Abwasser, Jahrgang
52. Ekama GA, Barnard GL, Gunthert FW, Krebs P, McCorquodale JA, Parker DS, Wahlberg EJ (eds) (1997) Secondary settling tanks. IWA Publishing, London, March, 1997
53. Wang LK, Hung YT, Shammas NK (eds) (2006) Advanced physicochemical treatment processes. The Humana Press, Inc., Totowa, NJ, 690 pp
54. Wang LK, Pereira NC, Hung YT, Shammas NK (eds) (2009) Biological treatment processes. The Humana Press, Inc., Totowa, NJ. 818 pp
55. Wang LK, Shammas NK, Hung YT (eds) (2009) Advanced biological treatment processes. The Humana Press, Inc., Totowa, NJ. 738 pp
56. U.S. EPA (1980) Innovative and alternative technology assessment manual, U.S. Environmental Protection Agency, Technical Report No. EPA-430/9-78-009, Cincinnati, OH, Feb, 1980
57. Wang LK (2007) Emerging flotation technologies. In: Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical treatment technologies. Humana Press, Totowa, NJ, pp 449–484
58. Wang LK, Guss D, Krofta M (2010) Kinetics and case histories of activated sludge secondary flotation systems. In: Handbook of advanced industrial and hazardous wastes treatment. CRC Press, Boca Raton, FL, pp 1155–1190
59. Wang LK, Ivanov V, Tay JH, Hung YT (2010) Environmental biotechnology. The Humana Press, Inc., Totowa, NJ

5
Electroflotation

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CONTENTS

Abstract Existing water and wastewater treatment technologies are often too costly or operationally complex for installation in single family homes and small community water systems serving less than 3,300 persons. Properly designed and installed septic tanks followed by soil absorption fields require minimum maintenance and can operate in all climatic conditions. However, when a soil system loses its capacity to absorb septic tank effluents, there is a potential for effluent surfacing, which often results in odors and, possibly, health hazards. Alternatively, the septic tank effluent containing nutrients may reach a lake causing problems due to eutrophication.

This chapter introduces a novel water/wastewater package treatment plant specifically developed for single family homes, apartments, and camping sites. The dimensions of the plant are 0.9 m × 0.6 m × 1.8 m high. The distinguishing features of the plant are its high rate electroflotation and UV processes. The chapter covers the following topics: conventional and innovative package water treatment plants, electroflotation theory, water purification by electroflotation and filtration, treatment of well water, treatment of lake water, treatment of highly contaminated water, and wastewater treatment by electroflotation and filtration.

Key Words Treatment • electroflotation • UV disinfection • well water • lake water • contaminated water • wastewater • process innovation.

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1. INTRODUCTION

Water supply systems in rural areas share, in principle, the general features of large urban water supply systems. However, rural water supply systems have to fit the needs of the rural populations served. The rural populations are usually small in density and scattered over wide areas. Often, it is economically unfeasible to install long water transmission lines for water treatment in a regional water purification plant.

The source of rural water supply is usually underground aquifers rather than river or lake waters. In comparison with urban water supply systems, pumping, distribution, storage, and treatment facilities of rural water supply systems are smaller, simpler, and less costly because ground water is usually cleaner than surface water (1).

Existing water treatment technologies, such as flocculation, sedimentation, filtration, ion exchange, granular carbon adsorption, etc (2, 3) are often too costly or operationally complex for installation in single family homes and small community water systems serving less than 3,300 persons. It is reported by the American Water Works Association Research Foundation (4) that these small water supply systems comprise approximately 78% of the number of water supplies in the U.S. Most small water systems use only chlorination for water disinfection, thus are not considered to be adequate (5).

Small package water treatment plants are a potential cost-effective solution to the common problems affecting the drinking water quality of a rural single family home or a typical small community and are within the technical expertise of small system operations.

The Drinking Water Research Division of the U.S. Environmental Protection Agency (U.S. EPA) has funded several research projects in this study area of small system technology. The U.S. EPA studies included: cost evaluation; arsenic removal by reverse osmosis, ion exchange, and activated alumina; uranium removal; reverse osmosis evaluation; fluoride and selenium removal by activated alumina and ion exchange; nitrate removal by ion exchange; barium and radium reduction by ion exchange; disinfection alternatives; and turbidity removal by various filtration methods (slow sand, direct, diatomaceous earth).

It has been known that the financial and personnel limitations faced by single families and small communities in rural areas can be alleviated by prefabricated package treatment installations. The question of the adequacy of treatment provided by these installations as they are managed and operated by unskilled people in rural areas must be properly answered.

Similar limitations apply to wastewater disposal for single families and small communities in rural and unsewered suburban areas. A septic tank followed by a soil absorption field (6) is the traditional onsite system for treatment and disposal of domestic wastewater from such areas. Almost one-third of the population in rural and suburban areas of the United States depends on such systems. Properly designed and installed systems require minimum maintenance and can operate in all climatic conditions. However, when a soil system looses its capacity to absorb septic tank effluents, there is a potential for effluent surfacing, which often results in odors and, possibly, health hazards. Alternatively, the septic tank effluent containing nutrients may reach a lake causing problems due to eutrophication (7, 8).

Eutrophication of a lake induced by septic tank effluents can be retarded by removing the source of plant nutrients, phosphorus, or/and nitrogen. This is accomplished by diversion of the septic tank treated effluent around the lake or by treatment of the septic tank effluent employing advanced treatment processes. Treatment of septic tank effluent by electroflotation is the simplest of such advanced methods.

2. CONVENTIONAL PACKAGE WATER TREATMENT PLANTS

During the past four decades, single family homes in resort areas and rural small communities have achieved cost savings by adopting package water treatment plants. A conventional package water treatment plant generally consists of prefabricated and largely preassembled clarification and filtration units. Morand and Young (9), under the sponsorship of the U.S. EPA, studied six conventional package water treatment plants. The results of the study are shown in Tables 5.1–5.3.

The six conventional package plants (W, T, V, M, P and C shown in Tables 5.1–5.3) had varied success in their treatment performance. Four of the plants (C, T, W, and P) had uniform high-quality source waters; however, only three of these (C, T, and W) consistently met the effluent turbidity standard. The low standard plate counts and the absence of coliforms in the treated water indicates that all six package water treatment plants having prechlorination and filtration facilities produced adequately disinfected water. Effluents of four of the six package plants were tested at least once for trihalomethane (THM); the total concentrations were greater than 100 μg/L. The point of chlorination (i.e., prechlorination) and often the large free

Table 5.1
Conventional package treatment plants – general characteristics

Site	Model year	Design flow rate (gpm)	Population served/no of meters	Average volume per day (gal)	Group served	Type of distribution pipe used	Source
W	Neptune Microfloc AQ-40 1973	200	1,500/552	110,000	City	PVC	Surface impoundment
T	Neptune Microfloc AQ-40 1973	200	1,000/360	78,000	City	PVC cast iron asbestos cement	Surface impoundment
V	Neptune Microfloc AQ-40 1976	200	–/423	72,000	PSD	PVC	River
M	Neptune Microfloc AQ-112 1972	560	–/1,680	330,000	PSD	PVC	River
P	Neptune Microfloc Water Boy 1972	100	–/411	82,000	PSD	PVC	Surface impoundment
C	Permutit Permujet 1971	200	State park	57,000	State park	Asbestos cement	River

PSD Public Service District.

Table 5.2
Conventional package treatment plants – treatment process characteristics

Site	Prechemical addition	Rapid mix		Flocculation		Sedimentation		Filtration		Notes
		Type	d.t. (s)	Type	d.t. (min)	Type	Loading (gpd/ft^2)	Media	Rate (gpm/ft^2)	
W	Cl. alum. soda ash	In pipe	3	Paddle	12.8	Tubes	100	Mixed Anthracite, 18 in. Silica sand, 9 in. Garnet sand, 3 in.	5	Poly added before tubes
T	Cl. alum. soda ash. poly	In pipe	3	Paddle	12.8	Tubes	100	Mixed Same as above	5	Post soda ash
V	Cl. alum. soda ash, poly	In pipe	3	Paddle	14	Tubes	100	Mixed Same as above	5	Post sodium hexameta -phosphate
M	Cl. alum. soda ash, poly	Chamber	30	Paddle	10	Tubes	100	Mixed Same as above	5	
P	Cl. alum. soda ash, carbon (summer)	Chamber not used	–	Paddle	10	Tubes	150	Mixed Same as above	5	
C	Cl. alum. soda ash, poly	In pipe	–	Upflow solids contact 2 h. d.t. rise rate – 1 gpm/ft^2				Silica sand, 24 in.	2	Soda ash added before filtration

d.t. = Detention time.

Table 5.3
Conventional package treatment plants – turbidity removal

Plant C		Plant W		Plant T		Plant V		Plant M		Plant P	
Raw	Clearwell effluent	Raw	Clearwell effluent	Raw	Clearwell effluent	Raw	Clearwell effluent	Raw	Clearwell effluent	Raw	Clearwell effluent
8.5	0.3	–	0.9	10.0	1.9	4.0	1.8	–	0.2	12.0	0.8
6.2	0.2	5.0	0.3	8.0	0.2	12.0	2.8	39.0	3.8	4.4	2.4
1.2	0.3	4.2	0.4	6.0	0.4	–	9.6	40.0	2.6	–	7.0
1.6	0.1	19.0	0.8	3.2	1.1	35.0	1.5	27.0	2.4	3.5	1.5
2.2	0.1	9.2	2.0	3.2	0.2	42.0	2.0	6.0	1.2	2.0	0.1
4.0	0.1	11.5	0.3	3.2	0.2	10.0	2.4	3.8	0.1	1.2	0.5
12.6	0.7	12.0	0.2	5.8	0.2	90.0	8.5	73.0	11.0	15.6	9.7
5.2	0.2	11.0	0.3	10.4	3.2	28.0	5.4	3.6	0.1	3.1	2.2
2.2	0.2	29.7	0.9	3.4	0.7	19.0	0.3	3.8	0.3	17.2	1.9
		12.8	0.2			47.0	1.2	6.0	0.5		
						13.0	0.8	70.0	16.0		
						8.0	0.3	25.0	3.4		
						6.0	0.3	>100.0	55.0		
						>100.0	0.5	>100.0	31.0		
						60.0	0.5	8.5	2.2		
						24.0	1.2	4.3	0.4		
						13.0	0.3	4.0	1.0		
						2.7	1.2	9.6	1.9		
						1.2	1.0	19.1	1.1		
						3.3	0.5	64.0	6.9		
								8.2	1.0		

chlorine residuals (>2 mg/L) detected in the treated water contribute to these high THM levels.

It was also observed that regardless of their source water quality, all conventional package plants require a minimum level of maintenance and operational skill. Lack of this minimum skill and attention precludes consistently successful performance, regardless of the raw water quality.

3. INNOVATIVE FLOTATION–FILTRATION PACKAGE PLANTS

3.1. *Flotation–Filtration System Type I (1.2 MGD)*

System Type I, the first package flotation plant built in America (10–19), consists mainly of flocculation, dissolved air flotation/sand filtration, and disinfection processes. Before installation of the plant, the total THM in Lenox, MA tap water ranged from 19.7 to 88.5 μg/L. After the plant was put on-line, the total THM of Lenox tap water has been reduced by more than 50%. Even without using any disinfectant, the innovative package water treatment plant was extremely efficient for removing 80–100% of the coliform bacteria from raw water. Since there is no need to use prechlorination, not only THM has been reduced, but also the capital cost for prechlorination facility and O&M costs for postchlorination are reduced. The plant effluent still required postchlorination as a final safeguard for water in the distribution system, but the chlorine requirement is significantly reduced by up to 40%.

The Lenox plant, which is an ideal package plant for small communities, has a design capacity of 1.2 MGD serving a population of 10,000, 6,500 inhabitants in town, and 3,500 tourists. Figure 5.1 presents a cut-off section of the package plant. Table 5.4 shows a summary of the plant's performance data. It can be seen that raw water turbidity, color, and coliforms are all significantly removed. It is important to know that the plant recycles and reuses its filter backwash wastewater for the production of drinking water. The water loss caused by floated sludge is less than 0.5% compared to a conventional plant, consisting of flocculation, sedimentation, and filtration, which has a normal water loss of 10% due to the discharge of filter backwash as wastewater.

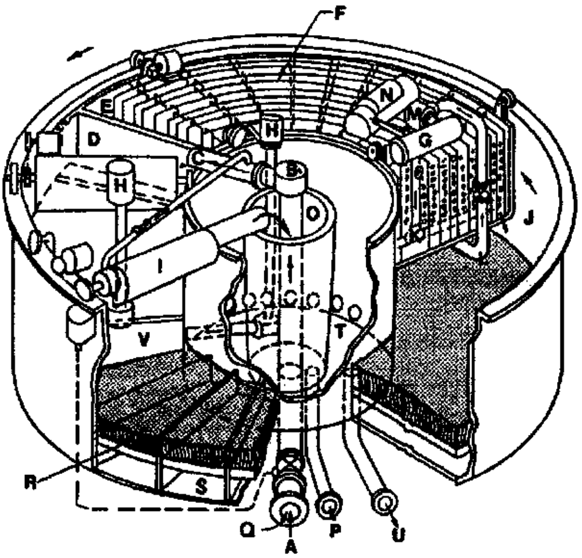
3.2. *Flotation–Filtration System Type II (100 gpm)*

Package Plant Type II, designed specifically for small communities, also consists of flocculation, dissolved air flotation/sand filtration processes.

The plant has a design capacity of 100 gpm (0.144 MGD). Assuming the water consumption rate in rural areas to be 100 gal/capita/d, one small package plant Type II would be able to serve about 1,500 people. The top and side views of the plant are shown in Fig. 5.2.

Figure 5.3 shows the same package plant system mounted on a trailer to provide mobility for its possible service in remote camping sites, construction sites, battle fields, etc.

It has been demonstrated that the Type II plant can attain significant removal of turbidity, color, trihalomethane precursors (in terms of trihalomethane formation potential, UV absorbance, humic substances, etc.), and coliform bacteria from the raw water of the City of Rome, NY. Table 5.5 presents a summary of typical monthly performance data (20–23).



A – RAW WATER INLET
B – HYDRAULIC JOINT
C – INLET DISTRIBUTOR
D – RAPID MIXING
E – MOVING SECTION
F – STATIC HYDRAULIC FLOCCULATOR
G – AIR DISSOLVING TUBE
H – BACKWASH PUMPS
I – SPIRAL SCOOP
J – FLOTATION TANK
K – DISSOLVED AIR ADDITION
L – BOTTOM CARRIAGE
M – PRESSURE PUMP
N – AIR COMPRESSOR
O – CENTER SLUDGE COLLECTOR
P – SLUDGE OUTLET
Q – CHEMICAL ADDITION
R – SAND FILTER BEDS
S – INDIVIDUAL CLEAR WELLS
T – CENTER CLEAR WELL
U – CLEAR EFFLUENT OUTLET
V – TRAVELING HOOD

Fig. 5.1. Cutoff view and description of the flotation–filtration system, type I.

3.3. Flotation–Filtration System Type III (10 gpm)

The miniature package treatment system consists of a mixing tank, static hydraulic flocculation tank, dissolved air flotation tank (Diameter = 3 ft.), and three sand filters. The system has a design capacity of 10 gpm (0.0144 MGD). This compact system can serve 150 people in a small housing development, or a town house complex. It too can be mounted on a trailer to have maximum mobility.

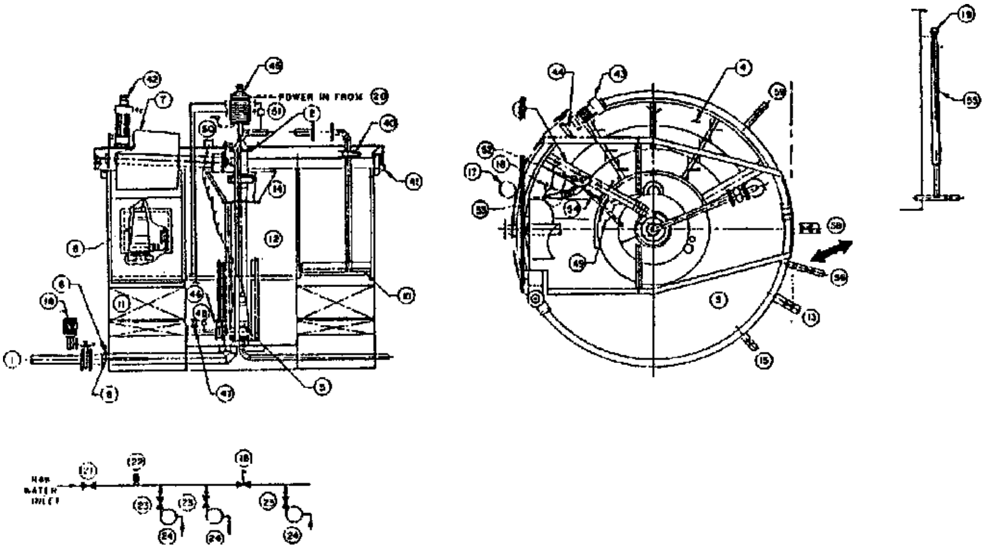
Under the supervision of the City of Pittsfield, MA and the Department of Environmental Quality Engineering (DEQE) in Massachusetts, raw surface water, the same source used for

Table 5.4
Performance of flotation–filtration system type I, Lenox, MA

Parameter	Performance data	
	Period 1	Period 2
Influent		
Flow, gpm	77–820	168–843
Temperature, °F	38–70.5	36–59
pH, unit	7.4–8.6	6.4–8.4
Turbidity Grab, NTU	0.75–8.2	0.8–5.4
Turbidity, (daily average), NTU	0.66–7.7	0.8–4.4
Color, unit	1–15	9–15
Coliform, #/100 mL	0–>2,000	0–41
Chemical treatment		
Polymer, type	XNAlC or C302	C302 and/or XMA9A
Polymer dosage, mg/L	0–5	0–3.9
Alum, type	AS	AS
Alum dosage, mg/L Al_2O_3	0–6.7	0–14
Other chemical, type	None	SA
Other chemical dosage, mg/L	0	0–4.8
Effluent before postchlorination		
Flow, gpm	74–815	165–840
pH, unit	6.8–7.9	6.3–7.5
Turbidity Grab, NTU	0.09–1.00	0.09–2.5
Turbidity (overall average) NTU	0.3	0.41
Color, unit	0–4	1–8
Coliform, #/100 mL	0–2	0–2
Polymer residue, mg/L	0–0.5	0–0.1
Alum residue, mg/L Al	0.03–0.3	0.01–0.2
Other chemical residue, mg/L	0	0
Sludge		
Flow, gpm	<1.0–7	3–3.5
Suspended solids, mg/L	168–43,270	242–15,677
Coliform, #/100 mL	0–2,000	NA

water supply to the city, was successfully treated by this miniature system. Table 5.6 summarizes the performance data (24–26). It is clear that turbidity, color, trihalomethane formation potential (THMFP), coliform bacteria, iron, manganese, lead and giardia cyst-sized particles (in terms of microscopic particle count) were significantly removed from the City of Pittsfield's raw water supply. The process system easily met all U.S. Environmental Protection Agency and the Massachusetts Drinking Water Standards.

The same Type III system was used to treat the acid-rain contaminated South Pond water. South Pond is located in northwestern Massachusetts, USA, about 6 miles south of the



1. RAW WATER INLET
2. HYDRAULIC ROTARY JOINT
3. RAPID MIXING SECTION
4. FLOCCULATOR
5. BACKWASH WASHING PUMP
6. BACKWASH RECYCLE PUMP
7. SLUDGE DISCHARGE SCOOP
8. CHEMICAL LINES
9. FLOTATION TANK
10. PRESSURE RELEASE MANIFOLD
11. SAND FILTER (SILICA SAND 11" DEPTH)
12. CLEAR WELL
13. CLEAR WELL EFFLUENT OUTLET (GATE VALVE)
14. CENTER SLUDGE COLLECTOR
15. FLOATED SLUDGE OUTLET (GATE VALVE)
16. BACKWASH HOOD AREA
17. LEVEL CONTROL
18. INLET MOTORIZED BUTTERFLY VALVE
19. CLEAR WELL ELECTRODES
20. CONTROL PANEL
21. RAW WATER INLET MANUAL VALVE
22. INELT FLOW METER
23. CHEMICAL PUMP DISCHARGE GATE VALVE
24. CHEMICAL PUMP
25. PRESSURE PUMP SUCTION GATE VALVE
26. PRESSURE PUMP DISCHARGE GATE VALVE
27. PRESSURE PUMP
28. Δ PRESSURE GATE VALVE
29. PRESSURE GAUGE 0–100 PSI
30. Δ PRESSURE GATE VALVE
31. SAFETY VALVE SET TO 100 PSI
32. AIR DISSOLVING TUBE
33. AIR DISSOLVING TUBE INLET ORIFICE
34. AIR COMPRESSOR 55 SCFH @ 90 PSI
35. AIR FILTER
36. AIR REGULATOR
37. AIR ROTOMETER 0 - 50 SCFH @ STD
38. GATE VALVE
39. GATE VALVE
40. PRESSURE REDUCING BUTTERFLY VALVE
41. LIMIT SWITCH
42. SCOOP DRIVE MOTOR
43. CARRIAGE DRIVE MOTOR
44. CARRIAGE DRIVE WHEEL
45. ELECTRICAL ROTARY CONTACT
46. BUTTERFLY VALVE
47. BACKWASH CYLINDER
48. PRESSURE GAUGE (0–100 PSI)
49. BACKWASH SHOE
50. DELAY TIMER
51. SOLENOID VALVE
52. GATE VALVE
53. PRESSURE GAUGE (0–100 PSI)
54. GATE VALVE
55. CLEAR WELL SITE TUBE
56. CLEAR WELL DRAIN (GATE VALVE)
57. BLEED OFF VENT
58. PRESSUREIZED INLET (GATE VALVE)
59. PRESSURIZED SUCTION PIPE (GATE VALVE)

Fig. 5.2. Flotation–filtration system, type II.

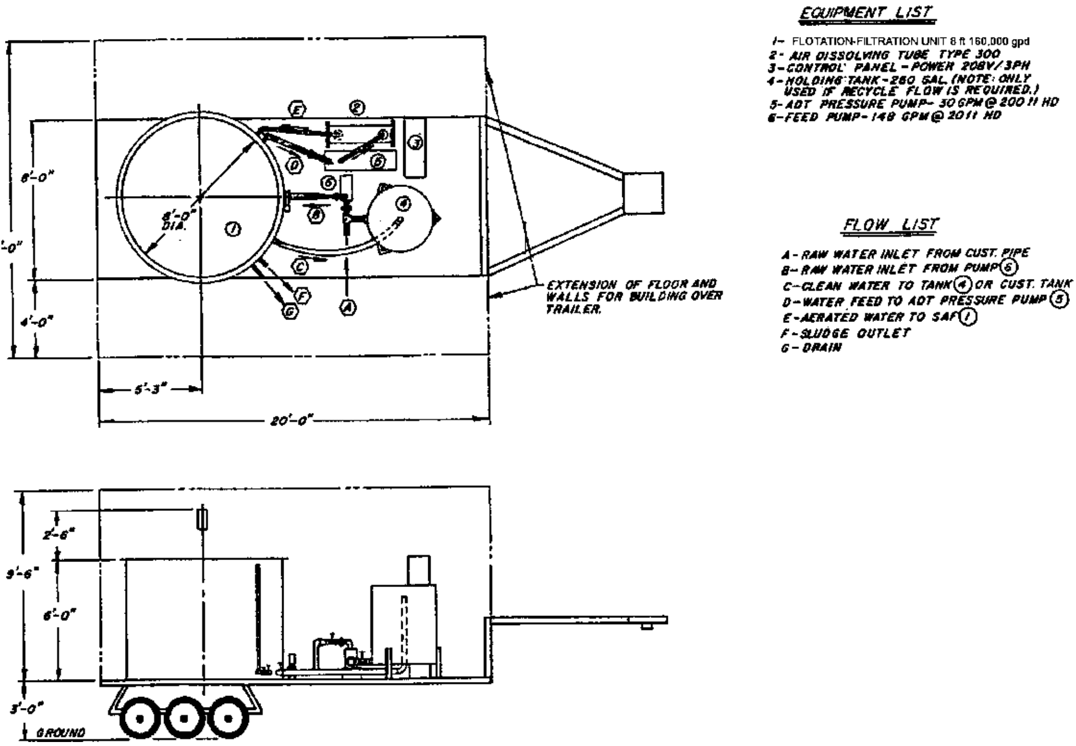


Fig. 5.3. Mobile flotation–filtration package plant, type II.

Vermont border. The pond lies at an elevation of 1980 ft in the Berkshire Hills and has an area of 18 acres. It is a shallow lake with an average depth of 10 ft having very limited and low-growing aquatic vegetation along the bottom. Predominant fish species include bullhead and panfish in low numbers. Surrounding the lake is a mixed northern hardwood forest of hemlock, beech, and sugar maple trees, with a blend of mountain laurel and blueberry bushes along the shoreline. During the summer months, 150 ft of the eastern shoreline is used as a campground beach for the state forest. South Pond has no cabins, cottages or other facilities discharging wastewater along its shore and the State of Massachusetts also prohibits fishers and boaters from using gas powered motors on the pond. However, the South Pond water has been contaminated by acid rain. Table 5.7 presents the raw water quality and the treatment results. It can be seen that the raw water quality was poor in terms of low pH, high acidity, color, turbidity, sulfates, and coliform bacteria. Since the raw water sulfate content was high and its nitrate content was low, it can be reasonably concluded that the lake water was acidified by sulfur dioxide, not by nitrogen oxides. It is encouraging to see (from Table 5.7) that flotation treatment (using sodium aluminate and lime) in the first treatment stage rendered the South Pond water to be suitable for recreational purposes. After the second stage filtration treatment, the filter effluent became of potable quality which is suitable for domestic consumption. The final effluent is neutral in pH, low in color, turbidity, acidity, nitrates and sulfates, and zero in phosphates and coliforms.

Table 5.5
Performance of flotation–filtration system type II, Rome, NY

Parameter	Range	Average
Influent		
Flow, gpm	100	100
Temperature, °F	34–40	37.6
pH, unit	7.1–7.3	7.2
Turbidity, NTU	0.65–1.2	0.89
Color, unit	40–50	42.5
Microscopic count, #/mL	4,214–12,939	8,833
Aluminum, mg/L	0–0.074	0.013
Alkalinity, mg/L $CaCO_3$	10–21	15.4
THMFP, mg/L	127–493	303
UV (254 nm)	0.169–0.213	0.185
Total coliform, #/100 mL	<1–TNTC	
Total plate count #/1 mL	4–6	5.0
Humic substances, mg/L	4.2–6.0	5.6
Chemical treatment		
Polymer, type	1849A	1849A
Polymer dosage, mg/L	1.5–2.0	1.9
Sodium aluminate, mg/L	4.8–6.4	6.1
Alum, ppm $Al_2(SO_4)_3 \cdot 14H_2O$	17.4–29.6	23.1
Other chemical, type	None	None
Other chemical, mg/L	0	0
Sandfloat effluent, unchlorinated		
Flow, gpm	98.5–99.4	98.9
pH, unit	6.8–7.1	7.0
Turbidity, NTU	0.1–0.39	0.12
Color, unit	2	2.0
Microscopic count, #/mL	13–67	37
Aluminum, mg/L	0–0.014	0.005
Alkalinity, mg/L $CaCO_3$	7–16	9.0
THMFP, ppb	19–97	61.2
Chlorine demand, mg/L	0.65–1.5	1.2
UV (254 nm)	0.019–0.045	0.034
Total coliform, #/100 mL	<1	<1
Total plate count #/1 mL	0	0
Humic substances, mg/L	0.3–3.1	1.19
Chlorinated effluent		
pH, unit	6.9–7.7	7.2
Turbidity, NTU	0.2–0.3	0.2
Color, unit	0–3	1.0
Microscopic count, #/mL	NA	NA
Aluminum residue, AL	0–0.014	0.005

(*Continued*)

Table 5.5
(Continued)

Parameter	Range	Average
Chlorine residue, mg/L	0.2–0.45	0.3
Temperature, °F	34–40	37.6
Corrosion control	OK	OK
THMFP, mg/L	19–97	61.2
Total coliform, #/100 mL	0	0
Total plate count	0	0
Sludge from sandfloat		
Flow, gpm mg/L	0.6–1.5	1
Total suspended solids, mg/L	394–4,213	2,433

4. WATER PURIFICATION BY ELECTROFLOTATION AND FILTRATION

4.1. *Description of Electroflotation System Type IV*

Type IV system is a novel water purification package plant specifically developed for single family homes, apartments, and camping sites (27). The dimensions of the plant are 0.9 m × 0.6 m × 1.8 m high (3 ft × 2 ft × 6 ft high), as shown in Fig. 5.4.

Figure 5.5 shows the process flow diagram of Type IV System. The primary distinguishing features of the compact package plant are: (a) the high rate electroflotation process that replaces conventional sedimentation for clarification; and (b) the trouble-free UV process that replaces conventional chlorination for disinfection.

The new miniature package plant includes:

1. Influent, effluent, and residues discharge pump
2. Two backwash pumps
3. Two chemical metering pumps
4. All necessary piping, valves, motors, controls
5. All ancillary equipment necessary to treat a water supply of 500 gal/d

Items to be furnished by the customer include:

6. Electrical power 20 AMP-115 VAC, 60 Hz, single phase
7. Alum and polyelectrolyte chemicals specified by the manufacturer
8. Storage tank (optional), and
9. Heated and vented area to house a cabinet 24 in. × 36 in. × 72 in.

4.2. *Electroflotation Theory*

Since the theories of chemical flocculation (28), sand filtration (29), and disinfection (30, 31) are well established, only the theory of electroflotation is discussed in this chapter.

Flotation is a unit operation for separating a solid phase from the liquid phase by introducing gas bubbles which adhere to one phase causing a decrease in the apparent density of that phase such that it will rise and float (32– 35).

Table 5.6
Performance of flotation–filtration system type III – treatment of surface water, Pittsfield, MA

Parameter	Range
Influent	
Flow, mg/L	3.2–12
Temperature, °F	39.2–62.6
pH, unit	6.1–7.5
Turbidity, NTU	1–3.5
Color, unit	25–70
Microscopic count, #/mL	1,967–17,328
Aluminum, mg/L	0–0.17
Alkalinity, mg/L $CaCO_3$	4–39
THMFP, mg/L	73–577
UV (254 nm)	0.056–0.303
Total coliform, #/100 mL	NA
Iron, mg/L	0.03–0.78
Manganese, mg/L	0–0.15
Chlorine demand, mg/L	0.7–3.3
Chemical treatment	
Polymer, type	1849A
Polymer dosage, mg/L	0.5–1
Sodium aluminate, mg/L Al_2O_3	6–13
Alum dosage, mg/L Al_2O_3	5–6
Other chemical, type	LIME
Other chemical dosage, mg/L	0–13.5
Filter effluent, unchlorinated	
Flow, gpm	7.38–11.9
pH, unit	6.8–8
Turbidity, NTU	0.1–0.7
Color, unit	0–5
Microscopic count, #/mL	5–125
Aluminum, mg/L Al	0–0.1
Alkalinity, mg/L $CaCO_3$	4–31
THMFP, ppb mg/L	4–18
Chlorine demand, mg/L	0.4–1.5
UV (254 nm; 1 cm light path)	0.027–0.097
Total coliform, #/100 mL	0–2
Iron, mg/L	0–0.08
Manganese, mg/L	0–0.09
Chlorinated water	
Chlorine type mg/L	Cl_2 or Ca $(OCl)_2$
Chlorine dosage, mg/L Cl_2	0.62–1.71

(*Continued*)

Table 5.6
(Continued)

Parameter	Range
Corrosion control chemical	SSN or SMP
Corrosion control chemical, mg/L	7–20
pH, unit	7.1–8
Turbidity, NTU	0.2–0.4
Color, unit	0–5
Aluminum residue, mg/L Al	0–0.1
Chlorine residue, mg/L	0.1–0.4
Total coliform, #/100 mL	0
Sludge from pilot plant	
Flow, gpm	0.08–0.15
Total suspended solids, mg/L	1,145–3,390

Table 5.7
Performance of flotation–filtration system type III – treatment of acidic pond water, Stockbridge, MA

Parameter	Raw lake water	Flotation effluent (1st stage)	Filtration effluent (2nd stage)
pH, unit	4.9	7.0	7.1
Color, unit	3.5	0.3	0.1
Turbidity, NTU	2.8	0.8	0.05
Acidity mg/L $CaCO_3$	24.0	1.9	1.8
NO_3–N, mg/L	0.4	0.3	0.2
PO_4–P, mg/L	0.1	0	0
SO_4, mg/L	70.0	10.0	9.0
Coliforms, #/100 mL	160	1	0

In dissolved air flotation (DAF), the gas used for flotation is air; while the gas used in electroflotation consists of hydrogen and oxygen produced by the electrolysis of water. The chemical reactions occurring at the electrodes to produce these gases are shown below:

Anode Reaction:

$$2H_2O \rightarrow 4H^+ + O_2\uparrow + 4e^- \tag{1}$$

Cathode Reaction:

$$4e^- + 4H_2O \rightarrow 2H_2\uparrow + 4OH^- \tag{2}$$

Total Reaction:

$$2H_2O \rightarrow 2H_2\uparrow + O_2\uparrow \tag{3}$$

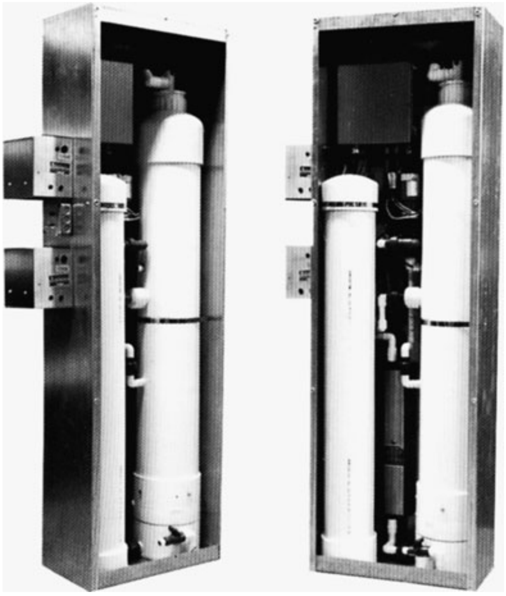


Fig. 5.4. Electroflotation–filtration package treatment plant, type IV.

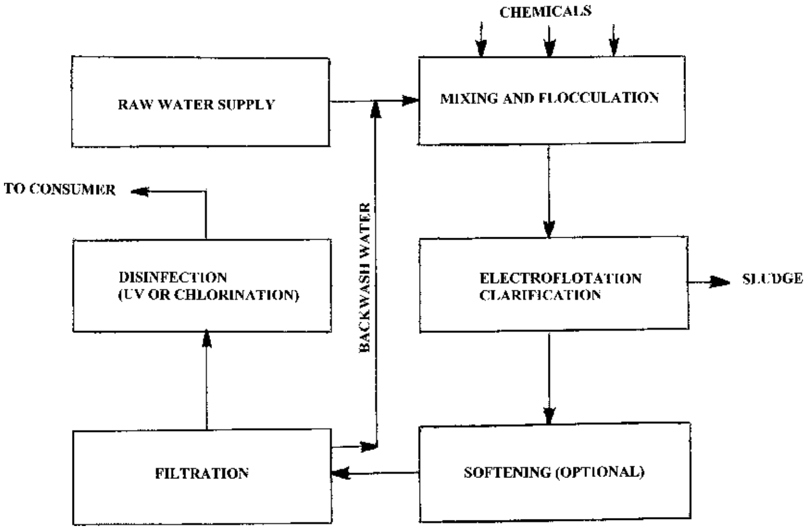


Fig. 5.5. Flow diagram of the electroflotation–filtration package treatment plant, type IV.

From these reactions, it can be seen that for each 4 electrons of current passed between the electrodes, one molecule of oxygen and two molecules of hydrogen are formed. Or in more convenient terms, 0.174 mL of gas, measured at standard temperature and pressure, is produced by each coulomb of current.

Table 5.8
Volume of gas production as a function of voltage and currant (test run = 1.5 min)

Voltage (V)	Amperage (A)	Voltage × amperage	Gas volume (mL)	Gas rate (mL/min)
0	0	0	0	0
3.9	0	0	1.5	1.0
7.8	0.5	3.9	8.0	5.3
12.3	0.6	7.4	17.0	11.3
17.3	1.0	17.3	26.5	17.7
23.3	1.6	37.3	30.0	20.0
29.3	2.3	67.4	50.0	33.3
31.0	2.8	86.8	65.0	43.3
39.0	3.5	136.5	81.0	54.0

Electrolysis of water produces small gas bubbles with diameters in the order of 100 μ that are formed at the electrodes and rise as fine mist. The rate of gas production as a function of the voltage and currant is given in Table 5.8.

Generation of bubbles through electrolysis has several advantages (36):

1. Purity – since the bubbles are created from water and no actual handling or transport of the gases occurs before their use, gas in the bubbles remains uncontaminated.
2. Process Control – controlling the rate of generation is easy: the more current applied, the more gas generated. Conversely, the less current applied, the less gas generated.
3. Simplicity – the resulting unit is easy to manufacture and simple in operation.

4.3. *Operation of the Electroflotation–Filtration Package Plant*

Figure 5.6 illustrates the miniature electroflotation–filtration package plant. Raw water influent is pumped (4) into the plant through an influent pipeline. As this fluid enters the alum flocculation cylinder (10), it is mixed with a concentrated solution of alum which is pumped (9) to this point from the alum storage cylinder. The alum solution and the fluid swirl in this tank to form a precipitate called alum floc. The liquid and floc emerge from the cylinder where another chemical, polyelectrolyte or sodium aluminate, is added in a similar fashion (11). The fluid then flows through a mixing cylinder (12) to a point in the tank (13) just below the electroflotation unit (14). This unit electrically separates the molecules of hydrogen and oxygen in the water and, thereby, forms gaseous bubbles which immediately rise to the surface. These bubbles attach themselves to the flocs, which have now entrapped the foreign matter in the fluid, and rise to the surface. Being buoyant, the sludge floats on the water surface and is collected (16) and returned to the front section of the influent storage tank by the sludge discharge pump (17). Gaseous materials are removed through a vent and fan (39).

The fluid, which now fills the tank (13), is drawn down through the bottom of the tank by means of the discharge pump (32). As water flows down the tank, it passes through a layer of sand (24) and a fine screen where unfloated particulates are filtered out. The water then passes

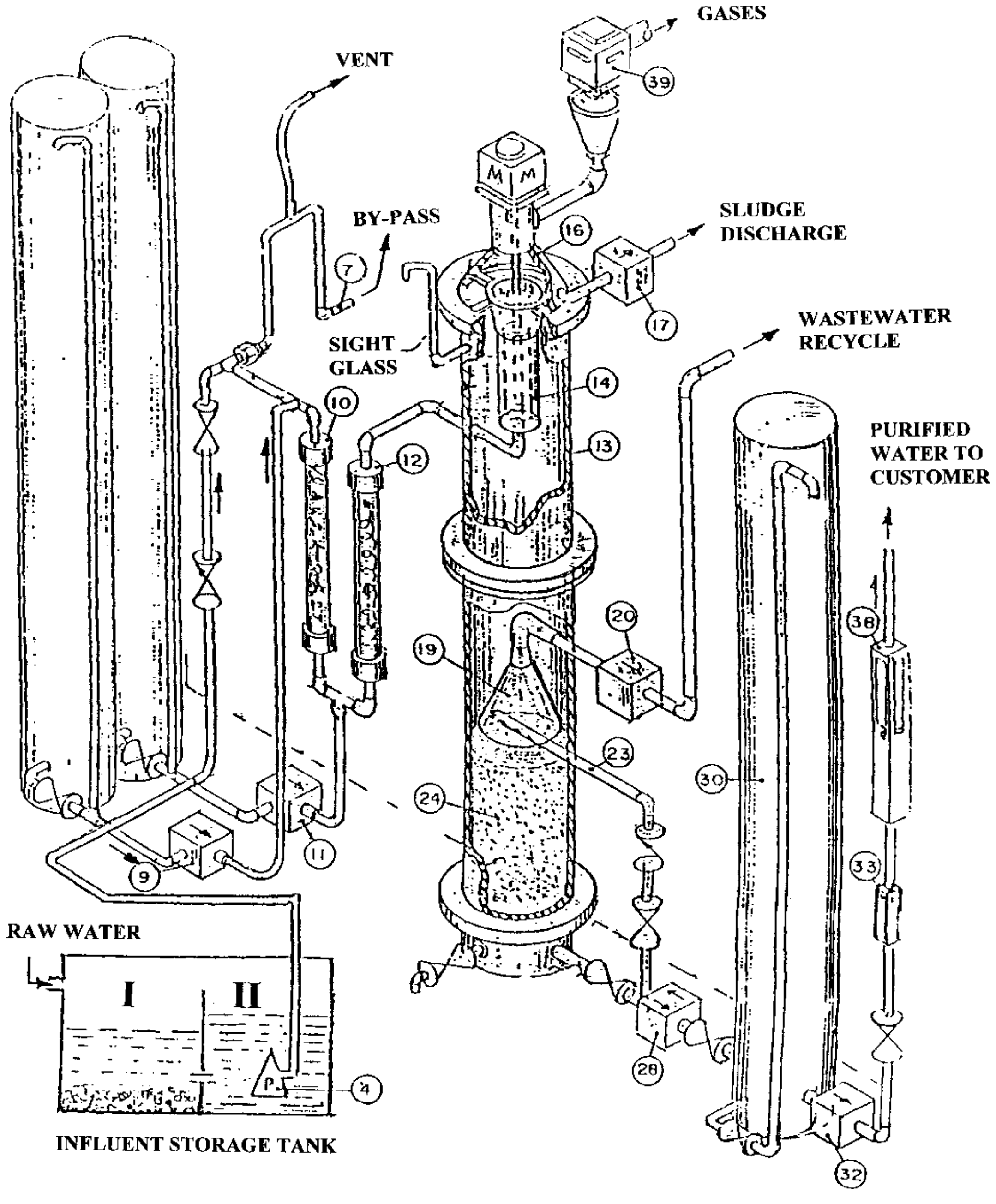


Fig. 5.6. Operation of the electroflotation–filtration package treatment plant, type IV.

through an ultra violet (UV) disinfection unit (38) where pathogens are killed. The purified potable water product is now fit for domestic consumption.

Water flow from the filter is controlled by a flow meter (33). Water flow into the system from the influent pump (4) which is in excess of the purified outflow is bypassed back to the influent storage tank through a bypass line (7).

As material builds up in and on the surface of the sand, the flow through the sand decreases. In order to maintain the design flow in the system over an extended period of time, the sand must be cleansed periodically. This is accomplished by a timer, which shuts off the influent flow and energizes the backwash cycle. During this short (20 s) cycle, water is pumped (28) back through the sand (24) from the clearwell (30). This backwash flow lifts the foreign matter from the sand. To facilitate this process, a small portion of the backwash water is diverted through a surface wash pipe (23) to help in the cleansing of the sand surface. The backwashed material is then collected (19) and discharged back to the influent storage tank by means of a wastewater recycle pump (20).

4.4. *Treatment of Well Water by Electroflotation–Filtration*

The performance of the electroflotation–filtration package plant in treating well water from a residential house in Richmond, MA is shown in Table 5.9 (27).

In the first 2-h continuous operation (0–120 min) at 0.36 gpm of influent flow rate, only 10 mg/L of alum (as $A1_2O_3$) was fed. The effluent turbidity was always lower than 1.0 NTU, which meets the Massachusetts Drinking Water Standards on turbidity.

In the second 2-h continuous operation (120–240 min) at the same flow rate of 0.36 gpm, 10 mg/L of alum (as $A1_2O_3$) and 0.5 mg/L of Magnafloc 1849A were fed to enhance the chemical coagulation and flocculation. In accordance with the New York State Water Quality Goals on effluent turbidity, the effluent turbidity shall be equal to or less than 0.5 NTU in over 50% of the operational time. The test results indicate that these standards are met when both alum and Magnafloc 1849 are used.

Other water quality parameters, effluent total coliform, color, pH, iron, manganese, etc. met both the Massachusetts and New York drinking water standards. There were no coliforms detected in the treated effluent.

Ammonia nitrogen, nitrate nitrogen, nitrite nitrogen, and sodium concentrations in raw well water almost remained unchanged after treatment.

It is important to note that the influent total alkalinity was high at 284 mg/L as $CaCO_3$; therefore, there was no need to use any sodium aluminate as alkalinity supplement.

The total hardness of influent well water was 276 mg/L as $CaCO_3$, which is considered to be moderately high. The hardness, however, is not high enough to necessitate softening.

4.5. *Treatment of Lake water by Electroflotation–Filtration*

The performance of the electroflotation–filtration package plant in treating lake water from Stockbridge Bowl, MA is shown in Table 5.10 (27).

Stockbridge Bowl is a deep lake located in Stockbridge, MA. The lake has various aquatic vegetation fast-growing along the lake bottom, and is classified as a recreation area for

Table 5.9
Performance of electroflotation–filtration system type IV – treatment of well water, Richmond, MA

Time (min)	Filter back-wash	Filter effluent quality								
		Turb NTU	Color unit	pH unit	Fe (mg/L)	Mn (mg/L)	NH_3–N (mg/L)	NO_3–N (mg/L)	NO_2–N (mg/L)	Coliform (#/100 mL)
0	NA	4.5	80	7.0	0.21	0.02	0.08	0.01	0.05	780
15		0.6								
30	BW	0.4	2	6.5	0	0	0.07	0.01	0.04	0
45		0.5								
60	BW	0.4	1	6.6	0	0	0.07	0.01	0.06	0
75		0.3								
90	BW	0.5	2	6.6	0.01	0	0.07	0.01	0.05	0
105		0.5								
120	BW	0.5	2	6.6	0.02	0	0.07	0.01	0.04	0
135		0.3								
150	BW	0.3	2	6.6	0	0	0.08	0.03	0.06	0
165		0.2								
180	BW	0.5	2	6.7	0	0	0.09	0.03	0.06	0
195		0.2								
210	BW	0.1	2	6.6	0	0	0.07	0.03	0.06	0
225		0.3								
240	BW	0.1	0	6.7	0	0	0.07	0.03	0.06	0

Flow rate, $Q = 0.36$ gpm; chemical dosage from 0 to 120 min: 10 mg/L alum as Al_2O_3; chemical dosage from 120 to 240 min: 10 mg/L alum as Al_2O_3 and 0.5 mg/L polymer 1849A.
BW Backwash.

fishing, boating, and swimming. There are many cabins, cottages, and camping facilities which discharge septic tank effluent along the lake shore. Under emergency situations, the State of Massachusetts allows the Town of Lenox to pump the Stockbridge Bowl water for treatment and subsequent domestic consumption.

The lake water testing (influent in Table 5.10) indicate that the lake water has high color, turbidity, total suspended solids, chemical oxygen demand, and particles count, making it unsuitable for human consumption without treatment.

The lake water was treated at a flow rate of 0.36 gpm for 4 h. Only 10 mg/L of alum (as $A1_2O_3$) was used as a coagulant. Table 5.10 indicates that after electroflotation–filtration treatment, the effluent pH was near neutral, and all other water quality parameters (such as turbidity, color, total suspended solids, chemical oxygen demand, and particle count) were reduced to drinking water level.

4.6. Treatment of Highly Contaminated Water by Electroflotation–Filtration

In the previous two sections, it has been demonstrated that the electroflotation–filtration process system has the ability to produce potable water from both groundwater (well water)

Table 5.10
Performance of electroflotation–filtration system type IV – treatment of lake water, Stockbridge, MA

Time (min)	Filter back-wash	Filter effluent quality							
		Turb NTU	Color unit	pH unit	TSS (mg/L)	COD (mg/L)	PO_4–P (mg/L)	Al (mg/L)	Particle count (#/100 mL)
0	NA	2.5	20	8.5	104	35	0.19	0.12	4,000
15		0.30							
30	BW	0.30	2	6.7			0		
45		0.28							
60	BW	0.30	2	6.7	0	10	0	0.05	10
75		0.24							
90	BW	0.24	1	6.7			0		
105		0.28							
120	BW	0.29	2	6.7	0	10	0	0.05	0
135		0.24							
150	BW	0.24	2	6.7			0		
165		0.24							
180	BW	0.27	2	6.7	0	18	0	0.05	20
195		0.28							
210	BW	0.24	1	6.7			0		
225		0.14							
240	BW	0.14	1	6.7	0	10	0	0.05	10

Flow rate, $Q = 0.36$ gpm; chemical dosage: 10 mg/L alum as Al_2O_3.
BW Backwash.

and surface fresh water (lake water). It would be useful to know whether or not the system can treat highly contaminated water.

Synthetic raw water was prepared according to the following concentrations (27):

Ammonium acetate	30 mg/L
Ammonium chloride	57 mg/L
Potassium nitrate	3 mg/L
Bentonite clay	50 mg/L
Potassium dihydrogen phosphate	13 mg/L
Dissolved protein (gelatin)	40 mg/L
Vegetable oil (Mazola)	25 mg/L
Anionic surfactant (LAS)	2 mg/L
Soluble starch (corn starch)	40 mg/L
Pure soap (Ivory bar)	3 mg/L

Lenox tap water was used in the synthetic raw water preparation. The anionic surfactant used was the Lonear Alkalyte Sulfonate (LAS, average molecular weight = 318) supplied in 5.97% concentrated solution. The water quality of the prepared synthetic raw water is shown in Table 5.11. The concentrations of impurities in the prepared raw water were high enough to almost represent a septic tank effluent.

The electroflotation–filtration package plant was operated for the treatment of the synthetic raw water for a period of 4 h using 10 mg/L alum and 10 mg/L sodium aluminate (both as $A1_2O_3$). The filtered effluent was collected at 15 min intervals for analyses of the water quality parameters. The treated water characteristics are presented in Table 5.12.

The results show that the electroflotation–filtration process system is able to treat the highly contaminated synthetic raw water successfully. The effluent turbidity and color met the drinking water standards. The percent removals of total suspended solids, chemical oxygen demand, and nitrate nitrogen were all over 90%. Phosphates were practically completely removed.

The excellent performance of the plant in treating the previous three types of water suggests that the newly developed electroflotation–filtration process system can treat both ground water and surface water, even if they are heavily contaminated.

The package plant (500 gpd capacity) costs $4,200 in terms of 2005 dollar value. Each unit can be easily connected to the existing potable water intake system of a house and would require maintenance just once a year. The fully automatic package plant can also be leased at a rate of $2.25/d, including the cost of required chemicals.

Table 5.11
Quality of highly contaminated water

Parameter	Data
pH, unit	7.1
True color, CU	15.0
Turbidity, NTU	49.0
Total alkalinity, mg/L $CaCO_3$	72.0
PO_4–P, mg/L	6.5
Aluminum, mg/L	0.1
Specific conductivity, µmho/cm	150
TSS, mg/L	115.0
COD, mg/L	220.0
NO_3–N, mg/L	3.6
NH_3–N, mg/L	18.8

Table 5.12
Performance of electroflotation–filtration system type IV – treatment of highly contaminated water

Time (min)	Filter back-wash	Filter effluent quality							
		Turb NTU	Color unit	pH unit	TSS (mg/L)	COD (mg/L)	NH_3–N (mg/L)	NO_3–N (mg/L)	PO_4–P (mg/L)
0	NA	49	15	7	115	220	18.8	3.6	6.5
15		0.53							
30	BW	0.50	2	5	12				0.17
45		0.48							
60	BW	0.46	0	5	11	24	18.7	0.4	0
75		0.37							
90	BW	0.31	0	5	0				0.01
105		0.43							
120	BW	0.49	0	5	6	20	12.3	0.3	0.03
135		0.47							
150	BW	0.43	0	5	9				0.03
165		0.40							
180	BW	0.36	0	5	8	18	12.7	0.4	0.02
195		0.33		5					
210	BW	0.44	0	5	9				0.01
225		0.38		5					
240	BW	0.37	0	5	7	20	12.5	0.3	0.01

Flow rate, $Q = 0.36$ gpm; chemical dosage: 10 mg/L alum as Al_2O_3 and 10 mg/L sodium aluminate as Al_2O_3.
BW Backwash.

5. WASTEWATER TREATMENT BY ELECTROFLOTATION AND FILTRATION

5.1. *Conventional Individual Wastewater Treatment System*

The conventional septic tank-soil absorption system consists of a buried tank, where wastewater is collected and scum, greases, and settleable solids are removed by gravity separation and a sub-surface drainage system where the clarified effluent percolates into the soil (see Fig. 5.7). Precast concrete tanks with a capacity of 1,000 gal, giving approximately 24 h of detention time, are commonly used for household systems. Waste solids are collected and stored in the septic tank, forming sludge and scum layers. Anaerobic digestion occurs in these layers, reducing the overall sludge volume. Septic tank effluent is discharged from the tank to subsurface adsorption fields or seepage pits (6). Sizes are usually determined by percolation rates, soil characteristics, and site size and location. Distribution pipes are laid in a field of adsorption trenches to leach tank effluent over a large area. Required adsorption areas are dictated by state and local codes. Trench depth is commonly about 24 in. to provide

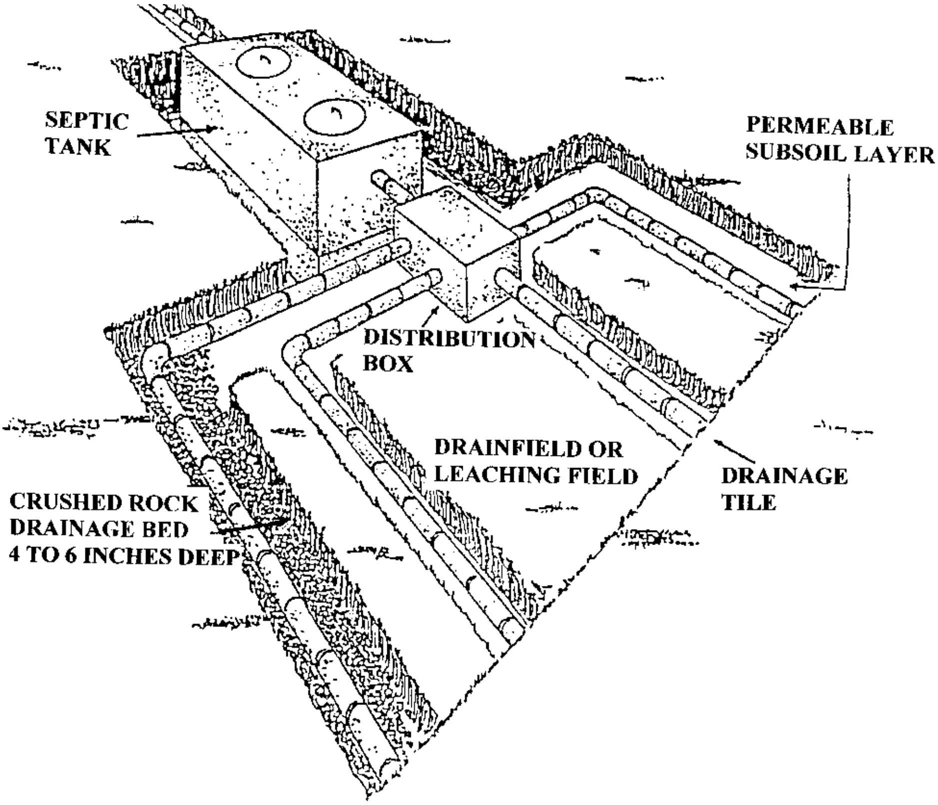


Fig. 5.7. Conventional layout of septic tank-subsurface drainage field treatment system.

minimum gravel depth and earth cover. Clean, graded gravel varying in size from 1/2 to 2½ in. should surround the distribution pipe and extend at least 2 in. above and 6 in. below the pipe. The provision of at least a 2 ft separation between the bottom of the trench and the high water table level is required to minimize groundwater contamination. Piping typically consists of agricultural drain tile, vitrified clay sewer pipe, or perforated nonmetallic pipe (37–39).

Pollutants in wastewater are removed by natural adsorption and biological processes in the soil zone adjacent to the field. Under proper conditions, BOD, TSS, bacteria, and viruses, along with heavy metals and complex organic compounds are adsorbed by the soil. However, chlorides and nitrates may readily penetrate aerated soils to reach groundwater or eventually to a lake or river. The sludge and scum layers accumulated in a septic tank must be removed every 1–3 years.

Design of absorption fields is dependent on soil and site conditions, the ability of the soil to absorb liquid, depth to groundwater, nature of and depth to bedrock, seasonal flooding and distance to well or surface water. A percolation rate of 60 min/in. is often used as the lower limit of permeability.

As mentioned earlier, when a soil system looses its capacity to absorb septic tank effluents, there is a potential for effluent surfacing, which often results in odors and, possibly, health hazards. Alternatively, the septic tank effluent containing nutrients may reach a lake causing problems due to eutrophication. Eutrophication of a lake induced by septic tank effluents can be retarded by removing the source of plant nutrients, phosphorus or/and nitrogen (40, 41). This is accomplished by the diversion of the septic tank treated effluent around the lake or by treatment of the septic tank effluent employing advanced treatment processes. An electroflotation–filtration package plant Type V has been developed for the treatment of septic effluents such that the effective life of a leaching field is significantly extended and the receiving water (groundwater, lake water, etc.) is properly protected.

5.2. Description of Electroflotation System Type V

Technically speaking, Type V is a small wastewater treatment plant specifically developed for single families, campers and institutions. It consists of chemical coagulation, electroflotation, and sand filtration. The influent of the plant is the septic tank effluent. The effluent of the plant is discharged into a leaching field for ultimate disposal. The floated sludge is periodically recycled back to the septic tank for storage. It is expected that periodically (1–7 years), the sludge accumulated at the bottom of the septic tank must be removed by a tanker for sludge disposal at a municipal wastewater treatment plant (37–39).

Figure 5.8 shows the flow diagram of a typical septic system used in Berkshire County, MA. The raw wastewater from a single family home discharges into two existing septic tanks. The capacities of the primary and secondary septic tanks, which are connected in series, are 2,000 and 1,000 gal, respectively. The two tanks function as pretreatment system. The septic tank system interrupts the domestic wastewater flow so that the denser settleable solids sink to the bottom of the tanks and the lighter floatable solids rise to the top of the tanks. Most of the settleable solids and floatable solids are liquefied by anaerobic digestion reactions. A small amount of insoluble solids remain in the septic tanks which should be removed periodically.

Ordinarily, the clarified septic tanks effluent goes out into a distribution box for uniform distribution, then into a drainfield (leaching field) for ultimate disposal. The wastewater seeps out of the drainage tiles into the permeable soil as shown in Fig. 5.7. Unfortunately, for the homeowner, a normally functioning septic system is only an ideal situation. The use of detergents, deodorant soaps, household bleaches, etc. act to kill the anaerobic bacteria in the septic tank that are needed to liquefy the settleable and floatable solids. A failed septic tank system will rapidly lead to the plugging of the leaching field and the contamination of groundwater by bacteria, phosphates and oxygen consuming organics present in the partially treated wastewater. Odor, inside or outside the home, is another environmental problem.

For the improved domestic wastewater treatment system, an equalization tank is inserted between the septic tank system and the distribution box as shown in Fig. 5.8. A submersible pump sends the septic tank effluent at a constant rate through a 2-in PVC line to an electroflotation–filtration Type V unit for physicochemical treatment using alum and potassium permanganate. When the unit is not in operation or being operated at low flow, the

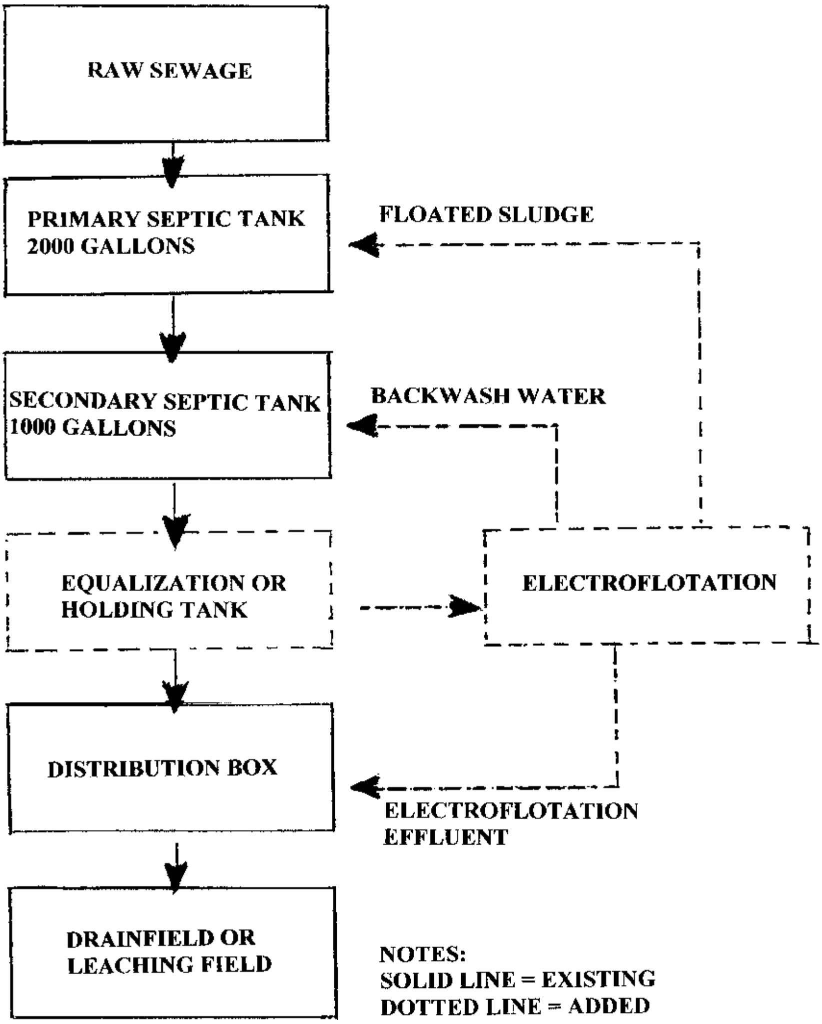


Fig. 5.8. Flow diagram-treatment of septic tank effluent by electroflotation–filtration package plant, type V.

excess volume of wastewater in the equalization tank is bypassed to the distribution box and the leaching field.

Under normal operating conditions, the electroflotation–filtration clarifier (diameter = 0.7 ft, depth = 4 ft) treats the septic tank effluent and discharges the clarified effluent into the distribution box for subsequent disposal by the leaching field. The floated sludge is discharged back into the primary septic tank and the periodically produced filter backwash water is discharged into the secondary septic tank (Fig. 5.8).

Figure 5.9 shows the typical elements of Type V package plant. The gas bubbles in electroflotation consist mainly of the hydrogen and oxygen bubbles produced by wastewater electrolysis as was explained in an earlier section on water treatment.

The general operational procedure of a Type V package plant is similar to Type IV. The unit is normally operated under the following average conditions (37– 39):
The electroflotation–filtration packaged system has an optional built-in UV disinfection unit to control pathogenic contents in the effluent if required. Similar wastewater treatment package plants are now available in the market (36, 42– 44).

Total detention time	16.4 min
Voltage	21.8 V
Amperage	1.8 A
Conductivity	545 μmho/cm
Flotation rate	1.81 gpm/ft^2
Filtration rate	1.81 gpm/ft^2

5.3. *Operation and Performance of Type V Package Plant*

This section discusses the performance of the electroflotation package plant Type V, which was installed to treat the septic tank effluent at a private residence in Berkshire County, MA.

In normal operation the septic tank effluent is pumped from the holding tank into the package plant at a uniform rate controlled at 0.7 gpm. The influent flow rate into the electroflotation unit is slightly higher than 0.7 gpm because a portion of the incoming wastewater is floated to the surface forming the sludge. Part of the clarified filtered wastewater is stored for filter backwash when necessary and the remaining filtered wastewater is disinfected and discharged as the unit effluent.

Every 15 min, the floated sludge is discharged to the septic tank at a rate equal to 0.4 gpm for a period of 15 s. The average floated sludge flow rate is estimated at:

$$0.4\,\text{gpm} \times (15/60)\,\text{min}/15\,\text{min} = 0.00667\,\text{gpm}$$

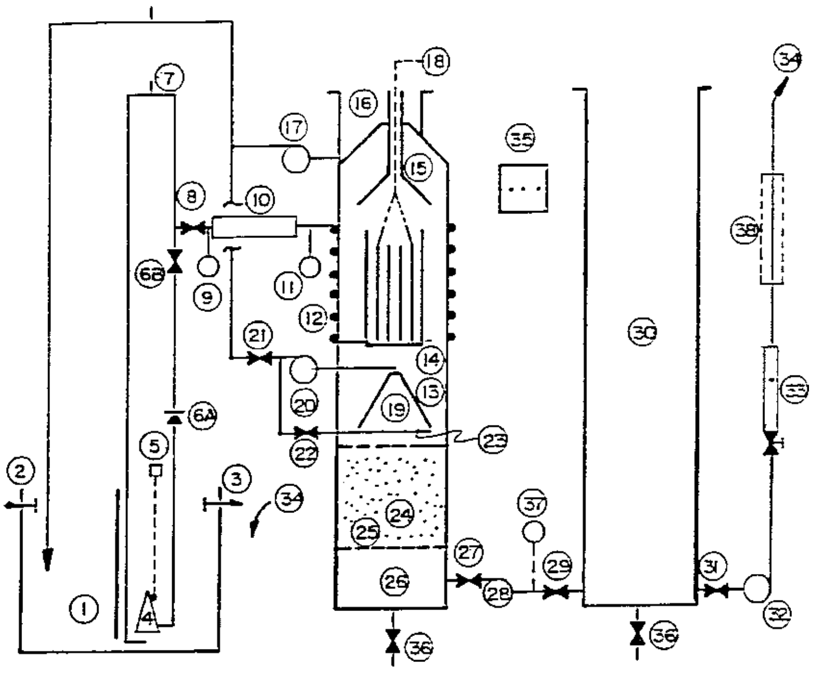
The built-in sand filter consisting of 11 in. of coarse sand, 0.85 mm size and 1.65 uniformity coefficient, is backwashed every 30 min. During filter backwash, both the influent and the effluent of the unit are stopped. The previously stored clarified-filtered washwater is then used for filter backwashing at a rate of 3.45 gpm, lasting for 47 s. The average washwater rate is estimated to be:

$$3.45\,\text{gpm} \times (47/60\,\text{min}/30\,\text{min}) = 0.09\,\text{gpm}$$

Based on a material balance of flows, the average influent flow rate shall be the summation of the average clarified-filtered washwater rate, floated sludge flow rate, and discharged effluent flow rate:

$$0.09 + 0.00667 + 0.7 = 0.8\,\text{gpm}$$

The performance of the electroflotation plant obtained from an optimized 4-week operational period is shown in Table 5.13. It is seen that the efficiency of the electroflotation–filtration system for the removal of turbidity, suspended solids, phosphate, and odor from the septic



1. Septic Tank
2. Septic Tank Inlet
3. Septic Tank Overflow
4. Submerged Feed Pump
7. Overflow of the excess feed keep the level in the main tank (13) constant. The capacity of the unit is determined by the setting of the flowmeter valve (33).
9. Alum Dosing Pump
10. Alum Flocculator
11. Flocculant Dosing Pump
12. Flocculating Coil
13. Main Tank
14. Electrodes for electro-flotation producing small gas bubbles.
15. Exhaust of larger bubbles.
16. Floated sludge accumulation.
17. Sludge Pump periodically automatically operated discharges sludge to the septic tank inlet.
18. Electrical Lines
19. Backwash Water Collector
20. Second Backwash Pump Discharge to the Inlet of the Septic Tank. Automatically operated by timer (35).
23. Shower for scrubbing the Fluidized Sand.
24. Silica Sand
25. Garnet on Fine Screen.
26. Clear Filtered Water.
28. Backwash Pump automatically operated. During the filtering cycle the filtered water flows through the standing pump in opposite direction.
30. Clear Well
32. Pump for discharge of filtered water.
33. Flowmeter with regulating valve to preset flow.
34. Discharge of clarified water returned to the outlet of the septic tank leading to leaching field.
35. Timer operates simultaneously the two backwash pumps and the sludge pump (17, 20, 28).
36. Drains
37. Hypochloride addition (optional).
38. Ultra Violet Disinfection (optional).

Fig. 5.9. Electroflotation–filtration package plant, type V.

Table 5.13
Performance of the electroflotation–filtration package plant in treating septic tank effluent

Parameters	Influent	Effluent	Percent removal
Turbidity, NTU	41.6	1.9	95.4
pH, unit	6.7	6.5	–
TSS, mg/L	19	0	100
COD, mg/L	143	62	56.6
BOD, mg/L, 5-day	111	72	35.1
NO_3, mg/L N	1.5	1.2	20.0
PO_4, mg/L P	5.0	0.02	96.0
NH_3, mg/L N	21.4	20.2	5.6
Odor, TON	450	20.0	95.6

Chemical treatment 18 mg/L $KMnO_4$ and 7.7 mg/L alum as Al_2O_3.

tank effluent is over 96%, which is an excellent performance. The plant's removal efficiencies for COD and BOD removal (56.6 and 35.1%, respectively) are moderate and considered to be satisfactory.

The chemical treatment cost is estimated to be $0.27/1,000 gal based on the following data:

$$\text{Chemical Treatment} = 28\,\text{mg/L}\,KMnO_4\text{ and }7.7\,\text{mg/L alum as }A1_2O_3$$

$$KMnO_4\text{ Cost} = \text{ USD } 1.50/\text{dry lb}$$

$$\text{Alum Cost }(8.3\%\text{ solution}) = \text{ USD } 0.06/\text{liquid lb}$$

Using the additional disinfection option shows that 100% of the total coliforms in the wastewater were killed by UV action. Potassium permanganate is mainly used for odor control and can be eliminated for cost saving.

Electroflotation has also been recently applied successfully for the treatment of industrial wastewater like effluents from degreasing units, electroplating, and metalworking (45); food processing and the decontamination of poultry chiller water (46, 47); restaurant wastewater (48); industrial coconut wastewater (49); oil products waste streams (50); and the removal of surfactants from polluted wastes (51, 52).

6. EMERGENCY WATER SUPPLY MEASURES

6.1. *Disinfection*

In emergency situations, bottled water or distilled water can be purchased from supermarkets or drug stores. For cost-saving, the contaminated raw water should be disinfected by an appropriate method before human consumption.

The most inexpensive disinfection unit is a solution dispensing system. The unit can continuously feed chlorine solution (i.e., a disinfectant) to the raw water (or untreated tap water) for killing pathogenic bacteria. Its power-operated valves give fast positive in-line operation. The entire dispensing system includes a pump, 15-gallon polyethylene reservoir, installation tubing and pH and chlorine residual test apparatus. The system weighs just 29 lb and operates at 0.5 gpm of flow. The current cost is $500 per unit. The recommended chlorine dosage is 3–6 mg/L of chlorine, depending on the daily variance of water quality.

Water disinfection can also be accomplished by a continuous UV water purification unit. The UV units, which have been successful in the swimming pool industry, are now moving into the potable water treatment field. Latest research shows that the necessary dosage of chlorine often exceeds the recommended safety levels. Chlorine disinfectant loses its effectiveness at 80–90°F, but germicidal UV continues to purify water at over 110°F.

Because of the documentation concerning over dosage of chlorine in small water supply systems, all agencies and organizations concerned with the health and welfare of single families and small institutions are now recommending the use of a germicidal UV water purification unit. The current cost of a small trouble-free UV 30 gpm water purification unit is approximately $2,000. Its installation is very simple and straightforward.

6.2. *Organic Removal and Disinfection*

When the water source (groundwater or surface water) is contaminated by toxic organics or undesirable color-causing substances, an activated carbon canister which is available up to 25 gpm capacity, should be used in conjunction with disinfection (chlorination or ultraviolet). The adsorption canisters are pre-engineered treatment modules designed for the removal of contaminants from water. Typical contaminants removed include: hydrocarbons, solvents, hydrogen sulfide, mercaptans, amines, aldehydes, PCB, pesticides, various volatile organic carbons, and other priority and toxic pollutants, including endocrine disruptors (53). It is easy to install and operate and is available at a price of $800/canister. However, it is important to know that the activated carbon canister does not kill pathogenic bacteria. A disinfection unit (chlorination or UV) following the activated carbon canister is required.

6.3. *Recommendations*

If the water supply is known to be contaminated by bacteria or other microorganisms, only disinfection is required. The trouble-free germicidal UV water purification unit is recommended for use by single families or small organizations. The cost-effective chlorination unit is safe for disinfection only if the user has basic knowledge in chlorination and will not allow overdosing with chlorine.

If the water supply is known to be contaminated by only toxic organics, an activated carbon canister is recommended.

If the raw water supply is contaminated by both toxic organics and pathogenic microorganisms, the combination of an activated carbon canister and a disinfection unit (either chlorination or UV) is required.

All the aforementioned water purification methods are temporary solutions to be used in emergency situations. For a permanent solution to single families and small communities, the cost-effective electroflotation–filtration system has the highest potential (54–56). The newly invented electroflotation–filtration process system is fully automatic and can treat highly contaminated water. Its capital and O&M costs are comparatively cheaper than the carbon canister and UV purifier combination.

REFERENCES

1. Metcalf & Eddy, Inc. (2003) Wastewater engineering, 4th edn. McGraw Hill, New York, NY
2. Wang LK, Hung YT, Shammas NK (eds) (2005) Physicochemical treatment processes, The Humana Press, Inc., Totowa, NJ, p 723
3. Wang LK, Hung YT, Shammas NK (eds) (2006) Advanced physicochemical treatment processes, The Humana Press, Inc., Totowa, NJ, p 690
4. AWWARF (1984) Small system technology, American Water Works Association Research Foundation, Denver, CO, p 7, 28 Mar 1984
5. Town of Stockbridge (1983) Annual reports of the Town Officers of the Town of Stockbridge, MA, p 68, 31 Dec 1983
6. Shammas NK, Wang LK (2009) Natural biological treatment processes. In: Wang LK, Shammas NK, Hung YT (eds) Advanced biological treatment processes, The Humana Press, Inc., Totowa, NJ, p 587–617
7. Wang LK, Pereira NC, Hung YT (eds) (2009) Biological treatment processes, The Humana Press, Inc., Totowa, NJ, p 818
8. Wang LK, Shammas NK, Hung YT (eds) (2009) Advanced biological treatment processes, The Humana Press, Inc., Totowa, NJ, p 738
9. Morand JM, Young NJ (1983) Performance characteristics of package water treatment plants, U.S. Department of Commerce, National Technical Information Service, Springfield, VA, Technical Report No. PB83–161018, Mar 1983
10. Krofta M, Wang LK (1981) Potable water pretreatment for turbidity and color removal by dissolved air flotation and filtration for the Town of Lenox, MA, U.S. Department of Commerce, National Technical Information Service, Springfield, VA, Report No. PB82–182064, p 48, Oct 1981
11. Krofta M, Wang LK (1982) Monitoring and control of Lenox water treatment plant, Lenox, MA, Lenox Institute of Water Technology, Technical Report # LIR/03–82/2, p 17
12. Krofta M, Wang LK (1982) Innovation in the water treatment field and systems appropriate and affordable for smaller communities, U.S. Department of Commerce, National Technical Information Service, Springfield, VA, Report # PB82–201476, p 30, Mar 1982
13. Krofta M, Wang LK (1982) First full-scale flotation plant in USA for potable water treatment, U.S. Department of Commerce, National Technical Information Service, Springfield, VA, Report # PB82–220690, p 67
14. Krofta M, Wang LK (1982) Startup and continuous operation of Lenox water treatment plant, Lenox Institute of Water Technology, Lenox, MA, Technical Report # LIR/06–82/4, p 28
15. Krofta M, Wang LK (1982) Operational data of Lenox water treatment plant, Lenox, MA, Lenox Institute of Water Technology, Technical Report # LIR/07–82/2, p 46, July 1982
16. Krofta M, Wang LK (1983) Design, construction and operation of Lenox water treatment plant, USA – project summary, U.S. Department of Commerce, National Technical Information Service, Springfield, VA, Report # PB83–171264, p 40
17. Krofta M, Wang LK (1983) Design, construction and operation of Lenox water treatment plant, USA – project documentation, U.S. Department of Commerce, National Technical Information Service, Springfield, VA, Report # PB83–164731, p 330

18. Krofta M, Wang LK (1983) Over one-year operation of Lenox water treatment plant – part 1, U.S. Department of Commerce, National Technical Information Service, Springfield, VA, Technical Report # PB83–247270, pp 1–264
19. Krofta M, Wang LK (1983) Over one-year operation of Lenox water treatment plant – part 2, U.S. Department of Commerce, National Technical Information Service, Springfield, VA, Technical Report # PB83–247288, pp 265–425
20. Krofta M, Wang LK (1983) Treatment of Rome raw water by Krofta Sandfloat process system – project summary, U.S. Department of Commerce, National Technical Information Service, Springfield, VA, Technical Report, p 35
21. Krofta M, Wang LK (1984) Treatment of Rome raw water by Krofta Sandfloat process system – project documentation part A, U.S. Department of Commerce, National Technical Information Service, Springfield, VA, Technical Report, pp 1–238
22. Krofta M, Wang LK (1984) Treatment of Rome raw water by Krofta Sandfloat process system – project documentation part B, U.S. Department of Commerce, National Technical Information Service, Springfield, VA, Technical Report, pp 239–376
23. Krofta M, Wang LK (1984) Treatment of Rome raw water by Krofta Sandfloat process system – project documentation part C, U.S. Department of Commerce, National Technical Information Service, Springfield, VA, Technical Report, pp 145
24. Krofta M, Wang LK (1984) Treatment of Farnham and Ashley reservoir water by Krofta Sandfloat process system – project summary, Krofta Engineering Corporation, Interim Technical Report # KEC/0l-84/1A, p 40
25. Krofta M, Wang LK (1984) Treatment of Farnham and Ashley reservoir water by Krofta Sandfloat process system – project documentation, Krofta Engineering Corporation, Interim Technical Report # KEC/01–84/1B, p 188
26. Krofta M, Wang LK (1984) Treatment of Farnham and Ashley reservoir water by Krofta Sandfloat process system – final project report, U.S. Department of Commerce, National Technical Information Service, Springfield, VA, Technical Report, p 194
27. Krofta M, Wang LK (1984) Development of innovative electroflotation water purification system for single families and small communities, Report # LIR/08–84/2, Lenox Institute of Water Technology, Lenox, MA, Published by The U.S. Department of Commerce, National Technical Information Service, Springfield, VA, Aug 1982
28. Shammas NK (2005) Coagulation and flocculation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes, The Humana Press, Inc., Totowa, NJ, pp 103–140
29. Chen JP, Chang SY, Huang JYC, Bauman ER, Hung YT (2005) Gravity filtration. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes, The Humana Press, Inc., Totowa, NJ, pp 501–544
30. Wang LK, Yuan PC, Hung YT (2005) Halogenation and disinfection. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes, The Humana Press, Inc., Totowa, NJ, pp 271–311
31. Shammas NK, Wang LK (2005) Ozonation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes, The Humana Press, Inc., Totowa, NJ, pp 315–358
32. Krofta M, Wang LK (2000) Flotation engineering, Technical Manual No. Lenox/1–06–2000/368, Lenox Institute of Water Technology, Lenox, MA
33. Krofta M, Wang LK (1999) Flotation and related adsorptive bubble separation processes, Technical Manual No. Lenox 7–25–1999/348, 4th edn. Lenox Institute of Water Technology, Lenox, MA

34. Clarke AN, Wilson DJ (1983) Foam flotation-theory and application, Marcel Dekker, New York, NY
35. Lemlich R (1972) Adsorptive bubble separation techniques, Academic Press, New York, NY
36. Trionetics, Inc. (2005) Electroflotation – How it works, http://www.trionetics.com/an004.pdf
37. Krofta M, Wang LK (1988) Treatment of septic tank effluent by electroflotation and filtration, Lenox Institute of Water Technology, Technical Paper # LIR/03–88/290L, 23 Mar 1988
38. Krofta M, Wang LK, Wang MHS (1989) Septic tank effluent treatment options: electroflotation and filtration, Technical paper presented at the 1989 Annual Meeting of New England Water Pollution Control Association, Boston Marriott, Copley Place, Boston, MA, 22–25 Jan 1989
39. Krofta M, Wang LK (1984) Development of innovative flotation–filtration systems for water treatment, part C: an electroflotation plant for single families and institutions. Proceedings of the American water works association water reuse symposium III, vol. 3. San Diego, CA, pp 1251–1264, Aug 1989
40. France RA, Aulenbach DB, Wang LK (1983) Investigation of nutrient interchanges between overlying water and sediments in lake, U.S. Department of Commerce, National Technical Information Service, Springfield, VA, Technical Report # PB84–121458, p 25
41. Aulenbach DB, Wang LK (1983) Investigation of chemical interactions in eutrophic Saratoga Lake, NY, U.S. Department of Commerce, National Technical Information Service, Springfield, VA, Technical Report # PB84–121466, p 38
42. Limburg Filter (2010) Electroflotation unit, http://www.limburgfilter.com/engels/products/wb2000.htm
43. Dr. Baer (2005) Electroflotation plant, http://www.dr-baer.de
44. Hydroclean (2010) Introducing the hydroclean redbox system, http://www.hydroclean.co.uk/redbox.htm
45. German Co., (2010) Electroflotation – purifying of industrial waste water contaminated with heavy metals, tensides, mineral oils, http://www.ircnet.lu/matching/completerec.cfm?BBS_ID=14077&org=106&back=true
46. Hernlem B, Tsai L, Huxsoll C, Robertson G (2000) Combined electroflotation and disinfection in food processing, Paper Number 74–12, Presented At The 2000 Institute Of Food Technologists Annual Meeting, Dallas, TX, 10–14 June 1989
47. Hernlem BJ, Tsai LS (2000) Chlorine generation and disinfection by electroflotation. J Food Sci 65(5):834–837
48. Chen G, Chen X, Yue PL (2000) Electrocoagulation and electroflotation of restaurant wastewater. J Environ Eng 126(9):858–863
49. Crespilho FN, Santana CG, Rezende MOO (2004) Brazilian industrial coconut wastewater treatment by electroflotation. Quím Nova 27(3):387–392
50. Ilin V (2002) A plant for removing oil products from effluents. Chem Pet Eng 38(5/6):297–299
51. Moulai-Mostefa N, Tir M (2002) Réduction de la concentration des tensioactifs dans une solution aqueuse par electroflotation. J Environ Eng Sci 1(6):427–431
52. Fukui Y, Yuu S (2004) Removal of colloidal particles in electroflotation. Am Inst Chem Eng http://www3.interscience.wiley.com/cgi-bin/abstract/109066640/ABSTRACT, Published Online: 17 June 2004
53. Shammas NK (2007) Endocrine disruptors: properties, effects and removal processes. In: Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical technologies, The Humana Press, Inc., Totowa, NJ, pp 485–504

54. Wu BC (1982) Separation of organics and inorganics from water by bubble separation processes, Master Thesis, Advisors: Dr. Milos Krofta and Dr. Lawrence K. Wang, Lenox Institute of Water Technology, Lenox, MA
55. Wang LK, Wang MHS (2007) Bubble dynamics of adsorptive bubble separation processes. 2007 National Engineers Week Conference, Albany Marriott, Albany, NY, 15–16 Feb 2007
56. Wang LK, Wang MHS, Suozzo T, Dixon RA, Wright TL, Sarraino S (2009) Chemical and biochemical technologies for environmental infrastructure sustainability. 2009 National Engineers Week Conference, Albany Marriott, Albany, NY, 5–6 Feb 2009

6

Wastewater Treatment by Electrocoagulation–Flotation

Nazih K. Shammas, Marie-Florence Pouet, and Alain Grasmick

CONTENTS

Abstract The electrocoagulation technology induces coagulation and precipitation of contaminants by a direct current electrolytic process followed by separation of flocculent without the addition of coagulation-inducing chemicals. The water is pumped through a unit in which electrodes made of iron or aluminum are installed. A direct current electric field is applied to the electrodes to induce the electrochemical reactions needed to achieve the coagulation. Compared with traditional flocculation–coagulation, electrocoagulation has also the advantage of removing the smallest colloidal particles; such charged particles have a greater probability of being coagulated and destabilized because of the electric field that sets them in motion. Electrocoagulation also has the advantage of producing a relatively low amount of residue.

This chapter discusses the electrocoagulation technology and the application of coupling electrocoagulation and dissolved air flotation (DAF) in wastewater treatment. Before discussing the beneficial synergic effect of coupling electrocoagulation and flotation, each process is first presented separately followed by a discussion of the combination of the two processes. Finally, the performance of the two combined processes is compared with the performance of the classical treatment by flocculation–coagulation–sedimentation. Seven case studies involving hazardous waste site remediation, municipal wastewater treatment and industrial effluent treatment are presented.

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Key Words Electrocoagulation • flotation • coagulation • electrocoagulation–DAF • electrodes • performance • municipal wastewater treatment • hazardous waste • remediation • manufacturer wastewater • steam cleaner • wastewater • ship bilge water.

1. INTRODUCTION

In wastewater treatment, the use of flotation, a physicochemical treatment process, would present some advantages over settling for solids separation (1):

1. Higher hydraulic loadings, i.e., shorter retention times
2. Better removal of smaller particles
3. Smaller area requirement

However, separation by flotation (2) needs a prior chemical destabilization process. Classical flocculation–coagulation (3) needs chemicals addition to be followed by a flocculation chamber where the energy introduced by mixing creates shearing forces that may not allow an optimal coagulation process to occur. According to the work of several authors (4–7), the process of electrocoagulation is a good alternative because it can avoid the disadvantages of the classical chemical destabilization process.

The electrocoagulation technology induces coagulation and precipitation of contaminants by a direct current electrolytic process followed by the separation of flocculent (settling or flotation) with or without the addition of coagulation-inducing chemicals. The water is pumped through a unit in which electrodes made of iron or aluminum are installed. A direct current electric field is applied to the electrodes to induce the electrochemical reactions needed to achieve the coagulation. Treated water is discharged from the system for reuse or disposal. Concentrated contaminants in the form of biosolids are collected for disposal or reclamation.

Compared with traditional flocculation–coagulation, electrocoagulation has also, in theory, the advantage of removing the smallest colloidal particles; such charged particles have a greater probability of being coagulated and destabilized because of the electric field that sets them in motion (8). Electrocoagulation has the advantage of producing a relatively low amount of residue also (4, 9, 10).

This chapter discusses the electrocoagulation technology and the application of coupling electrocoagulation and dissolved air flotation (DAF) in wastewater treatment. Before discussing the beneficial synergic effect of coupling electrocoagulation and flotation, each process is first presented separately followed by a discussion of the combination of the two processes. Finally, the performance of the two combined processes is compared with the performance of the classical treatment by flocculation–coagulation–sedimentation.

2. TECHNOLOGY DESCRIPTION

The following sections overview coagulation theory, the electrocoagulation technology, and the electrocoagulation system.

2.1. Theory of Coagulation

It has long been known that contaminants are stabilized in aqueous solutions due to small, electrostatic charges at the surface of the molecules or particles. If the surface charges are similar, the molecules or particles will repel one another. Competing with this repulsion is van der Waals' force, a weak intermolecular force that results in the attraction of molecules to one another. However, van der Waals' force is very small and decreases rapidly with increasing distance between particles. If the repulsion caused by the stronger, like charges can be overcome, the van der Waals' force will cause the particles to coagulate. The addition of electrolytes that have bivalent or, more effectively, trivalent cations is the conventional means for overcoming the repulsive force of the charges and causing coagulation into particles large enough to precipitate out of solution (3).

In conventional coagulation and precipitation, a chemical amendment is added to the contaminated solution. The amendment is generally alum (aluminum sulfate), lime (calcium oxide), ferric iron sulfate, or charged synthetic or natural organic polymers (polyelectrolytes). In each case, the charged portion of the chemical additive destabilizes and binds with the oppositely charged contaminants in solution, causing them to coagulate and, when of sufficient mass, to precipitate (3, 11). This method of contaminant removal has the disadvantages of requiring frequent and expensive chemical additions to the solution; leaving high concentrations of the anionic components of the additive in solution; and increasing the volume of the residue formed by subsequent precipitation of the coagulated contaminant (12).

Some chemical amendments may form stable hydroxide compounds. Others may be less resistant to degradation and may not pass the requirements of the EPA's toxicity characteristic leaching procedure [(TCLP) SW-846 Method 13 11] (13). Failure to pass the TCLP will result in the residue being characterized as hazardous waste, increasing residue disposal costs, and reducing disposal options.

2.2. Theory of Electrocoagulation

In electrocoagulation, alternating or direct current electricity is applied to a cathode–anode system in order to destabilize any dissolved ionic or electrostatically suspended contaminants. During the electrolytic process, cationic species from the anode metal dissolve into the water, Eq. (1). These cations react with the destabilized contaminants creating metal oxides and hydroxides which precipitate. If aluminum anodes are used, aluminum oxides and hydroxides form; if iron anodes are used, iron oxides and hydroxides form. The formation of the oxides and hydroxides, and their subsequent precipitation, are similar to the processes that occur during coagulation (or flocculation) and precipitation using alum or other chemical coagulants (12).

The differences are the source of the coagulant (in electrocoagulation it is the cations produced by electrolytic dissolution of the anode metal (11)), and the activation energy applied promotes the formation of oxides (14). The oxides are more stable than the hydroxides, and thus, more resistant to breakdown by acids (14). Oxygen gas is also produced at the anode by the electrolysis of water molecules, Eq. (2), and chlorine gas can be produced from chloride ions if they are present in the solution to be treated, Eq. (3). During the electrolytic production of cations, simultaneous reactions take place at the cathode producing hydrogen gas from water molecules, Eq. (4). Other important cathodic reactions include reduction of dissolved metal cations to the elemental state, Eq. (5). These metals plate on to the cathode. The chemical reactions taking place during electrocoagulation using iron anodes are shown below (11, 14–17).

At the anode:

$$\mathrm{Fe(s)} \rightarrow \mathrm{Fe^{3+}(aq)} + 3\mathrm{e^-} \tag{1}$$

$$2\mathrm{H_2O} \rightarrow 4\mathrm{H^+} + \mathrm{O_2(g)} + 4\mathrm{e^-} \tag{2}$$

$$2\mathrm{Cl^-(aq)} \rightarrow \mathrm{C1_2(g)} + 2\mathrm{e^-} \tag{3}$$

At the cathode:

$$2\mathrm{H_2O} + 2\mathrm{e^-} \rightarrow \mathrm{H_2(g)} + 2\mathrm{OH^-} \tag{4}$$

$$\mathrm{M^{N+}} + \mathrm{Ne^-} \rightarrow \mathrm{M(s)} \tag{5}$$

where:

(aq) = aqueous solution
(g) = gas
(s) = solid
M^{N+}(aq) = metal ion in aqueous solution
M(s) = metal solid
e^- = electron
N^+ = charge of metal ion
N = numerical number

In solution, the ferric ions supplied by dissolution of the anode participate in further spontaneous reactions to form oxides and hydroxides (11, 14, 17, 18). Renk (14) found that oxides preferentially formed in electrocoagulation experiments because the energy supplied by the system exceeded the activation energy for their formation. These reactions incorporated dissolved contaminants into the molecular structure forming acid resistant precipitates. These precipitates are typically capable of passing the TCLP. This can significantly reduce solid waste disposal costs. Similar reactions occur when aluminum anodes are used.

2.3. *System Components and Function*

The electrocoagulation technology is designed to remove contaminants including dissolved ionic species such as metals (19–22), suspended colloidal materials such as bacteria (5, 9, 10, 23), phosphorus (24), emulsified oily materials (25, 26), and complex organics (5, 27, 28) from groundwater or wastewater. The system induces coagulation of contaminants by means of a direct current electrolytic process (29). Floccules formed by this process are allowed to be separated in a clarifier. Treated water is discharged from the clarifier for reuse or disposal; contaminants are concentrated in flocs that are dewatered and discharged for ultimate disposal or reclamation.

Several operating parameters can be varied in the treatment system. These are (9, 12, 30, 31):

1. Length of electrodes
2. Spacing between the electrodes
3. Number of electrodes
4. Electrode material, either iron or aluminum
5. Treatment sequence
6. Flow rate and associated residence time for water in the electrocoagulation unit and clarifier
7. Amperage and accompanying voltage

2.4. *Key Features of the Electrocoagulation Technology*

The technology is unique in that it can remove radionuclides and metals from water without the addition of chemicals (5, 9, 10). Operation of the technology utilizes electricity to liberate ferric iron ions from the electrocoagulation electrodes as the contaminated water passes through the treatment unit. The ferric ions combine with dissolved or colloidal contaminants in the water forming flocs, which are removed in a clarifier. Use of the system can substantially reduce the volume of contaminated media from the volume of contaminated water to the volume of the dewatered flocs (5, 7, 9, 10, 32). In addition, the mobility of the waste is reduced.

2.5. *Influent Water Chemistry*

The electrocoagulation technology can treat a wide variety of wastewaters to remove dissolved and suspended contaminants (5, 9, 10). The chemistry of the wastewater, including the pH, the oxidation/reduction potential (Eh), dissolved oxygen, TDS, TSS, and the chemical form of the contaminants can affect formation of floccules, thereby affecting the ability of the technology to remove the contaminants of interest. Therefore, pretreatment such as aeration or pH adjustment may be necessary. In addition, the system should be optimized to the influent characteristics and the contaminants to be removed.

2.6. *Applicable Wastes*

The technology can be applied to many contaminants dissolved and suspended in water including metals, uranium, radium, selenium, phosphates, bacteria, oils, clays, dyes, organics, silica, as well as hardness (calcium carbonate). Waste streams that can be effectively treated by the technology are:

1. Plating plant effluent (10, 12, 19, 33)
2. Landfill leachates (12, 28, 34)
3. Petrochemical waste (12, 34)
4. Bilge water (12, 35, 36)
5. Mine process and wastewater (10, 28, 33, 34)
6. Food industry wastes (10, 27, 32–34, 37–39)
7. Surface or ground water (10, 12, 36)
8. Municipal wastewater (10, 19, 36)
9. Emergency potable water (10)

10. Commercial laundries and wash waters (10, 36, 40)
11. Radioactive isotope removal (10, 12, 34)
12. Textile wastewater (10, 12, 41)
13. Pulp and paper wastewater (19, 33, 34)
14. Slaughter house and tanneries wastes (19, 33)
15. Pretreatment for industrial wastes (42)
16. Pharmaceutical wastes (34)

2.7. *Advantages and Limitations of the Technology*

Electrocoagulation does not tend to remove inorganic contaminants that do not form precipitates, such as sodium and potassium. If a contaminant does not tend to form a precipitate or sorbs to solids, electrocoagulation will not be a reliable treatment method. Although certain large organic compounds can be removed such as tannins and dyes, electrocoagulation is not effective in removing lightweight organic materials, such as ethanol, methylene chloride, benzene, toluene, or gasoline (12). The sacrificial electrodes are dissolved into wastewater streams as a result of oxidation, and need to be regularly replaced. An impermeable oxide film may be formed on the cathode leading to loss of efficiency of the unit. However, this can be prevented by having the process water to be forced into turbulence and thus the oxide is never allowed to form (9).

The electrocoagulation process possesses the following advantages (7, 9, 10, 36, 43):

1. No chemicals required (other than pH control) and no increase in salinity.
2. Ability to handle a wide range of pollutants, i.e., it can process multiple contaminants: suspended & colloidal solids, heavy metals, free and emulsified oils, bacteria and organics.
3. Tolerates fluctuations in influent water quality.
4. The gas bubbles produced during electrolysis can float the pollutant to the top of the solution where it can be more easily concentrated, collected, and removed.
5. Ability to recycle water for reuse.
6. Reduced residue: the system produces half to one-third of the residue in chemical coagulation (7). The amount of dried residue is 0.20–0.37 kg/kg COD removed (32). The residue tends to be readily settable and easy to de-water, because it is composed of mainly metallic oxides/hydroxides (9).
7. Integrates benefits of chemical precipitation, floatation, and settling in much smaller footprint.
8. Fully automated, minimal operator attention.
9. Low power consumption: The power requirement is only 0.5 kWh/m^3 under a set of typical operating conditions (32).
10. Low operating costs: 15 g Al/m^3 of water and 0.6 kWh of electricity (50% for pumping water in and out) to remove 1 kg of suspended solids (43).
11. Electrocoagulation is more efficient than chemical coagulation in turbidity removal (44).
12. The technique can be conveniently used in rural areas where electricity is not available, since a solar panel attached to the unit may be sufficient to carry out the process.

3. PROCESS DESCRIPTION

As illustrated in Fig. 6.1, raw wastewater after passing through the grit chamber is pumped [1] to the electrocoagulation cell located on top of the diffusion chamber [2]. Raw wastewater

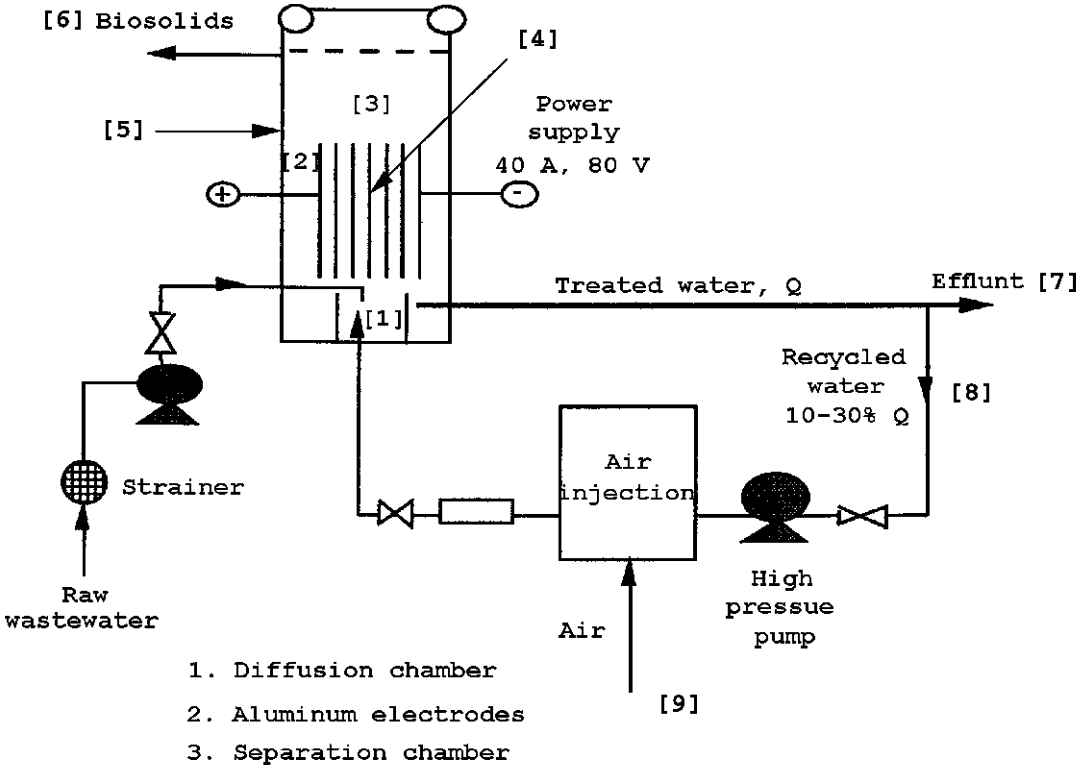

Fig. 6.1. Flow diagram of pilot plant.

undergoes electrochemical destabilization; thanks to an electrocoagulation device [3] placed at the entrance of the cell. Direct electric current, 40 A from a stabilized 80 V power supply (40 A – 80 V) is applied to a series of two-pole terminal electrodes [4]. The separation of treated wastewater and biosolids takes place in the separation chamber (flotation cell) [5]. Biosolids [6] are scraped from the top of the separation chamber, while the treated wastewater effluent [7] is discharged from near the bottom of the chamber. A portion of the treated wastewater is recirculated [8] back to the diffusion chamber after having been pressurized and saturated with air [9]. The decompression it undergoes there releases fine gas bubbles that adhere to the particles and cause them to float. The DAF process is augmented by electroflotation due to the release of oxygen and hydrogen bubbles caused by the electrolysis of water and the generation of flocs of aluminum hydroxides that trap the colloidal and supracolloidal particulates present in the wastewater (45).

The pilot treatment plant has a capacity that is capable of treating a flow of 1,000 L/h (6,250 gpd). The characteristics of the plant are given in Table 6.1.

The average characteristics of the municipal wastewater are shown in Table 6.2. The characteristics are comparable to those given in the literature (46).

Table 6.1
Characteristics of the electrocoagulation–flotation pilot plant

Parameter	Characteristic
Flotation unit	
Height	1.45 m
Horizontal section	0.25 m^2
Volume	0.32 m^3
Recirculation rate	10–30%
Pressurization	4 bar
Retention time	19 min
Electrocoagulation	
Electrode type	Aluminum
Number	21
Anode surface	0.15 m^2
Voltage	0–80 V
Amperage	0–40 A

Table 6.2
Characteristics of wastewater

Characteristic	COD	Solids
Raw wastewater (mg/L)	900	340
Settleable fraction (%)	28.0	70.0
Nonsettleable (%)	72.0	30.0
Fraction >1 µm (supracolloidal fraction) (%)	28.2	–
Fraction <1 µm (colloidal + soluble) (%)	43.8	–

4. TREATMENT BY DAF

Figure 6.2 presents the role of DAF alone in the removal of supracolloidal and colloidal particles. It is observed that the fraction removed by flotation is increased by the transfer of the soluble and colloidal fractions, which are removed with the settleable fraction during flotation.

The removal of colloids by DAF is not negligible: indeed about 40% of the fine colloids and more than 20% of the supracolloidal fractions are removed. Flotation has thus an impact on the very fine particles. In practice, these colloids are not destabilized but would be floated or trapped with the removed particles.

It has been observed that flotation in water treatment plants is not effective in the removal of the finest colloids (47). One could explain the observed efficiency by the presence of surfactants in wastewater. Surfactants have a structure, which can change the surface charge

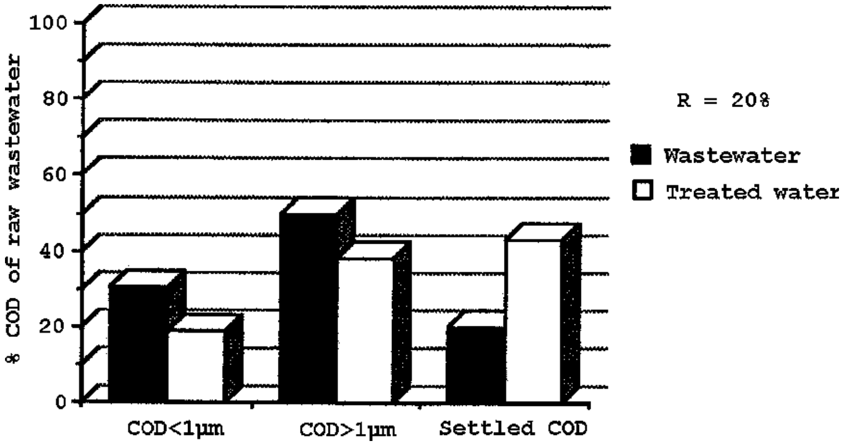

Fig. 6.2. Wastewater treatment by DAF without electrocoagulation.

of colloids and bubbles and thus improve the attachment of bubbles particles. The detergents are molecules composed of a hydrophilic or polar part and a hydrophobic or apolar part. They can get adsorbed on the liquid–gas, liquid–liquid, or liquid–solid interfaces and decrease the interface energy (48). Hydrophobicity of particles is an important issue in flotation (47). The presence of detergents whose concentrations can reach up to 10 mg/L in wastewater (49) could increase the hydrophobicity of colloids and thus could explain the observed results.

5. TREATMENT BY ELECTROCOAGULATION

As observed in Fig. 6.3, electrocoagulation causes destabilization of suspensions and a shift in granulometric distribution toward larger diameters. There is a reduction in the nonsettleable fraction, which produces a corresponding increase in the settleable fraction. The separation, without DAF, of solids from liquid is obtained preferentially by settling; however, part of the biosolids could be floated by the bubbles produced by the electrolysis of water (45).

By comparison of Figs. 6.2 and 6.3, it can be seen that electrocoagulation increases the removal of the supracolloidal fraction. A total of 65% of colloidal, supracolloidal, and soluble matter is removed by electrocoagulation.

6. COUPLING OF ELECTROCOAGULATION WITH DAF

6.1. *Effect of the A/S Ratio*

The A/S ratio (defined by the volume of air or gas introduced divided by the weight of floated solids) is one of the most important factors that affect the flotation process; the efficiency of the flotation pilot plant increases with increasing A/S ratio.

It is very difficult to measure the value of S, so this parameter was replaced by the SS (suspended solids) present in wastewater. The value of A is calculated according to Henry's law and considering that only 60% is actually dissolved (46). Table 6.3 shows the percentage

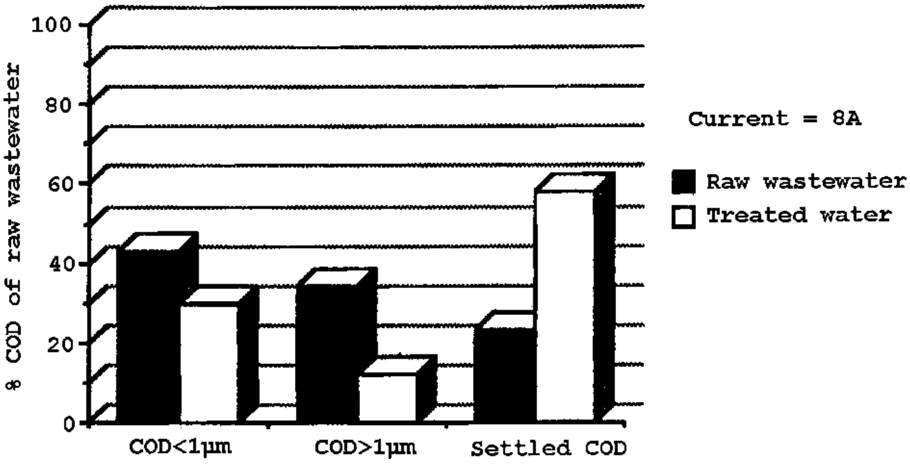

Fig. 6.3. Granulometric size distribution of COD particles before and after electrocoagulation.

Table 6.3
Recycle rate, suspended solids and A/S ratio (p = 4 bar)

Recycle rate pressurized flow as % of wastewater flow	Suspended solids (mg/L)	A/S ratio (mL/g)
0	214	0
15	255	26.4
20	278	31.5
30	240	51.6

of pressurized flow, average values of SS in raw wastewater and the corresponding A/S ratio. The evaluation of the A/S ratio was conducted at a current intensity of 6 A and a wastewater flow of 1 m^3/h.

Granulometric distribution of COD have been measured by determining the settleable and nonsettleable fractions. The nonsettleable fraction is thus composed of the colloidal, supra-colloidal, and soluble fractions (45). Figure 6.4 shows the percentage of the nonsettleable fraction in raw wastewater and in treated water as a function of the A/S ratio. At low A/S ratio, electrocoagulation does not produce a good separation of the organic fractions by flotation. It is observed that starting at an A/S ratio of 31.5 mL/g, a recycle rate of 20% (see Table 6.3) a better separation of flocs from the liquid takes place. At this point, the nonsettleable fraction decreased and the settleable fraction increased. Increasing the A/S ratio to 51.6 mL/g does not significantly improve the separation.

Hence, it can be concluded that:

1. For A/S $\leq$ 31.5 mL/g: the solid/liquid separation is preferentially obtained by settling
2. For A/S $\geq$ 31.5 mL/g: the solid/liquid separation is preferentially obtained by flotation

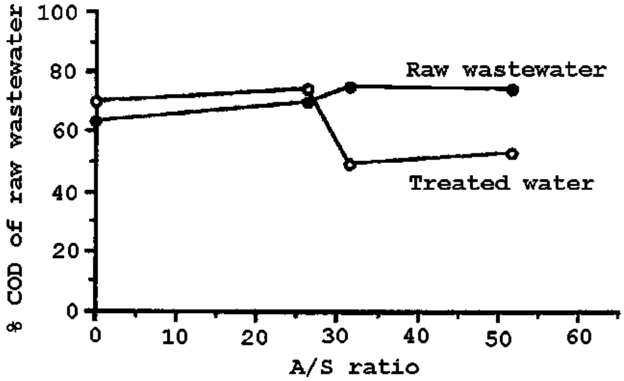

Fig. 6.4. Nonsettleable solids fraction in raw and treated wastewater as a function of A/S ratio.

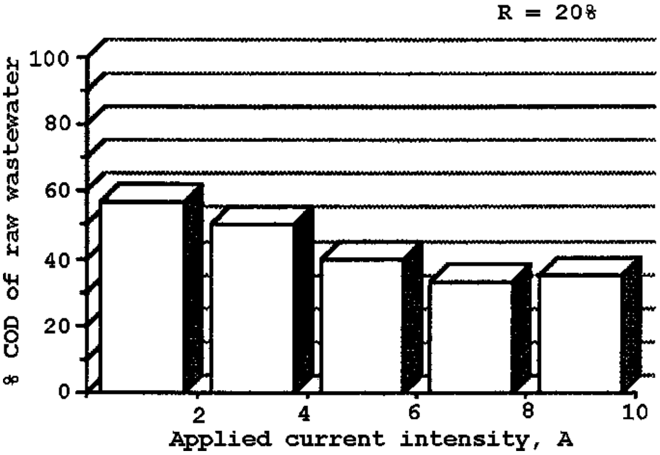

Fig. 6.5. Nonsettleable organic fraction in treated water as a function of current intensity.

Under the operating conditions, for an initial SS concentration of 278 mg/L, the optimal air flow corresponds to an A/S ratio of 31.5 mL/g and a recycle rate of 20% (see Table 6.3).

6.2. *Effect of Current Intensity*

To demonstrate the influence of the applied current intensity, the transfer of the nonsettleable fraction into a settleable fraction was measured for current intensity values varying from 0 to 10 A. According to Faraday's Law (50), the formation of microscopic bubbles of gas on electrodes and the formation of aluminum hydroxides are directly proportional to the strength of the applied current. Figure 6.5 shows that the transformation of colloidal and supracolloidal particles into settleable fractions increases as a function of the applied current intensity up to

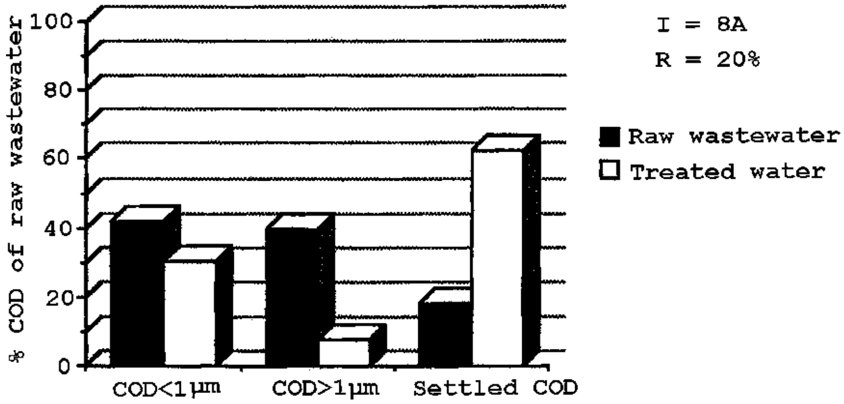

Fig. 6.6. Granulometric size distribution before and after treatment by electrocoagulation–DAF.

an optimal value of 8 A (51). Hence, it can be concluded that there is an optimum current strength, about 8 A, at which maximum destabilization of the colloidal particulates occurs.

6.3. *Effect of Coupling*

Figure 6.6 presents the evaluation of the granulometric size distributions during the coupling of electrocoagulation with flotation at optimal conditions. Based on this illustration, it is possible to note that (45):

1. 30% of the soluble fraction smaller than 1 µm is removed. This removal corresponds to that observed with DAF alone.
2. 80% of the supracolloidal fraction is removed. This value is comparable to the 20% removed by flotation alone and to the 65% by electrocoagulation alone. Hence the coupling of the two processes produces a significant increase in solids removal efficiency.

7. COMPARISON OF ELECTROCOAGULATION–DAF WITH COAGULATION–SEDIMENTATION

This section discusses a comparison between the performance of coupled electrocoagulation–flotation and the performance of an intensive treatment by classical flocculation–coagulation–sedimentation using a lamellar settler. The data for the latter were generated from the treatment of wastewater that has been precoagulated with $FeCl_3$ (10–30 mg/L). The wastewater was then treated by flocculation with aluminum sulfate coupled with sedimentation in a lamellar settler. The comparative results are obtained in relation to:

1. Removal efficiency, and
2. Treatment rate applied in relation to biosolids production.

7.1. Removal Efficiency

The characteristics of wastewater, treated wastewater effluent, and removal efficiencies for the two types of treatment trains are presented in Tables 6.4 and 6.5.

Considering the main pollution parameters turbidity, suspended solids and COD, the removal efficiencies of the two types of treatment can be considered to be the same. In addition, orthophosphates which represent about 80% of total phosphorus were completely removed while soluble nitrogen was not affected. It is observed that there is an increase in the pH of the wastewater treated by electrocoagulation, which can be explained by the production of the hydroxide ion (OH^-) at the cathode during the electrolysis. On the other hand, during the classical flocculation–coagulation by aluminum sulfate an acidification of the treated wastewater occurred as is reflected by the drop in pH value from 8.1 to 6.3.

7.2. Coagulant Dosage

In the coagulation–flocculation treatment, the optimal dosage of the coagulant, aluminum sulfate, was obtained at concentrations of 500–700 mg/L, i.e., about 45–63 mg/L of aluminum. In electrocoagulation treatment, the optimal intensity was 8 A, which corresponds to a theoretical aluminum concentration of 54 mg/L. However, It has been shown (51) that the faradic yield does not exceed 50%. So, in effect, the aluminum dosage during electrolysis

Table 6.4
Treatment by electrocoagulation–flotation

Parameter	Wastewater	Treated effluent	Removal (%)
pH	7.7	8.0	–
Turbidity (NTU)	254	20	92
Suspended solids (mg/L)	364	37	90
COD (mg/L)			
>1 μm	152	23	85
<1 μm	325	160	51

Table 6.5
Treatment by classical flocculation–coagulation–sedimentation

Parameter	Wastewater	Treated effluent	Removal (%)
pH	8.1	6.3	–
Turbidity (NTU)	321	22	92
Suspended solids (mg/L)	385	25	90
COD (mg/L)			
>1 μm	357	53	85
<1 μm	120	109	51

would be 50% of 54 mg/L, i.e., 27 mg/L, which is half the dosage required in chemical coagulation (45).

7.3. *Characteristics of Sludge*

The production of sludge is directly proportional to:

1. The characteristics of raw wastewater: settleable solids and other solids destabilized by coagulation
2. The concentration of coagulants

Chemical coagulant consumption in electrocoagulation is half the amount required by chemical coagulation, which results in less sludge production. It has been shown that sludge produced by DAF are two times more concentrated (52–55) compared to those obtained by gravity settling. The net result is that the electrocoagulation–flotation process produces less sludge on both accounts, less dry matter and lower sludge volume.

8. CASE STUDIES

The following are case studies that represent a wide spectrum of metals and radionuclide treatment conditions for industrial wastewater and U.S. Department of Energy (DOE) facility wastes (12).

8.1. *Remediation of Hazardous Wastes (Water Contaminated with Radionuclides or Metals)*

The electrocoagulation technology was evaluated by U.S. EPA (United States Environmental Protection Agency) under the Superfund Innovative Technology Evaluation (SITE) program. Potential sites for applying this technology include Superfund, U.S. DOE, U.S. Department of Defense, and other hazardous waste sites where water is contaminated with radionuclides or metals. Economic analysis indicated that remediation cost for a 100 gpm system could range from about \$0.003 to \$0.009/gal, depending on the duration of the remedial action.

A schematic diagram of the electrocoagulation system is shown in Fig. 6.7. The major components of the system included the following:

Influent Storage Tank: This tank collects influent to be processed by the electrocoagulation system in batch mode or to provide surge capacity during continuous operation.

Influent pH Adjustment Tank: The influent pH can be adjusted in these tanks if required to bring the influent pH into the range for optimum operation of the electrocoagulation tubes.

Electrocoagulation Tubes: The electrocoagulation tubes consist of a tube-shaped anode material that concentrically surrounds a tube-shaped cathode material leaving an annular space between the anode and cathode. Contaminated water passes through the center of the cathode tube, then through the annular space between the cathode and anode tubes. Several electrocoagulation tubes may be used in series.

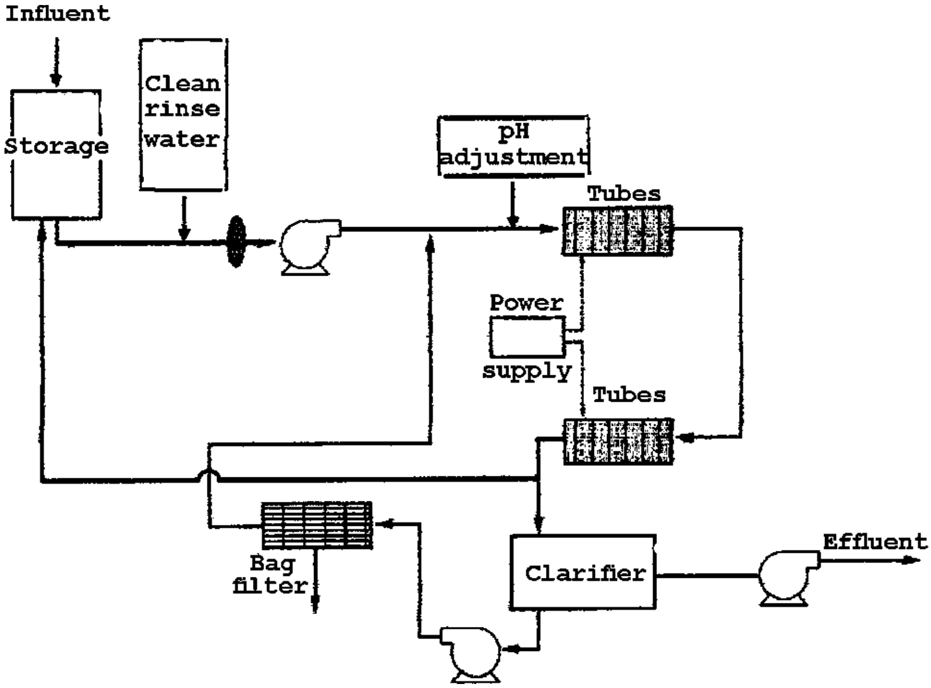

Fig. 6.7. Electrocoagulation treatment system.

Clarifier: The clarifier is designed to allow floccules (flocs) to continue to form in the treated water and to settle. Treated water exits the clarifier as the overflow. The settled flocs form a residue that is removed in the underflow.

Bag Filter: Heavy duty polypropylene bag filters are used to remove residue from the underflow. Spent bag filters and residue are periodically removed for disposal. Filtrate from the bag filters is recycled through the electrocoagulation tubes.

Transfer Pumps: Transfer pumps are used to pump water from the system influent storage tank through the electrocoagulation tubes to the clarifier. Overflow from the clarifier is pumped from a lift station to discharge. Residue is pumped from the bottom of the clarifier through the bag filter.

In summary, the electrocoagulation system involves the following basic steps:

1. Contaminated water is pumped through the electrocoagulation tubes.
2. Treated water is pumped to a clarifier to allow solids to settle out.
3. Clarified water is discharged from the system for reuse or disposal.
4. Solid waste is collected for disposal or reclamation.

Based on the SITE demonstration, the following conclusions were drawn by U.S. EPA about the effectiveness of the electrocoagulation technology:

1. Results indicated that removal efficiencies ranged from 32 to 52% for uranium, 63 to 99% for plutonium, and 69 to 99% for americium. Arsenic and calcium concentrations were also decreased by an average of 74 and 50%, respectively.

2. Evaluation of the electrocoagulation technology against the nine criteria used by the EPA in evaluating potential remediation alternatives indicates that the system provides both long- and short-term protection of the environment, reduces contaminant mobility and volume, and presents few risks to the community or the environment.
3. Solid waste generated by the treatment system during this demonstration is resistant to leaching of the radionuclides uranium, plutonium, and americium.
4. The volume of waste generated is substantially less than the volume of water treated.

8.2. *Municipal Wastewater Treatment*

An Iron Ore Treatment Plant near Denison, Texas, employs approximately 13,000 people. The plant uses orbital aeration basins for primary treatment of municipal wastewater, followed by clarification and aerobic digestion. The resulting biosolids are dried in open air beds, then removed for disposal.

The plant had difficulty operating within the scope of its permit due to an increase in influent volume due to growth. The facilities inability to treat additional influent also affected the economic growth of Denison.

The electrocoagulation process was tested at the Iron Ore Treatment Plant. It treated effluent at approximately 200 gpm. The treated waste stream was allowed to settle in a 27,000-gal vertical clarifier for approximately 2 h. Clear water was then drawn off and discharged to the second ring of the plant's orbital system. The very high quality and low water generated biosolids were passed directly to the drying beds, by passing polymer application and treatment in anaerobic digesters. The electrocoagulation process reduced the suspended solid levels by 98%.

Treatment goals were achieved by running the electrocoagulation process for approximately 12 h/day, 5 days a week. In a 24-h period, the system processed an average of 144,000 gal of effluent. At this level of processing, the plant operated at the required level of efficiency.

The electrocoagulation process increased the capacity of the plant while bringing plant effluent into compliance with discharge standards. The system reduced capital expense, enhanced treatment capability, and improved throughput. The system was used until a new, larger capacity wastewater treatment plant was built.

8.3. *Treatment of Manufacturer Wastewater*

A tractor manufacturer generated approximately 30,000 gal/day of wastewater from the production of approximately 30–50 units annually. The waste stream consisted of waterborne contamination including zinc, chrome, oil and grease, paint residue, and a material similar to cosmoline, which is used for temporary protection of unfinished metals. Because of this wide range of contaminants, a multiple pass electrocoagulation system treatment was designed using anodes of different materials.

Following treatment by the electrocoagulation process, the effluent flowed to a dual clarifier. Approximately 2–3 mg/L of polymer was added to enhance the settling characteristics of the residue.

The clear water effluent was discharged to the publicly owned treatment works. The residue was passed through a filter press, then transported to a permitted disposal facility. The system performed as designed, with all levels of contaminants reduced to or below target values. Zinc, the primary constituent in the effluent stream, was consistently measured at 0.15–0.2 mg/L, well below discharge limits.

The electrocoagulation system replaced the manufacturer's chemical precipitation system, which was extremely labor intensive and costly at approximately \$0.125/gal. The electrocoagulation system, including labor, capital amortization, maintenance, and consumable materials, was treating the waste stream for approximately \$0.055/gal.

8.4. Oil and Water Separation of Steam Cleaner Wastewater

Several electrocoagulation systems have been installed in facilities that use steam equipment to remove oil, dirt, grease, and other materials from oil field equipment. The system is particularly valuable where there is a problem with the separation of oil and water containing concentrations of metals.

At these facilities, the electrocoagulation process is the central treatment element, with pH adjustment preceding and clarification following electrocoagulation. The following results presented in Table 6.6 show the effectiveness of the electrocoagulation process on this type of waste. Cost reductions of up to \$3,000/month were achieved.

Table 6.6
Treatment of steam cleaner wastewater

Element	Influent (mg/L)	Effluent (mg/L)	Removal (%)
Antimony	0.01	0.014	99
Arsenic	0.30	0.01	97
Barium	8.0	0.10	99
Beryllium	<0.01	<0.01	–
Cadmium	0.141	0.031	78
Chromium	7.98	0.05	99
Cobalt	0.13	<0.05	62
Copper	6.96	0.05	99
Lead	7.4	1.74	76
Mercury	0.003	<0.001	67
Molybdenum	0.18	0.035	81
Nickel	0.4	<0.05	87
Selenium	<0.005	<0.005	–
Silver	0.01	0.01	–
Thallium	0.10	<0.10	–
Vanadium	0.23	<0.01	96
Zinc	19.4	1.20	94

8.5. Treatment of Ship Bilge Water

In August 1992, the U.S. Coast Guard (USCG) approved the use of the electrocoagulation process for the treatment of 176,200 gal of ship bilge water at Kodiak Island near Anchorage, Alaska. The ship bilge water was contaminated with high concentrations of oil and metals. A summary of contaminant removal efficiencies for bilge water is shown in Table 6.7. The electrocoagulation process was effective in removing oil and metals with removal efficiencies ranging between 71 and 99%.

Effluent samples were taken following treatment by the electrocoagulation system and prior to entering the 300-gal clarifier. Because of the small clarifier and limited retention time, an anionic polymer was added to the sedimentation as a coagulant aid. Following retention in the clarifier, the effluent passed through activated carbon filters for final polishing and removal of any trace hydrocarbons. The volume of the waste was reduced by 98%, from 46,500 gal of bilge water to less than 600 gal of residue.

The mobility of the electrocoagulation system eliminated the need to transport the bilge water for treatment off the island resulting in an estimated cost savings of $185,000. The average cost of treating the bilge water on-site, estimated at $0.45/gal was approximately 10% of the cost for treatment on the island.

8.6. Los Alamos National Laboratory Treatability Study

In November 1994, electrocoagulation system was tested on wastewater at the Los Alamos National Laboratory (LANL) in Los Alamos, New Mexico. The primary objective of the tests was to compare the electrocoagulation process with the conventional methods of chemical treatment.

Table 6.7
Treatment of ship bilge water

Contaminant	Influent (mg/L)	Effluent (mg/L)	Removal (%)
Petroleum hydrocarbons	72.5	ND (0.2)	99.0
Heavy metals			
Aluminum	4.16	0.74	82.0
Boron	4.86	1.41	71.0
Iron	95.4	ND (1.0)	99.0
zinc	3.41	ND (0.5)	99.0
Dissolved cations			
Calcium	293	137	53.2
Magnesium	943	300	68.2
Manganese	0.93	ND	99.0
Sodium	8,690	5,770	33.6
Potassium	287	222	23.0
Dissolved anions			
Phosphorus	5.38	1.43	73.4

The wastewater treated was a grab sample from the influent to LANL hazardous wastewater treatment plant and contained plutonium, americium, and various other metals. The focus of the treatability study was on the radionuclides.

The electrocoagulation process was more efficient than the chemical treatment process in one of three test runs. However, LANL was pleased with the results and requested additional testing of the electrocoagulation system.

8.7. Rocky Flats Environmental Technology Site Treatability Study

In April 1995, a bench-scale study was conducted by testing the ability of the electrocoagulation process to remove uranium, plutonium, and americium from water derived from the U.S. DOE's Rocky Flats Environmental Technology site solar evaporation ponds (SEPs).

As part of the manufacturing processes at near Golden, Colorado, wastes were produced that contained uranium, plutonium-239/240, americium-241, and other contaminants. Some of this waste was collected in SEPs. The SEPs stored and treated liquid process waste having less than 100,000 pCi/L (picocurie/liter) of total long-lived alpha activity. Water decanted from the residue and liquid from the A and B SEPs was treated for this bench-scale study.

Testing of the electrocoagulation process using decant water from the SEPs indicated that the technology is capable of consistently removing more than 95% of the uranium, plutonium, and americium.

NOMENCLATURE

(aq) = Aqueous solution
e^- = Electron
(g) = gas
M^{N+}(aq) = Metal ion in aqueous solution
M(s) = Metal solid
N^+ = Charge of metal ion
(s) = Solid
N = Numerical number

REFERENCES

1. Shammas NK, DeWitt N (1992) Flotation: a viable alternative to sedimentation in wastewater treatment plants. Water Environment Federation 65th annual conference, Proceedings of the liquid treatment process symposium, New Orleans, LA, 20–24 September 1992, pp 223–232
2. Wang LK, Fahey EM, Wu Z (2005) Dissolved air flotation. In:Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana, Totowa, NJ. pp 431–500
3. Shammas NK (2005) Coagulation and flocculation. In:Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana, Totowa, NJ. pp 103–140
4. Vik EI, Carlson OA, Eikum AS, Gjessing ET (1984) Electrocoagulation of potable water. Water Res 18:1355–1360
5. Powell Water Systems, Inc. (2009) Electrocoagulation vs. chemical coagulation. http://www.powellwater.com/ec-vs-chemical.htm

6. KASELCO (2010) Wastewater treatment utilizing electrocoagulation. Kaspar Electroplating Corporation, http://www.kaselco.com
7. Robinson V (2009) Electroflocculation in the treatment of polluted water. Electropure Australia Ltd., Wadonga, VIC, Australia, http://www.rotaloo.com/15greyelec.html
8. Persin F, Rumeau M (1989) Le traitement électrochimique des eaux et des effluents. Tribune de l'Eau 3(42):45–46
9. Beagles B (2009) Electrocoagulation (EC) – science and applications. Green Pages, http://www.eco-web.com/cgi-local/sfc?a=/editorial/index.html&b=/editorial/06053.html, May 2009
10. Powell Water Systems, Inc. (2002) Electrocoagulation capabilities. http://www.powellwater.com/, January 2002
11. Barkley NP, Farrell CW, Gardner-Clayson TW (1993) Alternating current electrocoagulation for superfund site remediation. J Air Waste Manage Assoc 43(5):784–769
12. U.S. EPA (1998) CURE Electrocoagulation Technology, Innovative Technology Evaluation Report. EPA/540/R-96/502. National Risk Management Research, Laboratory Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH, September 1998
13. U.S. EPA (1994) Test methods for evaluating solid waste, Laboratory manual, physical/chemical methods, vols IA–IC; Field manual, physical/chemical methods, vol II, SW-846, 3rd edn (revision 3). Office of Solid Waste and Emergency Response, Washington, DC
14. Renk RR (1989) Treatment of hazardous wastewaters by electrocoagulation. Proceedings of the ninth national symposium on food processing wastes, Denver, Colorado, August 1989, EPA-600/2–78, p 264
15. Vik EA, Carlson DA, Eikum AS, Gjessing ET (1984) Electrocoagulation of potable water. Water Res 18(11):1355–1360
16. Jenke DR, Diebold FE (1984) Electroprecipitation treatment of acid mine wastewater. Water Res 18(7):855–859
17. Hydrologies, Inc. (1993) CURE – electrocoagulation wastewater treatment system. U.S. EPA Superfund Innovative Technology Evaluation (SITE) Program, Proposal # SITE-008,05
18. Drever JI (1988) The geochemistry of natural waters, 2nd edn. Prentice Hall, Englewood Cliffs, NJ
19. WMRC (2004) Electrocoagulation technology, ace plating, Fact Sheet TN00–071. Illinois Waste Management and Research Center, Oak Brook, IL, June 2004
20. WMRC (2001) Achieving zero process water discharge at ace plating company, Fact Sheet TN01–078, Illinois Waste Management and Research Center, Oak Brook, IL, December 2001
21. Jumpatong K, Buddhasukh D (2003) Electrocoagulation of some heavy metals. http://www.science.cmu.ac.th/journal-science/301Electrocoagulation.pdf
22. Gao P, Chen X, Shen F, Chen G (2005) Removal of chromium (VI) from wastewater by combined electrocoagulation-electroflotation without a filter. Sep Purif Technol 43(2):117–123
23. Holt PK, Barton GW, Mitchell CA (1999) Electrocoagulation as a wastewater treatment. The third annual Australian environmental engineering research event, Castlemaine, VIC, Australia, 23–26 November 1999
24. Yu MJ, Koo JS, Myung GN, Cho YK, Cho YM (2005) Evaluation of bipolar electrocoagulation applied to biofiltration for phosphorus removal. Water Sci Technol 51(10):231–239
25. McKay Creek Technologies (2003) New electrocoagulation process treats emulsified oily wastewater at Vancouver shipyards. Environmental Science & Engineering, January 2003
26. Kumar A, Varadarajan C, Pendse R, Jampana SS (2004) Pollution prevention assessments: case histories. A report for a grant awarded by the U.S. Environmental Protection Agency, Toledo, OH, March 2004

27. Aqua-Terra Consultants (1996) Solids recovery from seafood processing stick water using electrocoagulation. Alaska Department of Environmental Conservation, February 1996
28. Mills D (2000) A new process for electrocoagulation. J Am Water Works Assoc 92(6):34–43
29. Environmental Technology Compilation (ETC) (2009) Electrocoagulation. http://cptech.dost.gov.ph/etc-0114-FD023.php
30. Mameri N, Yeddou AR, Lounici H, Belhocine D, Grib H, Bariou B (1998) Defluoridation of septentrional sahara water of North Africa by electrocoagulation process using bipolar aluminum electrodes. Water Res 32(5):1604–1612
31. Holt PK, Barton GW, Mitchell CA (2005) The future of electrocoagulation as a localized water treatment technology. Chemosphere 59:355–367; Chemical Eng J 95:205–211
32. Guohua C, Xueming C, Po LY (2000) Electrocoagulation and electroflotation of restaurant wastewater. J Environ Eng 126(9):858–863
33. Ravi K (2002) Electrocoagulation: a resurgent technology? Water Technology Magazine, June 2002
34. Pars Environmental Inc. (2009) Electrocoagulation: an innovative waste-water treatment technology. http://www.parsenviro.com/electro-1.html
35. Pulido ME, La Motta EJ, Nandipati RM, Josse JC (2001) Field-scale demonstration of electrocoagulation and enhanced media filtration for treatment of shipyard stormwater. J Ship Prod 17(4):191–201
36. Stormwater Management Inc. (2009) Electrocoagulation system. http://www.stormwaterinc.com/ec-system.php
37. Tsai LS, Hernlem BJ, Huxsoll CC (2002) Disinfection and solids removal of poultry chiller water. J Food Sci 67(6):2160–2164
38. Hernlem BJ, Tsai LS (2000) Chlorine generation and disinfection by electroflotation. J Food Sci 65(4):834–837
39. Hernlem BJ, Tsai LS, Huxsoll CC, Robertson G (2000) Combined electroflotation and disinfection in food processing, IFT, Paper #74–12, Dallas, TX
40. Ferret.com (2009) Electrocoagulation wash water treatment systems. http://www.ferret.com.au/articles/31/0c030131.asp
41. McGarrahan J, Yang C-L (2004) Electrochemical coagulation for textile effluent decolorization. 36th Mid-atlantic industrial and hazardous waste conference, University of Connecticut, Storrs, 8–10 October 2004
42. Mickley and Associates (2004) Pretreatment capabilities and benefits of electrocoagulation, Report number: A899334. http://www.stormingmedia.us/89/8993/A899334.html, Boulder, CO, December 2004
43. Robinson V (2000) A new technique for the treatment of waste water. Enviro 2000-ozwater ozwaste conference, Darling Harbor, Sydney, 10–12 April 2000
44. Han M, Song J, Kwon A (2002) Preliminary investigation of electrocoagulation as a substitute for chemical coagulation. Water Suppl 2(5–6):73–76
45. Pouet M-F, Grasmick A (1995) Urban wastewater treatment by electrocoagulation and flotation. Water Sci Technol 31(3–4):275–283
46. Degrémont (1989) Memento Technique de l'Eau, Edité par Tech et Doc Lavoisier
47. Janssens JG, Buekens A (1993) Assessment of process selection for particle removal in surface water treatment. J Water Suppl Res Technol, AQUA 42(5):279–288
48. Falletti F (1990) Etude de la Régénération par Microfiltration Tangentielle sur Membranes Minérales de Fluides de Coupe Aqueux et des Solutions Aqueuses de Dégraissage, Thèse de Doctorat, Université de Montpellier II, 25 October 1990

49. Brunner PH, Capri S, Marcomini A, Giger W (1988) Occurrence and behavior of linear alkyl benzene sulfonates, nonylphenyl. nonylphenol mono and nonylphenol diethooxylates in sewage and sewage sludge treatment. Water Res 22(3):1465–1472
50. Glasstone S (1962) An introduction to electrochemistry, 10th edn, Revolucionaria. Van Nostrand, New York
51. Daniel B (1992) Etude de l'Electrocoagulation d' Eaux Usées Urbaines, Rapport d'avant-projet d'Ingéniorat. ISIM, Université de Montpellier II
52. Zabel TF (1985) The advantages of dissolved air flotation for water treatment. J Am Water Works Assoc 77(5):42–46
53. Wang LK, Shammas NK, Hung YT (eds) (2007) Biosolids treatment processes. Humana, Totowa, NJ, p 820
54. Wang LK (2007) Emerging flotation technologies. In:Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical treatment technologies. Humana, Totowa, NJ, pp 449–484
55. Wang LK, Shammas NK (2007) Pressurized ozonation. In:Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical treatment technologies. Humana, Totowa, NJ, pp 1–56

7

Treatment of Paper Mill Whitewater, Recycling and Recovery of Raw Materials

Nazih K. Shammas, Lawrence K. Wang, and Mark Landin

CONTENTS

Abstract The characteristics and application of titanium dioxide and other fillers in the paper industry are introduced, the filler retention is defined, and the resources in whitewater and conventional processes are presented. Topics covered include a description of the paper industry, paper mill discharges, whitewater treatment and reuse, raw material recovery, opacity and fillers, available treatment technologies, and a study of a dissolved air flotation (DAF) process for recovery of fiber and titanium dioxide.

The opacifying power of titanium dioxide as usually recovered by DAF is diminished by the persistence of the flocs necessary for the flotation. A recovery simulation to overcome that deficiency is described in which a cationic starch is used as the flotation aid, and the recovered solids are deflocced with enzymes. Handsheets were formed incorporating titanium recovered in this fashion for comparison with ones made with virgin titanium dioxide. The handsheets formed from this process had optical properties similar to those of papers made with the same amount of virgin filler over a large range of titanium dioxide contents in the paper.

Key Words Paper mill • whitewater • fibers • titanium dioxide • dissolved air flotation • fillers • retention aids • recovery • recycling • DAF.

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1. THE PAPER INDUSTRY

It is estimated that 2–75 m^3 of water (see Table 7.1) are needed for each ton of paper product produced by paper mills, depending on the type of paper and the extent of water recycling (1, 2). According to Hynninen et al. (3), 10–300 m^3 of water are needed per ton of paper produced by combined pulp and paper mills, making the paper industry one of the largest industrial users of water and also one of the largest generators of wastewater. This wastewater contains valuable raw materials. Due to increasing raw material costs and stringent pollution controls on paper mill wastewater discharges, it has become economically favorable for the industry to recover the raw materials in its wastewater and to reuse the clarified water.

1.1. History

Paper is essentially a sheet of fibers with a number of added chemicals that affect the properties and quality of the sheet (4). It was the Chinese who developed the first paper nearly 1900 years ago in 105 AD. They filtered a slurry of beaten mulberry tree bark through a screen of bamboo strips. From China, the technology spread westward, first to the Middle East, then along the southern Mediterranean coast, and finally into Europe. It is estimated that the first paper production in Europe occurred in Moorish Spain in the eleventh century. As papermaking technology spread westward, different fibrous raw materials were tried. The Arabs substituted cotton for the mulberry tree bark that the Chinese had used and the Moors replaced the cotton with flax that grew in abundance in southern Spain (5). One thing that mulberry bark, cotton, and flax had in common was their high content of cellulose. Cellulose fibers have the capacity to hydrogen-bond to each other, forming a coherent sheet.

In the thirteenth century, the Italians improved upon the papermaking process by macerating the fibers with the help of metal beaters (5). This maceration had two purposes: primarily, it broke internal bonds within the fiber, rendering it more conformable, increasing interfiber contact, and thus facilitating bonding. Second, it shortened the fibers, producing paper with greater uniformity because of better distribution of the cellulose fibers in the paper sheet. The Italians also added gelatin sizings to the paper. These gelatin sizings helped control the

Table 7.1
Estimation of water consumption for paper production

Type of paper	Water consumption (m^3/metric ton)	Degree of closure (%)
Printing and writing	40–75	40–70
Tissue	57	40–70
Newsprint	24–35	65–85
Packaging and board	2–20	>95

absorbency of the paper so it would not absorb a great quantity of ink that could result in fuzzy, blurred script on the page (5).

The production of paper up until this time had been done by hand – a very slow and tedious process. A mold consisting of tightly strung wires attached to a rectangular frame was dipped into a vat containing the fiber suspension. The mold was then removed from the vat and the water drained through the wires, trapping a fiber mat. The fiber mat was then removed from the mold and excess water was pressed out of the mat and it was allowed to air dry. Once dried, a sheet of paper had been produced (5).

1.2. Modern Day Papermaking

The advent of the Fourdrinier (6) and cylinder papermaking machines in the early nineteenth century revolutionized the papermaking industry. Because of these machines, paper now became much cheaper to produce, resulting in a dramatic drop in paper price and subsequent skyrocketing of paper demand. With this increased demand, new raw materials were needed to provide the cellulose fiber, the paper's main component.

Cellulose is a high molecular weight, complex polymeric carbohydrate that is the chief fibrous constituent of the cell walls in plants. Besides cellulose, these plant fibers contain hemicelluloses (plant polysaccharides less complex than cellulose) and lignin, which cements together the fibrils in the cells and the cells in the plant. The proportions at which these components are present in various plant fibers are shown in Table 7.2 (7).

In 1867, wood grinding and subsequent processing made wood yet another source of cellulose fiber (5). Unfortunately, as shown in Table 7.2, lignin is plentiful in wood. Lignin is hydrophobic and inhibits the plasticization by the maceration, thus inhibiting with bonding. Furthermore, lignin imparts a brown color to the paper (7). Therefore, for high quality pulp, chemical extraction is necessary to remove the lignin.

Pulping processes free and recover the fiber from the wood. This can be accomplished mechanically, chemically, or by a combination of both (8). In an integrated paper mill, the pulping process and papermaking facility are located in the same plant. Therefore, the pulp is sent directly to the papermaking process. Nonintegrated paper mills must buy their pulp from a market source because they do not produce their own wood pulp. This chapter concentrates

Table 7.2
Fiber composition

	Composition, %		
	Cellulose	Hemicellulose	Lignins
Cotton	96	3	1
Flax	85	10	5
Softwood	50	20	30
Hardwood	50	30	20

on wastes produced during paper production from nonintegrated mills and does not discuss pulping and the wastewater problems associated with it.

A nonintegrated paper mill begins the papermaking process with the production of paper stock from the "furnish," the mixture of raw materials from which the paper is produced. Its makeup will vary with the desired finished paper product characteristics. Often, two or more pulp types are blended during stock production. Softwood fibers, which are relatively long, create a good fiber network and provide wet web strength during sheet formation. Softwood fibers are used in the production of high strength, tear-resistant paper products. Hardwood fibers are shorter and contribute to paper smoothness, opacity, printability, and porosity (9).

As seen in Fig. 7.1, to make stock, dry pulp sheets purchased by a nonintegrated paper mills are resuspended in water and blended with other components (10). The stock is then mechanically processed in beaters or continuous refiners. The refiners can be of disk nature – the paper stock is passed between two ribbed surfaces or Jordan (11) – a barred conical plug rotating in another with bars that fibrillate and cut the pulp. The fibers are macerated until they are shortened enough to produce good distribution of fiber in the sheet and produce a paper of the desired strength.

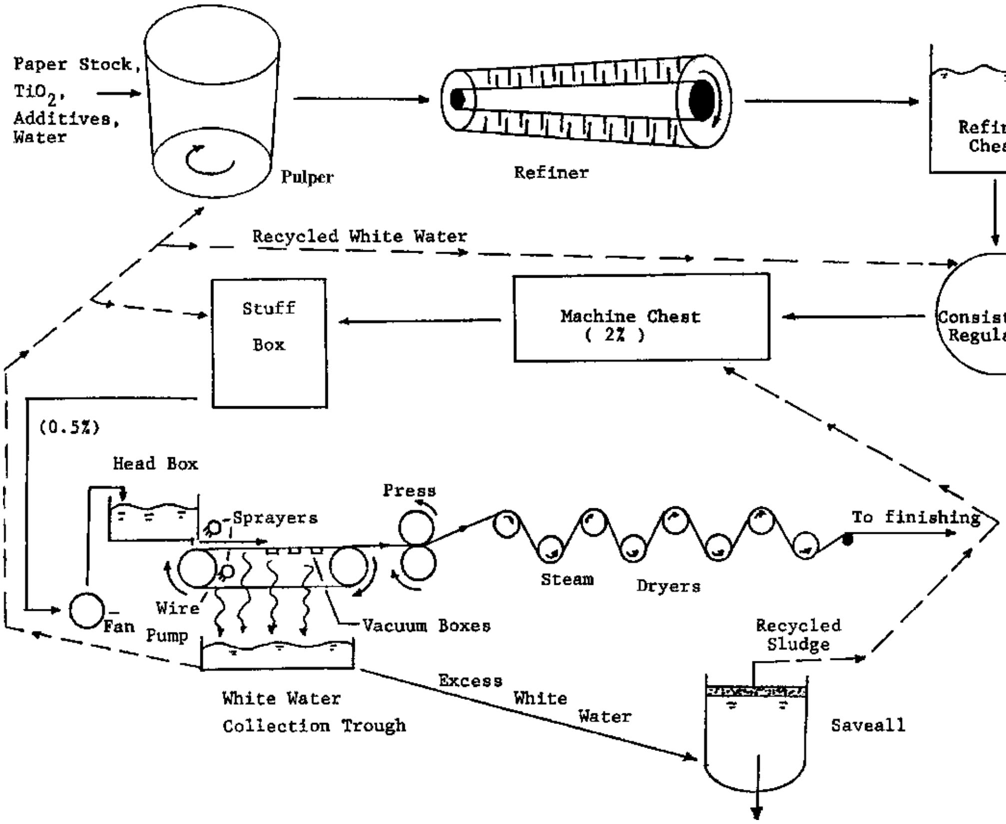

Fig. 7.1. Flow diagram – Fourdrinier principle.

From the refiner, the stock passes through a series of holding tanks, referred to as "chests." The purpose of these chests is to regulate flow and fiber concentration of the slurry, called the "consistency." As seen in Fig. 7.1, the flow of stock generally proceeds from the refiner to the refiner chest, machine chest, and stuff box. The stock is then pumped through the fan pump up to the head box. Along the way, water or whitewater, the filtrate from the forming of the sheet, is added to the stock to regulate the consistency (approximate solids consistencies are given in the parentheses in Fig. 7.1).

Additives can also be introduced in the chests to improve machine performance and give the final paper product desired qualities. The most important of these additives are fine particles of insoluble inorganic solids, referred to as "fillers." Filler pigments are introduced to provide paper characteristics, such as opacity, brightness, softness, smoothness, and ink receptivity. Examples of fillers are clays, such as kaolin, calcium carbonate, talc, and titanium dioxide. Examples of other additives are: dyes, sizes, starches, natural gums, and retention aids. Dyes can be added for color, and sizes such as alum and rosin introduced to increase ink resistively that prevents ink feathering. Polymers are added to provide the wet-strength required in certain papers. By improving fiber-to-fiber bonding, starches, natural gums, and modified cellulose additives improve paper strength, erasability, and abrasion resistance (10, 11). Retention aids, usually long-chained polymers of either positive or negative charge, are added to reduce loss of fillers and other additives through the wire mesh "wire" or "forming fabric" on which the paper sheet is formed. Fillers, in particular, are very difficult to retain because they have no affinity for the cellulose fiber. Fillers tend to pass through the wire and become a component of the "whitewater," as the filtrate from the forming called, because of its milky appearance it when fillers are being used (12, 13).

The forming of paper can occur on two very different machines – the Fourdrinier machine or the cylinder machine. With the Fourdrinier equipment, as seen in Fig. 7.1 and in greater detail in Fig. 7.2, the stock enters the headbox, a flow distributor that regulates stock flow. It then flows onto the wire through a narrow slot along the bottom of the headbox called the "slice." Once on the wire, some of the stock, which has a solids consistency of about 0.5%,

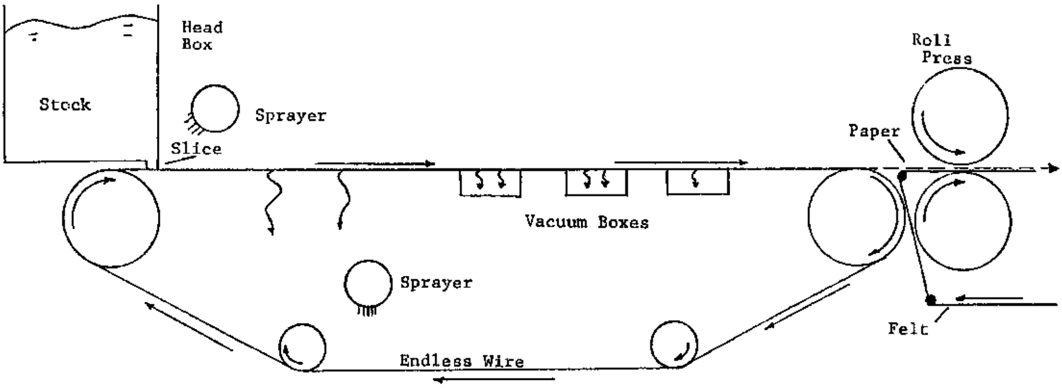

Fig. 7.2. Fourdrinier machine.

drains through the wire mesh by gravity. The wire then passes over vacuum boxes which pull more water through the mesh. A suction pickup roll transfers the fiber mat from the wire to a cloth conveyor belt, called a “felt.” The felt conveys the fiber mat through roll presses that further dewater the mat. When the paper leaves the “wet end” of the papermaking process at the suction pickup roll, it has a solids consistency of 35–40% (9). The wire, now minus the fiber mat, is passed through a series of showers that clean off any residual stock. This cleaning water is collected and usually is added to the whitewater. The cleaned wire is returned to the headbox and the whole process repeats as previously described. It should be noted that this process occurs at wire speeds varying from 200 ft/min, in older, specialty machines to 5,000 ft/min in newer, large machines.

The cylinder machine operates differently from the Fourdrinier. As seen in Fig. 7.3, a perforated hollow cylinder tightly covered by a fine wire mesh rotates in a vat of water and fiber. The water drains through the screen and deposits fiber. The mat is couched off the cylinder onto a felt which conveys the web through roll presses and drying operations.

The drying equipment consists of a series of steam heated hollow metal drums. Felts are used to hold the paper against the drum to maximize contact between the drying cylinder and paper, thereby hastening drying. After the paper is dried, it can go through a series of finishing steps such as calendaring and off-machine coating that smooth the paper and give it unique surface properties.

2. PAPER MILL DISCHARGES

The paper and pulp industry is the third largest industrial user of water behind the metals and chemical industries (11). Sixty-five percent of the water used in the paper and pulp industry is

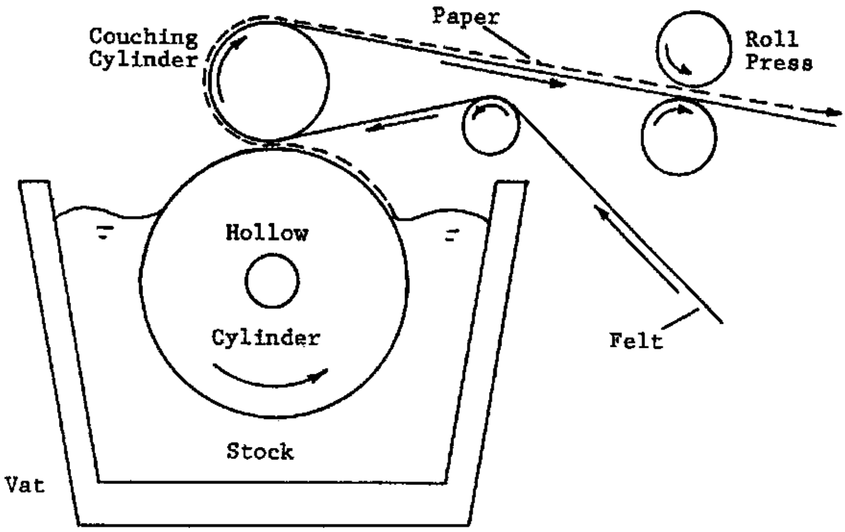

Fig. 7.3. Cylinder machine.

used in the processing of wood pulp and the remaining 35% is used in the production of paper (11).

The stock leaving the headbox of a paper machine is more than 99% water. Most of that water becomes the filtrate from the forming, the whitewater. Ideally, all of this would be recycled in the diluting of the incoming stock; however, the introduction of fresh water, in service applications such as sprays and pump seals, increases the volume, so that the amount of whitewater exceeds that needed by the process stream and the excess flows to waste. This excess whitewater that is not recycled can be sent on to additional treatment processes.

2.1. *Whitewater Composition*

The composition of the whitewater will vary with the type of paper being produced and the type of machine used to make the paper. Some of the variables that will influence the whitewater composition include the type of stock and nonfibrous furnish used, the mesh of the wire or forming fabric, and the amount of suction used in the vacuum boxes. Ordinarily, the whitewater will consist of fiber debris, small fibers, soluble matter, and a high percentage of nonfibrous suspended matter – fillers, starches, and dye stuffs (14).

Whitewaters generally have a higher percentage of filler than the original stock. Fillers have a very low affinity for the fibers in the paper and are therefore very easily passed into the whitewater. This causes the elevated filler concentrations in the whitewater. The percent of fillers present in the whitewater can be two to three times that in the stock.

The amount of fiber present in the whitewater will vary with the grade of paper produced. Very little of the fiber will pass into the whitewaters during heavyweight paper production while higher amounts of fiber can be expected from lightweight tissue paper production. At higher machine speeds, greater losses of fiber and filler will occur because the filtering characteristics of the fiber mat cannot be fully utilized (14).

2.2. *Whitewater Treatment Operations*

The whitewater that is not directly recycled back into the production process can be passed through resource recovery operations in a unit called “saveall.” The savealls are used to recover the fiber and fillers from the whitewater. Savealls usually remove between 30 and 60% of the oxygen demanding organics that can cause water quality problems in a receiving stream (15). However, the saveall equipment that is, in general, more effective in removing suspended matter from the whitewater cannot remove dissolved organics. The organics that remain in the clarified effluent from the saveall may include fiber, starches, gums, and dyestuffs. Unfortunately, these organics can cause a reduction of the oxygen concentrations in any stream that receives the effluent from these operations.

The primary purpose of savealls is recovery of materials, but if the wastewater can be clarified adequately, it can be used in place of fresh water in some of the service applications, thus reducing the amount of excess whitewater, resulting in further economies.

To lessen the potential pollution impacts, the clarified effluent can be sewered (sent to a municipal wastewater treatment plant) or further treated on-site before release to a receiving stream. This additional treatment is often of a biological nature to oxidize the dissolved organics and therefore lower the oxygen demand in the receiving stream (16–20).

2.3. *Paper Mill Discharge Characteristics*

Wastewater discharges from the paper and pulp industry are estimated to be 4,180 MGD. These discharges are broken down by the waste producing facility as follows (10):

1. 3,600 MGD – integrated facilities
2. 320 MGD – nonintegrated facilities
3. 260 MGD – other facilities

Integrated mills, which are involved in wood processing as well as pulp production, are the largest source of wastewater.

Paper mill effluents, unlike those from integrated mills, are fairly low in dissolved organic matter but are high in suspended matter – fiber (organic) and filler (inorganic). For example, a wastewater resulting from the production of a high quality paper produced an effluent with the following characteristics (21):

1. COD (Chemical Oxygen Demand) = 350–1,100 mg/L
2. SS (Suspended Solids) = 500–2,400 mg/L
3. Temperature = 22–30°C

As a waste, these parameters are undesirable because suspended organic matter creates turbidity and discoloration in the receiving stream, as well as sludge deposits on the stream bed. The organic matter may undergo oxygen demanding microbial decomposition whether the organics are found in suspension or in the sediments. Fillers will create a milky appearance in the receiving body of water that is aesthetically unacceptable, this being particularly true of titanium dioxide (TiO_2), with its extremely high refractive index (RI).

Oikari et al. (22) discussed the toxicological aspects of paper mill effluents – their distribution, residues, and effects on caged fish. They found that the effluents apparently caused increased blood hemoglobin and decreased plasma protein concentrations in caged fish located up to 11 km away from the paper mill discharge.

Dines (23) conducted a survey of the Swale in southeast England to determine the impact of nearby paper mill discharges on the region. He collected a wealth of data concerning the soft sediment fauna, including its sediment redox profile, and its organic carbon and cellulose content levels. From this information, he determined that the Swale fauna was impoverished due to the paper mill wastes. However, he predicted that the region would respond quickly to improvements in paper mill effluent treatment.

Pattern recognition techniques were used by Crowther (24) to determine the extent of pollution impacts from paper mill discharges on a receiving stream. These techniques enabled him to place boundaries between areas of chronic and acute pollution created by the paper mill discharges.

Webb (25, 26) discussed the effects that paper mill effluents have on the growth of undesirable wastewater fungus in the receiving stream. He determined the nutrients from paper mill effluents that were responsible for the increased growth of fungus and discussed possible ways of removing these nutrients.

Tana and Nikunen (27) investigated the impact of pulp and paper mill effluent on egg hatchability of pike. More recent studies were conducted by the New York State Department of Environmental Conservation (28), which formulated a quick and easy checklist of pollution measures for the pulp and paper industry; by Environment Canada (29) that determined the chemical releases from Canadian pulp and paper mills; by McKague and Reeve (30) who analyzed the plant sterols in pulp mill effluents; and by Zhuang et al. (31) who characterized the extractable organochlorine in fish downstream from bleached Kraft pulp mills.

3. WASTE MINIMIZATION AND WHITEWATER REUSE

3.1. Waste Minimization

Waste minimization techniques that can help paper mills reduce the amount of waste generation include (32):

1. Production planning and sequencing
2. Process/equipment adjustment or modification
3. Raw material substitution
4. Loss prevention and housekeeping
5. Waste segregation and separation
6. Recycling

The paper industry recycles a great deal of the water that it uses in the production of paper. It is estimated that gross water use is nearly three times the actual water intake (11). Overflow whitewater from a paper machine is reused for a variety of reasons (33):

1. To conserve water
2. To reduce the amount of wastewater effluent produced by the mill that must meet state and federal guidelines regarding stream pollution
3. To conserve fiber and other raw materials that are carried away in the wastewaters
4. To conserve heat

The most effective measure for the reduction of wastewater/water consumption and the improvement of economic performance is the implementation of the best available process and abatement technologies in combination with the following (4):

1. Training, education, and motivation of staff and operators
2. Process control optimization
3. Sufficient maintenance of the technical units and the associated abatement techniques
4. Environmental management system that optimizes management, increases awareness, and includes goals and measures, process and job instructions, etc.

3.2. The Whitewater Circuit

The composition of whitewater that varies according to its source from the paper production equipment determines where it can be reused in the system. Figure 7.4 shows

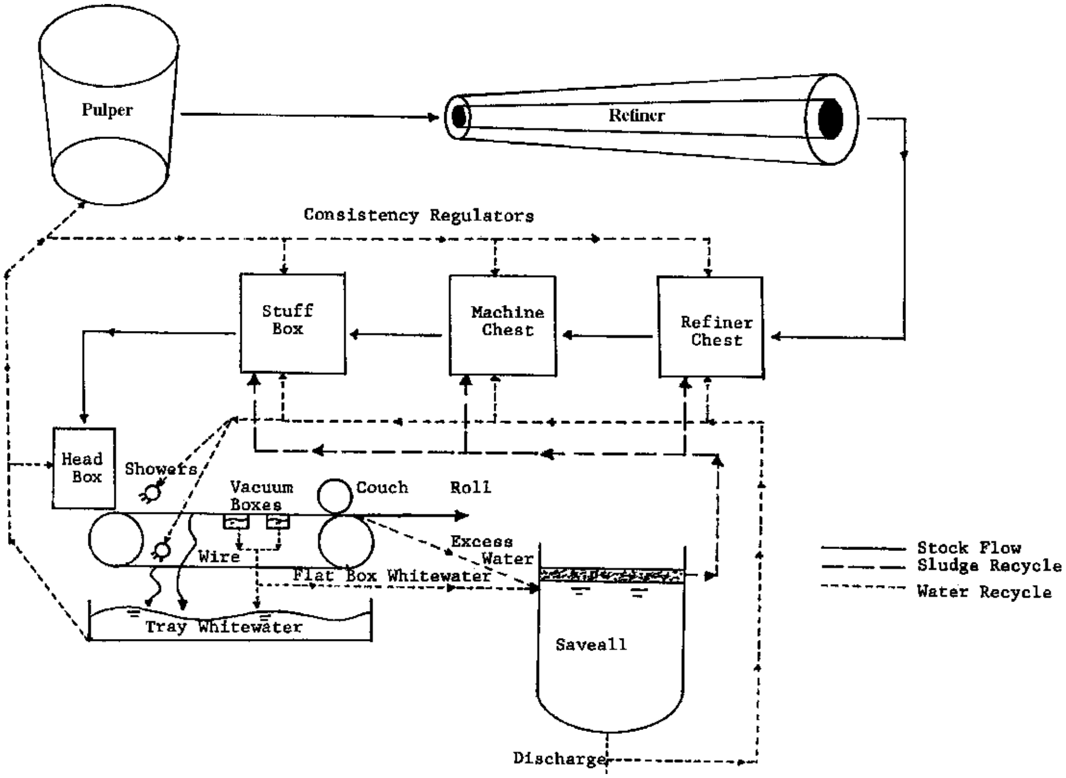

Fig. 7.4. Recycle flow diagram.

the whitewater recycle in a typical paper mill (34). The tray whitewater, collected under the wire, has a consistency from a tenth to over one half of that in the headbox. Fillers and fines levels relative to fiber consistencies are two or more times that in the headbox stock. This whitewater is rich in fibers and fillers and is used to form the slurry of incoming dry pulp, and to make the subsequent dilutions in the refining chest, stuff box, headbox, or other points as make-up water to help regulate stock consistency. Flat box whitewater, collected from the vacuum boxes, has a consistency of one-half to two-thirds that of the tray whitewater and has filler and fines content three times that of the headbox level. Some mills will segregate this water to the saveall. The couch roll excess water is low in volume and solids content. Forty to fifty percent of the couch roll excess water is from the lubrication showers and 50–60% of the water is from the paper sheet. This excess water is generally sent directly to the saveall. The clarified effluent from the saveall can be reused in the showers, reused as make-up water in the consistency regulating chests, or discharged to the sewer or receiving stream. The fibers and fines recovered by the saveall can be sent to the chests as stock make-up.

Monadnock paper Mills (35) applied various whitewater reuses and found that even with an increase in production of 45% over the course of the 1980s and 1990s, through conservation efforts Monadnock has reduced water usage by more than 50%, from 1,400,000 to 650,000 gpd. All treatment plant effluents have met and continue[s] to meet the high quality standards of U.S. EPA and the State of New Hampshire.

Lusky (36) studied another reuse plan that recovered and reused warmed water from the cooling system. This water could be reused in showers and as seal water in vacuum pumps. This along with water conservation steps and an innovative whitewater storage system were able to produce a saving in 1983 dollars of 2,650,000 $/year, which is equivalent to 4,230,000 $/year in terms of current 2006 US dollars.

Volkov and Kovaleva (37) described a system that treated and recycled effluents from two paper mills. One innovative process that was installed was to use the effluent water from one of the paper mills as the process water for a second mill in the same facility. They foresee a multistage treatment of the mill effluent that will enhance further recycling.

Scott (38) discussed the recovery, cooling, and recirculation of vacuum pump seal water to reduce effluent volumes. He discussed the design considerations in this reuse plan and explained some of the problems that were associated with the start-up of the plan and their suggested solutions.

In spite of the advantages of reusing a maximum amount of whitewater, many mills find it necessary to sewer part of their whitewater to prevent the buildup of dissolved substances in the system, which can impair the quality of the paper as well as the operation of the machine. These substances can also create problems with foaming, slime growth, excessive corrosion, poor sizing, and sticking of the paper to the press rolls. To minimize these effects, good whitewater storage facilities must be maintained that will prevent microbial decomposition or sedimentation of solids before the whitewater can be reused. However, industry innovations like antifoaming agents and slimicides have improved the situation and made it possible for a paper mill to reuse 100% of the whitewater (14). This is called “closing the system”.

3.3. *Closed Water Systems*

Closed systems discharge no effluent. Therefore, there are no dissolved or filterable solids, no bacteria or toxic materials that can be sent to a receiving stream. The solids leave the system in the paper and as sludge. Therefore, the costs associated with the final treatment of waste effluent are eliminated. Table 7.3 shows the cost savings of a closed system as compared with one that uses biological treatment to purify its waste effluent (39).

The volume of water contained in a closed system should be kept to a minimum. It is recommended that the process water volume should be no more than the volume of water evaporated in the drying processes in 3 days. This prevents the water from staying in the system too long, which causes problems with bacterial and slime growth. Make-up water can be added at 240–480 gal/ton of paper produced, introducing it at those places with the most stringent requirements for purity, namely high pressure showers, cleaning felts, couch roll showers, and seal water (40).

Table 7.3
Comparison of closed system and biological treatment capital costs

Biological treatment	2006 US$[a]
Settling clarifier (125 CBM/h)	84,000
Aeration basin (400 CBM)	134,000
Secondary clarifier	84,000
Sludge recycling	6,000
Sludge thickening equipment for two tons primary, 4 tons biological, plus 1 ton lime (approx. 2–4 tons per day)	57,000
Land, installation, pumps, valves, foundations, etc.	159,000
Total Capital Investment	524,000
Closed system	
Large surge tank (270 CBM)	38,000
Flotation clarifier (90 CBM/h)	62,000
Sludge press if needed (for maximum 1 ton per day)	9,000
Piping, valves, pumps, installation, foundations, etc.	63,000
Total Capital Investment	172,000

[a] Costs were updated from 1985 using US ACE Civil Works Construction Cost Index for Utilities, US Army Corps of Engineers, Washington, DC. PDF File is available at http://www.nww.usace.army.mil/cost (2006).

Problems associated with closed water systems include the buildup of materials that corrode equipment and degrade paper quality. Guss (40) discussed corrosion effects and the remedies for it. Corrosion can occur because of the buildup of dissolved solids and as a result of bacterial action encouraged by long retention times, poor housekeeping, and anaerobic conditions. These problems can be minimized by: smaller additions of corrosive materials, designing a system with low process water volume and short recirculation loops to deter microbial growth, and the use of a dissolved air flotation (DAF) saveall to keep water conditions aerobic.

Panchapakesan (41) discussed the importance of optimizing the whitewater system design and its benefit in improving runability and lowering paper mills operating cost. In general, closing the mill whitewater system has the following advantages:

1. Minimize fresh water consumption
2. Less chemical consumption
3. Lower losses of fiber, fines, and fillers
4. Reduced cost of heating whitewater
5. Environmental compliance

On the other hand, the same researcher (41) advises that closing the whitewater system more than desired can result in the following detrimental effects:

1. Excessive temperature buildup
2. Higher suspended solids in whitewater
3. Higher dissolved solids in whitewater

4. Higher deposits and bacterial growth
5. Corrosive effects

Geller and Gottsching (42) studied the closing of paper mill systems and found that closing the system leads to: considerable loading of process water; dissolved, fixed, and volatile solids accumulating in the system, increasing abrasion and corrosion problems; and operational troubles and deterioration of paper quality. Their remedy for this situation was to pass the whitewater through a trickling filter (43) prior to reuse. This eliminated many of the impurities and microbial growth in the system.

Niemela and Voatanen (44) discussed the bacterial growth in closed systems and the conditions that produce the greatest growth. He emphasized the importance of periodic cleaning of equipment with lye and water to eliminate bacterial growth.

Gassinger (45) discussed the use of calcium sulfate as filler and its effects on a closed system. He found that by salinity control, corrosion problems were avoided and the paper yield was optimized without any detrimental effects on paper quality.

4. RAW MATERIAL RECOVERY AND ENERGY CONSERVATION

4.1. Recycling and Recovery

Paper manufacturers have found it economical to recover the water and raw materials and reintroduce them to the papermaking process (46). This is economical because recovery (47):

1. Reduces amount of equipment necessary for wastewater treatment
2. Reduces plant maintenance
3. Returns useful materials to the papermaking process

According to the EU (European Commission) (4), the best available techniques (BAT) for reducing emissions to receiving waters are:

1. Minimizing water usage for different paper grades by increased recycling of process waters and water management
2. Control of potential disadvantages of closing up the water systems
3. Construction of a balanced whitewater, (clear) filtrates and broke storage system and use of construction, design and machinery with reduced water consumption when practicable. This is normally when machinery or components are replaced or upgraded
4. Application of measures to reduce frequency and effects of accidental discharge
5. Collection and reuse of clean cooling and sealing waters or separate discharge
6. Separate pretreatment of coating wastewaters
7. Substitution of potentially harmful substances by use of less harmful alternatives
8. Effluent treatment of wastewater by installation of an equalization basin
9. Primary treatment, secondary biological, and/or in some cases, secondary chemical precipitation or flocculation of wastewater. When only chemical treatment is applied the discharges of COD will be somewhat higher but mainly made up of easily degradable matter

For nonintegrated paper mills, according to the EU (4), the emission levels that are associated with the use of BAT are presented for uncoated and coated fine paper and tissue

Table 7.4
EU emission levels associated with the use of BAT for nonintegrated paper mills

Parameters	Units	Uncoated fine paper	Coated fine paper	Tissue
BOD_5	kg/t of paper	0.15–0.25	0.15–0.25	0.15–0.4
COD	kg/t of paper	0.5–2	0.5–1.5	0.4–1.5
TSS	kg/t of paper	0.2–0.4	0.2–0.4	0.2–0.4
AOX	kg/t of paper	<0.005	<0.005	<0.01
Total P	kg/t of paper	0.003–0.01	0.003–0.01	0.003–0.015
Total N	kg/t of paper	0.05–0.2	0.05–0.2	0.05–0.25
Flow	M^3/t of paper	10–15	10–15	10–25

separately in the Table 7.4. However, the differences between the paper grades are not very distinct.

The BAT emission levels refer to yearly averages and exclude the contribution of pulp manufacturing. Although these values refer to nonintegrated mills they can also be used to approximate emissions caused by papermaking units in integrated mills. The waste water flow is based on the assumption that cooling water and other clean water are discharged separately.

Common treatment of wastewater from a paper mill or a consortium of paper mills in the municipal wastewater treatment plant is also considered as BAT when the common treatment system is appropriate for dealing with paper mill effluents. The removal efficiencies of the common wastewater treatment system should be calculated and the comparable removal efficiencies or concentrations of releases established before considering this option as BAT.

BAT concerning solid waste is the minimization of the generation of solid waste and recovery, reuse and recycle of reusable materials as far as possible. Separate collection of waste fractions at source and intermediate storage of residuals/waste can be beneficial to allow for a greater proportion to be reused or recycled rather than sent to landfill. Reduction of fiber and filler losses, the application of ultrafiltration for coating wastewater recovery (only for coated grades), efficient dewatering of the residues and sludge to high dry solids are further available techniques. BAT is the reduction of the amount of waste to be landfilled by identification of possibilities for recovery operations and – if feasible – utilization of waste for material recycling or incineration with energy recovery. Reduction of solid waste can be achieved by optimizing the fiber recovery by upgrading of stock preparation plants, optimization of the amount of cleaning stages in the stock preparation, application of DAF as in-line treatment of water-loops to recover fibers and fillers, and to clarify process water (4).

For more details on pollution prevention and control, regulations and guidelines in the pulp and paper industry, readers are referred to the following appropriate (particular country or region) publications: USA (48, 49), Canada (50), European Union (4) United Nations (51, 52), World Bank (53, 54), and Taiwan (55).

4.2. *Energy Conservation*

In general BAT is considered to be the use of energy efficient technologies (4). A lot of options for energy saving in many stages within the manufacturing process are available. Usually these measures are linked with investments to replace, rebuild, or upgrade process equipment. It should be noticed that energy saving measures are mostly not applied only for energy saving. Production efficiency, improvement of product quality, and reduction of overall costs are the most important basis for investments. Energy savings can be achieved by implementation of a system for monitoring energy usage and performance, more effective dewatering of the paper web in the press section of the paper machine by using wide nip (shoe) pressing technologies and use of other energy efficient technologies as e.g. high consistency pulping, energy efficient refining, twin wire forming, optimized vacuum systems, speed adjustable drives for fans and pumps, high efficiency electric motors, well sized electric motors, steam condensate recovery, increasing size press solids, or exhaust air heat recovery systems.

Energy efficient nonintegrated paper mills consume heat and power as follows (4):

1. Nonintegrated uncoated fine-paper mills have a process heat demand of 7–7.5 GJ/t and a power demand of 0.6–0.7 Mwh/t
2. Nonintegrated coated fine-paper mills have a process heat demand of 7–8 GJ/t and a power demand of 0.7–0.9 Mwh/t
3. Nonintegrated tissue mills based on virgin fiber have a process heat demand of 5.5–7.5 GJ/t and a power demand of 0.6–1.1 Mwh/t

4.3. *Saveall Processes*

Savealls usually operate under a filtration (rotating disc filters or drum filters) or flotation principle (34, 41, 56). The choice of which saveall system to use will depend on the grades of paper produced, the removal requirements, the amount of whitewater recirculation desired, and the time elapsed between changes of grade (14). Each type of saveall system is discussed in the following sections.

4.3.1. *Filtration*

Several types of filtration equipment (41) are being used in mills today to clarify and reuse whitewater. One of the most elementary forms of filtration is screening. Using inclined wire screens, whitewater is passed through the screen openings. The inclined screen removes the longer, more valuable paper fibers and lets the smaller fibers and fillers pass through. The water recovered from this process is of poor quality and can be reused for stock dilution or discharged (14).

Rotary screen or drum type savealls revolve in a vat of whitewater. The water passes through the screen and a fiber mat forms on the wire. Like inclined screens, these tend to have poor fines retention and the recovered water can only be used where good water quality is not necessary (34).

Vacuum filter savealls rely on a vacuum to induce whitewater flow through the filter. The cylindrical filter rotates in a vat of whitewater and has a removal efficiency of 92–97.5% for papers with 6.5–19% ash (14). In papers with high filler contents, long fiber stock is often added to form an effective fiber mat for the filtration of the filler. The recovered fiber can be sent to the stock chests and the clarified water may be pure enough to be used in coarser showers.

Disk filters are a variation of the vacuum filter. The disks consist of a number of ribbed sectors covered with a filtering medium. These disks rotate through a vat of whitewater. As the disk sector enters the water, a vacuum is applied. This vacuum draws water through the medium. The initial water is of lower quality because a good filter mat has not yet been formed. This portion of the filtrate is recycled. As the filter mat forms, the discharge through the mat is clarified and can have a solids content of less than 50 mg/L. This clear water is recovered for reuse in the system. Once the disk sector rotates out of the whitewater, the vacuum is turned off and the mat is removed. The recovered mat containing fiber and filler is reintroduced to the papermaking operation. This system provides good clarified water quality at minimum lag times (34).

Some of the many different studies that have been performed on filters are described below.

Bachand and Hagerty (57) discussed the design of a gravity straining system to remove suspended solids from the whitewater. Characteristics of the recycled water were presented and examples of the amounts and particle sizes of the suspended solids were tabulated.

Rodman and Homonoff (58) discussed a two phase filtration system. First, sieving by screens removed longer fibers and the filtrate is then passed through a fibrous network that removes the very small particles.

Cylindrical operating filters with 99% cleaning efficiency are described for removing particles from the whitewater of paper machines in a patent by Ragnegaard et al. (59).

Fremont (60) discussed a method of removing fine suspended solids from effluent streams. The whitewater is first passed through two contiguous layers of an open-celled compressible hydrophobic polymeric material such as rubber. This is then compressed to remove the solids loaded in the layers and regenerate the media. The layers are spaced so the open-celled pores of each layer are randomly orientated.

The ultrafiltration of colloidal suspensions and macromolecular solutions was discussed by several researchers (61–65). Doshi and Trettin (61) determined that the pressure–filtration relationships were constant and that the permeability of the cake formed on the membranes depended upon the physicochemical state of the solute.

The water leaving a saveall requires further polishing for use in fine shower nozzles. A variety of polishing filters were studied by Hysek (66). One filter that worked well and prevented plugging of paper machine showers was the Ronnenigen-Peter filter, which utilized plastic or stainless steel screens with a venturi washing system. The proper filtering selection was dependent on raw water quality, shower nozzle size, raw water pH, the suspended solids content, and the required pressure.

4.3.2. *Sedimentation*

Basins, which use gravity settling (67) alone as their suspended solids removal mechanism, are very inefficient. They also require a lot of space due to long detention times. To improve sedimentation clarification, researchers studied different flocculating agents aiming at enhancing the process (68). They investigated aluminum sulfate, sodium aluminate, bentonite, activated silica, and polymers (69–73). This has produced better results, however, not good enough compared with DAF, which has replaced sedimentation in current practice.

4.3.3. Flotation

DAF savealls are used to remove solids from the whitewater by decreasing their apparent density using air flotation. In flotation, air, dissolved in the water, forms microscopic air bubbles in whitewater when the pressure is reduced. These air bubbles attach themselves to the suspended solids. This causes the net specific gravity of the suspended matter/air bubble agglomeration to become less than that of the water. When this happens, the mass will rise to the surface and form a floated sludge that can be skimmed off the surface. The clarified water can then be drawn off the bottom of the tank and be reused or discharged (74, 75).

Most commonly, air (1–2% by volume) is dissolved in water under high pressure (40–60 psi) in an air dissolving tube (ADT) or simply by sparging in a closed tank. The high pressure results in the water becoming supersaturated with air relative to that soluble at atmospheric pressure. The whitewater is then released into a tank at atmospheric pressure. Due to the lower pressure, air bubbles form, entrap the suspended materials, and rise (76). In a variant of this system, the whitewater enters the top of a U-shaped tank, several meters deep, in which air is injected near the bottom of the entrance leg. As the flow rises in the outlet leg, where it enters the flotation chamber, the hydrostatic pressure is reduced and air comes out of solution, causing the flotation. Frequently, flocculants are added to the whitewater prior to flotation to enhance flotation characteristics.

There are three types of flotation systems that operate under atmospheric pressure (77, 78): full flow pressurization, partial flow pressurization, and recycle flow pressurization. These systems are shown in Figs. 7.5, 7.6, and 7.7.

The entire influent flow is passed through the aerator in DAF system using full flow pressurization. This method works very well with suspended materials that will flocculate quickly upon release into the flotation tank. When this happens, the air bubbles can easily become entrapped in the forming floc and this can result in very good separation capabilities.

In partial flow pressurization, only 30–50% of the influent flow is passed through the ADT. The remainder is sent directly to the flotation tank. The pressurized whitewater is then released into the tank containing the nonpressurized whitewater. This system works best on suspended materials with low specific gravities and low suspended solids concentrations. Because less flow is being pressurized, operation and maintenance costs are reduced in this system.

In a recycle flow pressurization system, 15–50% of the clarified effluent from the flotation tank is aerated and recycled back into the flotation tank. This system works well because it does not subject the whitewater to the shearing action of the pressure release valve. Because this system subjects the flocs to minimum shear it generally has very good flotation characteristics.

Furukawa (79) studied whitewater treatment using flotation technology. He found that softwood pulps float less readily than hardwood pulps. Flotation rates increased when up to

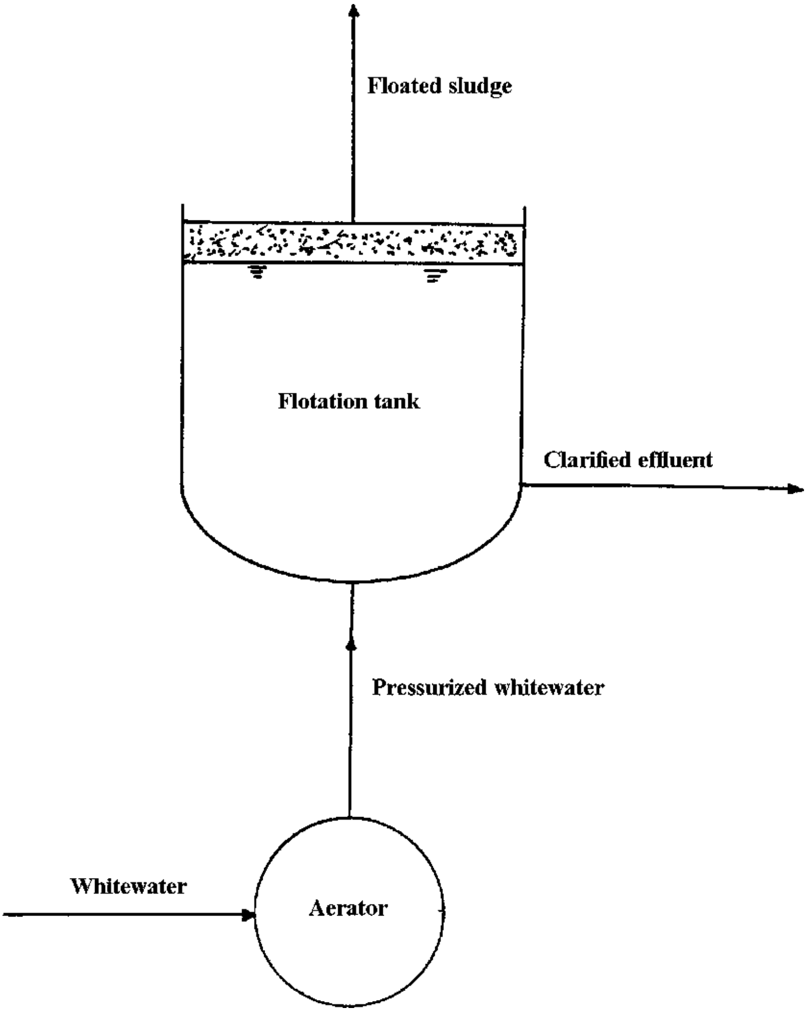

Fig. 7.5. DAF – full flow mode.

50% filler was present but were impeded by the presence of alum. He found that the efficiency of flotation using the flocculant aids, polyethylimines (PEI), and polyacrylamides (PAA) varied depending on the origin of the preparation. PAA were generally more effective in removing filler particles. When alum was present, PEI worked better as the flotation aid up to a dosage of 11 mg/L. At dosages above 11 mg/L, PAA worked best.

Miyamae et al. (80) discussed the removal of calcium carbonate, a filler, using flotation. The concentration of calcium carbonate ranged from 100 to 250 mg/L. To the whitewater, they added a polyalkylenepolyamine and an ethyltrimethylammonium chloride or its co-polymer acrylamide at a pH of 75 to 8.5. The dissolved air solution was added at 20–100% by volume. This flotation recovered 100% of the calcium carbonate. Flotation was found to be the most effective conventional method (81).

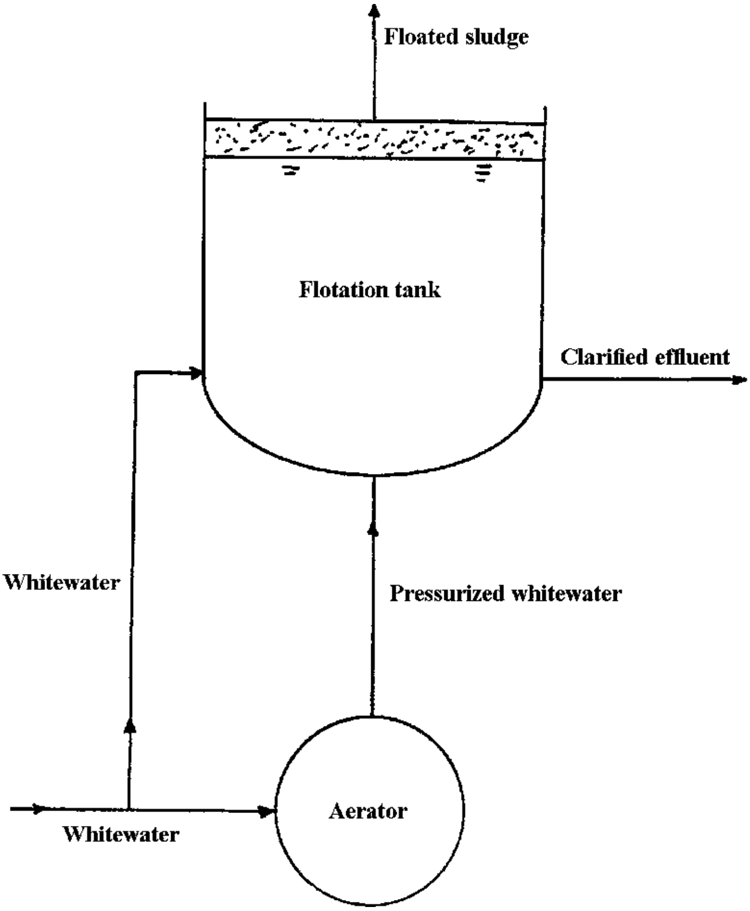

Fig. 7.6. DAF – partial flow mode.

Gehr and Henry (82) studied methods to improve the DAF process. They found that a three cylinder batch apparatus should be used initially to predict full scale flotation. They found improvements in air dissolution and air monitoring systems can greatly affect performance. They also found that the recycling of flotation effluent can reduce the polymer dosage.

Lewandowska et al. (83) studied flotation and sedimentation. They found that with an effluent containing 900–1,200 mg/L suspended solids, sedimentation removed 90% of the solids and produced a sludge with a consistency of 0.88–2.19%. Using flotation, the average sludge consistency was 6.4%, but the degree of clarification was less. Better clarification was observed using high dosages of organic flocculant and alum, but then the sludge consistency was lower. They recommended that for the best results, the two systems should be used in series.

It has been reported (84) that fiber could easily be recovered with or without chemical addition using the full flow pressurization mode. When titanium dioxide was added to the whitewater they found that the majority of the fibers and about 50% of the titanium dioxide

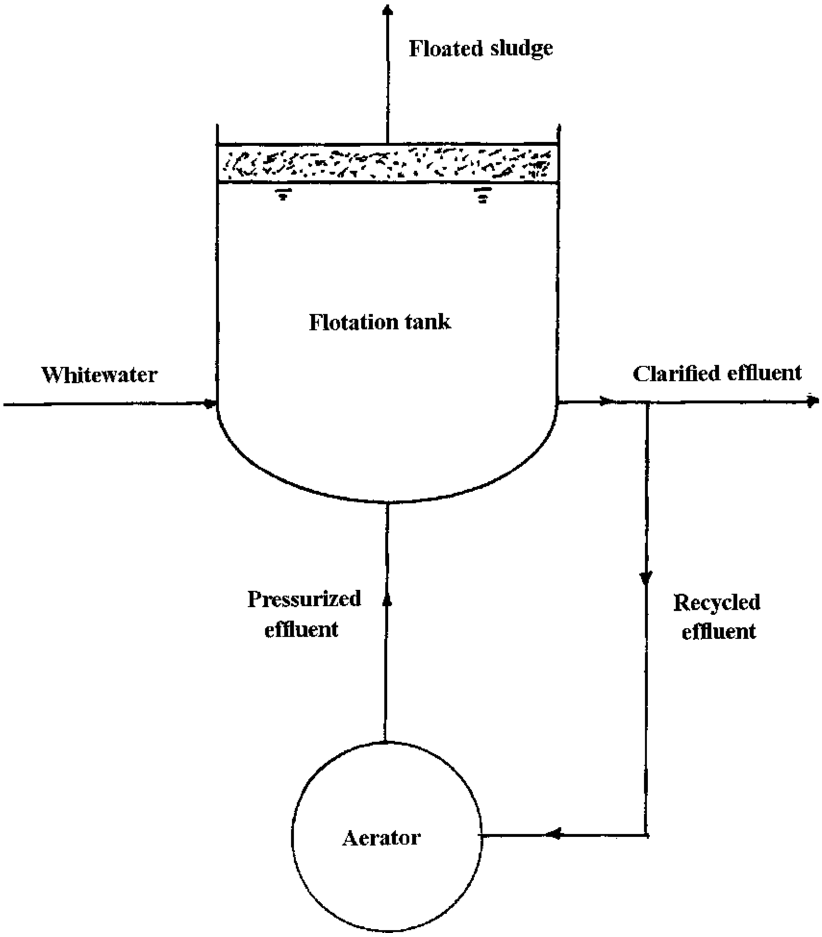

Fig. 7.7. DAF – recycle flow mode.

were recovered. Using a recycle flow pressurization mode, they were able to recover 99% of the titanium dioxide and fiber using magnesium carbonate, calcium hydroxide, and a polymer.

Wenta and Hartman (85) reported that a DAF separator has treated an influent with a total suspended solids (TSS) concentration of greater than 2,500 mg/L. A TSS removal efficiency of greater than 95% was achieved when supplementing treatment with chemicals, even at a hydraulic loading in excess of 6 gpm/ft^2.

5. OPACITY

The opacity of a sheet of paper is a very important characteristic. High opacity papers will not allow print to show through a paper sheet. Low opacity papers are more transparent and can be nearly see-through. The opacity of a sheet of paper is determined by the amount of light incident on the sheet that will be absorbed, scattered, or reflected by the sheet (86). Paper has two optical parameters, its absorption coefficient and its scattering (reflective) coefficient. Of these two, the scattering coefficient has the greatest effect on opacity. Two properties contribute to the scattering coefficient, the index of light refraction on the reflecting surface and the total area of light scattering surface. Fillers are used to enhance these scattering conditions. The scattering coefficient is dependent on the mixture of fibers and fillers, the amount and distribution of filler in the sheet, and the refractive indices of filler and fiber. The scattering coefficient is therefore dependent on many circumstances, aspects, or mechanisms that affect the contact between the fiber and fillers and their uniformity in papermaking. Some of these are (86):

1. The concentration of titanium dioxide, mineral fillers, fiber fines, and debris
2. Fiber bonding and debonding (structural changes which effect the density of the paper)
3. Fiber or filler embedding by a bonding additive

5.1. *Fillers*

Fillers that have indices of refraction close to that of the cellulose fiber in the paper increase opacity by increasing the debonded surface and air–solid interfaces which scatter light (86). If the filler has a RI markedly different from that of cellulose, refraction and reflection will occur even if there is not an air–solid surface. This is in addition to that produced by the air–solid interfaces created by debonding. Because fillers that have high refractive indices are able to increase opacity by two mechanisms, they are generally the best opacifiers. This can be demonstrated when titanium dioxide filler is compared with clay filler. Titanium dioxide, which has a high RI, produces opacities that are three to ten times as high as clay (which has a low refractive index) at similar loadings (14).

Titanium dioxide (TiO_2) is a crystalline, fine, white powder having an extremely small particle size of 0.1–0.4 μm that forms a negative colloid in aqueous phase. Titanium dioxide exists in two forms that are commercially available – anatase and rutile (14). The titanium and oxygen atoms in a TiO_2 crystal unit cell are tightly bonded, with small distances between them. The unit cell volumes of anatase and rutile are 136 and 62 A^3, respectively. The tighter packing of rutile causes light to travel slower in rutile than in anatase.

Titanium dioxide owes its high opacifying power to its high index of refraction (2.7 for rutile, 2.55 for anatase) and its particle size (14). Because of these properties, only a fraction as much titanium dioxide is needed compared with other fillers to produce the same opacifying effects. This is important because titanium dioxide costs up to ten times as much as other fillers (87). Titanium dioxide is used most often to opacify light weight paper, waxed paper, and high quality paper in concentrations of anywhere from 1 to 15% (14). In waxed paper and saturated laminates, there are no air interfaces between the particles. The spaces are filled with resins. Therefore, the entire opacifying effect comes from the differences in refractive indices and this is why titanium dioxide, with its extremely high RI, is used.

In paper and board manufacturing processes, titanium dioxide is used as a filler and brightener in high quality paper. The name filler is chosen because it differentiates between the white pigments, which are used for loading, and the colored pigments, which are applied for the coloring of paper. Loading means the incorporation of inorganic materials into the fibrous web to improve the quality of papers or boards. In filling operation nonfibrous materials plug the spaces between fibers in a web of paper or board, thus reducing the unevenness of the material surface.

Titanium dioxide fillers can be added not only in printing papers but in many other grades such as bonds, ledger, writing, papeterie, bible, and airmail papers to increase their opacity. Opacity is important to avoid show-through of the printed image to the reverse side. In addition to the prevention of show-through, many papers require opacifying fillers, such as titanium dioxide, to maintain sufficient opacity after impregnation with paraffin wax, or after treatment with synthetic resins for use by the plastics industry. In boards it is often necessary to prevent the show-through of dark-colored middle layers by the incorporation of opacifying fillers in the top liner.

Technically speaking, brightness is the reflectivity of the filler measured at a narrow wavelength band (peak at 457 μm) on a brightness meter conforming to the specifications of the Technical Association of the Pulp and Paper Industry (TAPPI). A high-brightness paper reflects a large portion of light and offers a means of attaining a great deal of contrast between the sheet and the printed image. Titanium dioxide is an excellent brightener because of its very high RI. The RI of a filler depends on the filler's chemical constitution and crystal form. It indicates the degree of slowing down of white light passing through the filler crystal and the angle by which the light is bent, or refracted, from its source.

Because of the high cost of titanium dioxide, many studies have been conducted using a mixture of fillers including titanium dioxide. Scot (88) reported that a 50:50 mixture of calcium carbonate and titanium dioxide was able to produce light scattering results nearly equal to those found with pure titanium dioxide. However, it is believed that the enhanced light scattering performance of the pigment blend was the sole result of the thorough dispersion and hence greater light scattering efficiency of the titanium dioxide present in the blend.

Polymers are often added to the stock as retention aids. Howard (89) studied the effects that polymers have on the light scattering of titanium dioxide pigments in paper. He found that if polymers are added in overdose to the stock, gross pigment coagulation will occur, with particle surfaces closer than the wavelength of light, and this will produce low light scattering capabilities of the titanium dioxide in the sheet. If polymers are added in the correct dosages, he found that the scattering coefficient was independent of the nature of the retention aid or its mode of addition to the stock.

Alince and Lepoutre (90) studied the effects of the pigment on the light scattering in filled sheets. They found that the light scattering coefficient was a function of the pigment treatment and the state of dispersion. Prior to fiber addition, they treated the pigment and titanium dioxide with a cationic low molecular weight (PEI) or a higher molecular weight cationic starch. They found that PEI treated pigment was well dispersed in the sheet with a high light scattering coefficient. Therefore, the pigment had very high opacifying characteristics. The cationic starch-treated titanium dioxide formed large agglomerates, which diminished the light scattering properties and therefore, this paper had lower opacity. However, they noted that the polymers which give the best dispersion also provided the least retention. Also, with well dispersing pigments, the fiber bonding was reduced, thereby weakening the sheet.

The process of forcing pigments into the open pores of the fiber shaft is referred to as lumen-loading. This is done by agitation of the fibers and filler followed by washing. Miller and Paliwal (91) studied this process using titanium dioxide as the filler pigment and PEI as a retention aid. They found that paper made with lumen-loaded fibers had improved strength characteristics. This is because the filler is in the fiber, not on it and thereby cannot interfere with fiber-to-fiber bonding which can weaken the sheet. They found that the lumen-loaded paper had slightly lower opacity due to over flocculation of the pigment in the lumens, which reduces the scattering coefficient of the titanium dioxide.

A principal objective of fillers is to improve paper opacity. In addition to being cheaper than fibers, fillers also improve finish, smoothness, and the printability of the sheet. This is because fillers are more readily wetted by ink than are the fibers, due to the fine capillaries present in the fillers through which the ink can pass (14).

5.2. *Filler Retention*

In the paper industry, retention is the measure of the fraction of filler and of fines in the headbox stock which is present in the paper. High degrees of retention facilitate control of the composition of the product and reduce the amount of the filler and fines recycled from the whitewater. Better sheet formation and drainage occur. High degrees of retention promote the even distribution of fillers throughout the paper sheet, and improve the runability and cleanliness of the paper machines (92, 93).

Many factors affect retention. Retention will decrease with increasing: machine speed, suction, dilution of stock, increased shake, and coarser mesh of the forming medium (14). The shearing force of the water as it rushes through the sheet will pull fiber and filler through the sheet and into the whitewater. Because the filler and fibers tend to possess a negative electrostatic charge, they repel each other. This mechanism also impedes retention.

Retention will increase with increasing: sheet weight, refining of stock, sizing, fiber length, recirculation of whitewater and temperature (14). Many different mechanisms are involved in the retention process. Some of these mechanisms are: filtration of the fibers and filler particles on previously deposited fibers, mechanical attachment of the filler to the fiber wall, adsorption of the filler to the fiber, diffusion of the pigment into the lumen of the fiber, and flocculation of the fibers and fillers with the help of alum or polymers.

Smaller particles rely on adsorption mechanisms to retain them in the sheet. Larger particles can be mechanically filtered through the sheet and do not rely as heavily on adsorptive processes. Total retention is a combination of adsorption and mechanical filtration (94).

Fiber and coarse fillers such as talc and filler clays are retained mostly by mechanical filtration due to their large particle size. Some pigments such as titanium dioxide have a very small particle size and their retention can not be explained by mechanical filtration because the particle size is smaller than the pores in the paper. Finer fiber and fillers may be retained by mechanical filtration if coagulants and flocculants are added that increase the effective particle size (95). Coagulation (a colloidal retention mechanism) and flocculation (a physical retention mechanism) were discussed in previous chapter. In general, coagulants and flocculants are referred to as retention aids because of their assistance in the retention process.

Arno et al. (96) discussed zeta potential and its effect on filler retention (FR). It was known that zeta potential was important for colloidal retention mechanisms. However, it was found that these forces are weak and sensitive to shear. Therefore, the importance of optimizing zeta potential to increase coagulation and retention decreases as shear increases. When polymeric retention aids were used, no relationship could be found between the zeta potential and FR.

Strazdins (97) found similar results. He observed that charge effects are less important when high molecular weight polymers were used. The reason for this is that high molecular weight polymers act by bridging mechanisms and can perform the flocculation against the electrostatic charge barrier.

Many sources discussed the interferences that anionic materials have on retention. The problem is that these anionic species react with the cationic polymeric retention aid before it can react with the fiber (98, 99). Braun and Ehms (99) found that by using a high molecular weight nonionic polymer, polyethylene oxide (PEO), this problem was avoided and good retention was achieved. Britt (100) also discussed solutions to this problem. He recommended replacing anionic additives with ones that will not cause interference, removing anionic residues by washing, neutralizing unwanted anionics, and using a nonionic polymeric retention aid.

Bozlcov et al. (101) discussed using two component polymeric systems. Initially, the whitewater is treated with anionic PAA and then with nonionic PEO. They found that these two polymers, when used in combination, performed better than each individually.

Copozil is a retention aid that consists of a positively charged cationic starch that provides bridging between fibers and fillers and negatively charged anionic silica which causes agglomeration of small flocs by charge neutralization. It was found that this combination produced good retention, dewatering, and strength capabilities. Because there are small uniform flocs, drainage is improved on the wire and the flocs will reform quickly after high shear, thereby maintaining good retention (102).

Waech (103) found that retention is improved if the filler is added after the retention aid. It was found that when the retention aid was added first, retention of titanium dioxide was twice that of when the filler was added initially.

Single-pass FR can be calculated by the following equation:

$$\mathrm{FR} = 100(\mathrm{Ms}/\mathrm{Fs})/(\mathrm{Mi}/\mathrm{Fi}), \tag{1}$$

where FR is the FR in percent, Ms is the weight of filler material in the finished sheet paper, Fs is the weight of fiber in the finished sheet paper, Mi is the weight of filler material in the initial stock entering the paper machine slice, and Fi is the weight of fiber in the initial stock entering the paper machine slice.

It should be noted that (Mi/Fi) and (Ms/Fs) are also termed Initial Association Ratio and Sheet Association Ratio, respectively. Most of the filler which is not retained is immediately returned to the system as in the whitewater used to makeup the headbox stock and is not lost. The filler carried out of the system in overflow whitewater is only partly recaptured by the saveall. Thus, good retention leads to minimizing the amount of purchased filler required for a given filler content of the paper at the reel of the paper machine, as well as minimizing the pollution load for treatment of the mill effluent. Twenty-five percent is a common single-pass FR value for a paper with 7.4% filler in the paper, although up to 88% of FR can be obtained for a paper with 40% filler content when modern retention aids are applied.

In general, FR can be improved by filtration, flocculation, chemical bonding, electrokinetic forces, etc.

5.3. *Deflocculation*

Much of the particulate matter that passes through the wire during the production of paper is in a flocculated state – it is an agglomeration of particles. When the agglomeration is recycled in the paper production process, it can cause a deterioration in the quality of the paper produced. Therefore, it is desirable to deflocculate (break up) these agglomerates, before sending them back into the paper production process.

To deflocculate materials, the mechanisms by which they originally flocculated must be reversed. With current retention aids, flocculation occurs by polymeric bridging and electrostatic patch formation as discussed in the previous section. Flocs formed by polymers with a high charge density tend to form via the electrostatic patch mechanism. When these particles are subjected to high shear forces, little or no degradation of the polymer occurs. Therefore, the flocs reform quickly after the shear has diminished due to the strong electrostatic attraction that still exists. Flocculation that occurs between particles due to bridging with a low charge density polymer is different. When these flocs are subjected to a high shear, 90% of the polymer becomes detached from the particle and 70% is degraded due to the shear action. Therefore, little reformation of the floc can occur and the particle is deflocculated (104).

6. DESCRIPTION OF AVAILABLE TECHNOLOGY

6.1. *Fillers and Titanium Dioxide*

Table 7.5 indicates the chemical and physical properties of various common fillers summarized by Schwalbe (105). The fillers listed in the table include coating clay, filler clay, calcined clay, silicoaluminate, calcium silicate, silica, diatomaceous silica, talc, calcium carbonate, calcium sulfate, barium sulfate, zinc sulfide, and titanium dioxide.

Uono et al. (106) have added a water-soluble or dispersed cationic polymer (3–7% of filler) such as PEI or cationic PAA to a filler such as talc or titanium oxide. This mixture was added to a pulp slurry containing an anionic polymer (0.1–0.7% of pulp) such as polyacrylic acid or its copolymer as a paper strengthening agent. This process increases retention of the filler and the surface strength of paper, thus preventing bleeding of ink in high-speed printing.

Measuring and optimizing the concentration of paper and board additives is essential for quality control as well as furnish cost control (107). The Poly-Ash selective ash analyzer uses

Table 7.5
Chemical and physical properties of fillers

Pigment	Chemical composition, %	Specific gravity	Ultimate particle size, μ	Particle shape	Refractive index	Reflectance, %[a]			Seattering coefficient, 100S	Strength loss + 100S	Abrasiveness, mg	Non-volatile 105°C, %	Ignition factor, ash to filler	Price, index f.o.b. origin
						400 μm	457 μm	567 μm						
Filler clay	43–52 SiO_2; 34–42 Al_2O_3	2.60	2–5	Stacks		74	81.9	88.3	9.5–11.5	0.6	13	99.5	1.150	2.4
No. 2 coating clay	43–52 SiO_2; 34–42 Al_2O_3	2.61	0.25–5	Platelets	1.53	81	84.5	87.9	14–16	0.7	11	99.6	1.160	4.4
No. 1 coating clay	43–52 SiO_2; 34–42 Al_2O_3	2.60	0.25–3	Platelets	1.55	88.0	91.0	92.0	21	0.9	15	88.9	1.14	9.0
Caleined clay	52 SiO_2; 43 Al_2O_3	2.63	0.5–7	Platelets	–	–	92.0	–.	–	–	140–300	–	–	10.0
Silicoaluminate	67 SiO_2; 12 Al_2O_3; 9 Na_2O	2.10	0.025	Spherical	1.55	–	92.7	93.0	22.4	0.8	10–15	88.9	1.07	28
Calcium silicate	79.5 SiO_2; 7.2 CaO; 12.9 volatile	2.08	0.10	Spherical	1.30	86.2	96.5	96.0	25.4	0.8	–	91.9	1.10	36
Silica	87 SiO_2; 0.4 CaO; 11.6 volatile	1.95	0.07	Spherical	1.46	94.5	93.2	90.5	20.6	1.4	9.0	94.3	1.054	37
Diatomaceous silica														
Natural	83 SiO_2; 3.5 Al_2O_3; 3 volatile	2.1	1–8	Diatoms	1.46	62	68	78	29	–	40–175	97.0	1.06	7.6
Processed	91.8 SiO_2; 3.3 Al_2O_3; 1.3 Fe_2O_3	2.30	1–8	Diatoms	1.45	–	90	–	17	–	200–1,000	99.8	1.04	11.6
Tale	52–63 SiO_2; 27–34 MgO	2.80	3–8	Platelets	1.57	–	85							

Calcium carbonate														
Natural product	96 $CaCO_3$	2.65	3	Rhombs	1.65	–	93	–	–	–	13–30	–	1.78	6
Precipitated	98.6 $CaCO_3$	2.65	0.3	Rhombs	1.65	99.0	99.5	98.7	25	–	7	–	1.78	12
Raffold	65 $CaCO_3$; 35 $Mg(OH)_3$	2.50	0.3	Rhombs	1.53	–	95	–	–	–	16	–	1.64	3
Calcium sulfate	98 $CaSO_4$	2.9	0.5–6.0	Needles	1.57	97.0	97.0	96.0	9.4	–	–	99.75	1.003	6
Barium sulfate	97 $BaSO_4$	4.35	0.5	Cylinders	1.64	–	98.5	95.9	12	–	11	99.97	1.005	20
Zinc sulfide	95 ZnS	4.0	0.3	Needles	2.37	–	98.0	–	–	–	–	–	1.2	108
Titanium dioxide														
Anatase	98 TiO_2	3.9	0.2	Tetragonal	2.55	82.5	97.8	96.9	41.5	0.2	19	100	1.008	102
Rutile	98.5 TiO_2	4.2	0.33	Tetragonal	2.71	45.0	98.0	98.25	57	0.2	17	100	1.008	110

[a] Measured with G.E. recording spectrophotometer.

dual X-ray to measure each inorganic additive component individually. Clay is measured by preferential absorption while titanium dioxide and calcium carbonate are measured by X-ray fluorescence. Titanium dioxide and calcium carbonate standards assure accurate on-line calibration and gage stability.

Calcium carbonate (average diameter 0.1–1 μm) and another pigment such as clay or titanium oxide have been separately dispersed by Shibazaki and Edagawa (108) in water with a dispersing agent (0.3–1.5% of pigment). The former slurry (7–90%) is mixed with the latter, (93–10%) to which a binder (5–25% of pigment) such as starch is added. Application to paper gives high whiteness and gloss and good printability.

The optical properties (notably opacity) of a typical paper grade (50 lb basis wt.) as a function of sheet caliper and filler loading (with calcium carbonate vs. titanium dioxide) have been reported by Smaine and Glatfelter (109), along with papermaking variables that affect sheet opacity such as ash content, retention aid, broke, hardwood pulp, starch pickup, and others.

Olson (110) has reported a method of making an opaque paper using an opacifying filler consisting of a combination of titanium dioxide and calcium carbonate.

Koppelman (111) reported that inorganic fillers that increase sheet opacity and can extend titania include hydrous kaolin, anhydrous kaolin (calcined clay), silica, hydrated alumina, and sodium aluminosilicate. Their relative opacifying power depends partly on their refractive indices and partly on their agglomerate structure in the filled paper sheet. The wet-end incorporation of these fillers as partial replacement for titania also requires consideration of other paper properties, such as retention, interaction with additives, porosity, strength, coatability, and printability.

6.2. *Retention*

Titanium dioxide and ferric hydroxide are often used as pigments for the manufacture of decorative overlays. A study of addition of fillers under various conditions by Vasileva et al. (112) indicated that introduction of filler into the fiber suspension under neutral or weakly alkaline conditions combined with additions of aluminum sulfate and sodium aluminate mixtures caused an increased retention of pigment in the paper. Water extracts from paper were close to neutral. The effectiveness of titanium dioxide and ferric hydroxide retention with the use of the same amounts of aluminum in the pulp depended on the pH. When a combination of aluminum sulfate and sodium aluminate was used, the optimum amount of sodium aluminate required depended on water hardness.

The retention of anatase titanium dioxide on bleached beaten Kraft pulp and RC fibers was studied (113) using zeta potential measurements to elucidate causes of frequently low single-pass FR. A tea strainer (75-μm screen) was used as a forming wire model, and FR was calculated from the turbidity of the supernatant. Results showed that high retention was achieved in the absence of hydrodynamic shear, but that this retention can be halved on conventional handsheet machines. Single anatase particles can adhere strongly to cellulose surfaces and are not removed by shear forces up to 70 pN. Evidence of floc formation of fiber surfaces was obtained by SEM, suggesting that filler removal from fibers by hydrodynamic shear is due to the larger hydrodynamic radius of the flocs, or else to soluble molecules derived from the fibers that modify the surface of filler particles and hence their adhesion to the cellulose fibers.

Improved solids retention on the paper machine is discussed by Kock and Luciani (114) as a way to combat effluent problems in the paper industry. Covered are retention through chemical means, laboratory testing for the selection of retention aids, the application of retention aids on the machine, and procedures for rapid evaluation of retention.

Amide-amines useful as coating hardeners, retention agents in papermaking, and flocculants in waste water treatment have been prepared by Itoh Oil Co. (115) from hydroxy fatty acid esters, epichlorohydrin, and polyamines. Thus, 339 g castor oil fatty acid methyl ester was treated with 92 g epichlorohydrin to form ethers and then with 60 g ethylenedlamine and 72 g N-methyliminobis (propaneamine) to give amide-amines useful as hardener/plasticizer for epoxy coatings.

The theory of dispersion on which the Escher Wyss Disperger is based has been discussed by Linck (116) with particular focus on the effects of this equipment on various waste paper contaminants such as wax, asphalt, latex, and pigments.

Based on a mathematical model of FR by Raczynska (117), two stages are defined, viz., initial retention (filler sorption before the headbox) and FR on the wire. Laboratory tests with kaolin and titanium dioxide fillers corroborated the model and demonstrated the importance of initial retention and the efficacy of some commercia1 retention aids.

Following a definition of retention aids and suggestions regarding retention aid selection, the need for controlling the electrokinetic charge (zeta potential) of cellulosic fibers and colloidal particles in suspension has been discussed by Trombetta (118). The electrophoretic charge analyzer permits a rapid calculation of the correct dosage level for additives to achieve optimum cost and performance; specific advantages are enumerated, and operation of this instrument is described.

Retention and drainage aids consisting of noncrosslinking polyamides are obtained by reaction of polymeric compounds that are polyfunctional with respect to amino acid and basic polyureas resulting from condensation of urea polyamines (119).

The influence of dissolved and colloidal solids in newsprint pulp on the effectiveness of fines-retention aids based on PEO, PEI, and PAA was studied by Pelton et al. (120). Also examined were the effects of stock consistency and temperature on the retention activity of PEO and PAA and the influence of molecular weight, pH, and alum concentration on fines retention with PEO. The material in newsprint pulp that could be removed by washing but not by dialysis had a detrimental effect on the action of cationic retention aids but a positive effect on the action of PEO. Only PEO with a molecular weight of 5,000,000 increased the fines retention; retention with this polymer was proportional to the initial pulp consistency. Retention increased when the pulp temperature was raised from 5 to 50°C, both with and without PEO. PAA improved the fines retention when added at concentrations of 0.15% or greater; its effectiveness was independent of consistency from 0.065 to 0.65% and of temperature from 5 to 90°C. The effect of PEO on retention was independent of pH from 3 to 11 and of alum concentration from 0 to 0.3% (at pH 4–6); higher alum concentrations improved the fines retention.

An experimental program was carried out to measure the retention of a dilute suspension of titanium dioxide after permeation through a preformed bed of synthetic (nylon) fibers (121). The results were compared with a mathematical retention model. The model performed adequately and can be used to predict various trends in collection efficiency that are influenced by changes in system parameters. Both the model and the experiments indicated that retention decreases with increasing porosity, increasing approach velocity, and decreasing ionic strength of the suspension. Differences between the predicted and measured values are thought to be due to particle removal during permeation and flow perturbations within the fiber pad.

The DYSCO (Dynamic Simulation and Control) simulator is described by Parker (122). The dynamic capability extends the range of problems that can be studied, and the modular construction facilitates extension of its application. Problems with plant startup and shutdown, process control, and emergency procedures can be studied. The effect of changing retention aid dosage on the retention of fines and fillers and the analysis of a simplified web-break control system of a real fine-paper machine are given as examples to illustrate DYSCO's utility and limitations. The addition of a good physical property package should make DYSCO a powerful tool for analyzing process flow sheets.

A general discussion concerning retention of fillers and pulp-derived fines in the furnish during sheet formation is presented by Britt (123). Basis weight and shear forces related to machine speed, the major factors influencing retention, tend to reinforce one another. Machine design and furnish composition are also factors. The Dynamic Drainage Jar test, which shows a wide range in properties, can be used to classify retention aids in terms of resistance to shear. The shear-resistant polymers are thought to act via a macromolecular bridging mechanism between adjacent surfaces, whereas the more dispersed flocculants act via electrokinetics, i.e., by influencing the zeta potential. Because furnish composition and grade affect retention, there will be differences between retention of filler and of pulp fines. Larger pulp fine particles give higher retention than filler when no retention aids are present; however, when these chemicals are used, filler gives a higher increase. Problems involved in the use of retention aids include the detrimental effect of chemical additives used for flocculation on sheet formation, and the sometimes adverse effect of pigment fillers (e.g., titanium dioxide) used for strong flocculation under conditions of high retention on optical efficiency, i.e., scattering coefficient. The use of additives may also affect drainage and formation properties. Data are presented which illustrate the effect of retention aids on improving first-pass retention in an open and a closed system.

Laboratory handsheets containing titanium dioxide have been prepared by McKenzie and Davis (124) using a cationic polyacrylamide resin, alum, sodium aluminate, and alum-polyacrylamide mixtures to promote retention. The influence of order of addition of components, polymer addition levels, and pH on retention and optical properties was studied and a microscopic examination of the handsheets was carried out. They found that retention is affected by the zeta potential of the components and by the possibility of polymer bridge formation. The formation of large aggregates of additive particles, particularly in conjunction with colloidal alumina, can adversely affect retention. The opacifying efficiency of titanium dioxide is greater when aluminum is present in the system than when retention is promoted by cationic polyacrylamide alone. Certain differences were observed between the retention behavior of titanium dioxide and starch when cationic polyacrylamide was used as the retention aid. These differences may be related to the different nature of the surfaces of the two additive starches being able to provide polymer chains that could take part in polymer bridging reactions.

6.3. *Effluent and Saveall Processes*

Wang et al. (125, 126) have presented various biological, chemical, and physicochemical processes having potential for the treatment of pulp and paper mill effluents.

Effluent recycling has many advantages over end-of-line wastewater treatment. It has been shown by Sçhirtzinger (127) that secondary-fiber mills can operate with a closed water system. For integrated mills and fine-paper mills with many grade changes, it is more difficult to completely close the water system; however, fresh water use can be limited to 2,000 gal/ton of paper produced. Economic advantages include lower costs of effluent treatment and of end-of-line treatment plants, savings in heat and chemical recovery, and reduced fiber and filler losses. Operating difficulties can be eliminated by adjustments in the chemistry of the recycled water system and by attention to flow and material balance.

Guss stated (128) that the proper clarification of effluents is an important subject for deinking mills. More and more plants have to close the water cycles and reuse part or all of their deinking effluent. Eliminating effluent discharge while reducing costs and maintaining quality have become the main goals for deinking clarification. The effluents from deinking are normally used to carry away undesirable components of waste paper. These undesirables include dispersed and undispersed ink, contaminants, and to various degrees, fine fibers and coating clays. Deinking effluents (if discharged) also carry away valuable chemicals, heat, and fibers. Clarification of effluents for recycling therefore demands removal of the undesirable elements with minimum loss of the valuable ones. This demand can be met by fine screening in a spray filter, followed by chemical flocculation of solids and ink, which are then removed in the flotation–sedimentation clarifier. The Guss paper (128) is divided into two sections. The first section lists special problems and considerations for deinking clarification. The second section discusses design features and application experience for the flotation clarifier as used in closed deinking systems.

Closed water systems in paper and pulp mills are attractive to secondary fiber users because of the large amount of evaporated water involved and the absence of any pulping operation requiring washing out of dissolved materials. Optimal design factors suggested by Guss (129) include isolation of individual loops, minimal total water volume, adequate surge capacity, and properly motivated operating personnel. Closed systems can be achieved with existing equipment and operating techniques. They can be designed for tissue machines, board machines, cylinder machines, and the new forming machines. Problems include motivation of personnel to adopt new methods, corrosion, and chemical and water balance. The benefits of a closed system include material, heat, and chemical savings, elimination of biological waste and fresh water treatment costs, and the long-range freedom from further pollution control restrictions.

In certain production programs of paper plants it is possible to work with completely closed water cycles in the plant so that neither polluted water nor treated waste water has to be discharged. A report is given by Brecht et al. (130) on another waste paper processing plant that does not discharge waste water either under normal operating conditions or during weekly cleaning operations. Only unpolluted cooling water is discharged into the sewer. The advantages of such a completely closed water cycle are quite evident. The fresh water input is limited to the amount of water evaporated on the paper machine and in general with a corresponding reduction in costs for industrial water treatment; in particular, however this will definitely eliminate a residual water treatment installation that will undoubtedly require a biological treatment stage in the future; moreover, expected future waste effluent taxes will not be incurred, and there will be no material losses with the waste water. The measures used for closing the system in the investigated plant are discussed in detail and a position is taken concerning the problems related with it in several aspects.

Hashimoto (131) reported a new method for treatment of reclaimed paper. Reclaimed paper and water are stirred in a pulper to roughly fiberize and dilute to 3–4% slurry, which is fed into a cleaner to remove heavy impurities such as metal. The mixture is fed into and stirred in the first fiberizer, filtering through a screen plate (3–5 mm opening). The filtrate is fed into a chest, whereas the precipitate is transferred to a dewatering apparatus whose water is then also returned to the pulper. The dewatered waste paper is fed into a mixer to which 1.5–3% NaOH is added at 40–70°C. The mixture is diluted with water, treated for 5–20 h, and then fed into the second fiberizer. The filtrate passing through a screen plate is fed into the chest, while the precipitate is separated by a vibrating screen to eliminate light impurities. A combination of mechanical treatment with chemical treatment reduces the size of the apparatus and the cost of the operation.

In a work by Stratton and Swanson (132), starch-containing broke was treated with alpha-amylase in a mill hydrapulper under optimized conditions. Increases in first-pass retention of ash and of fines and in saveall operating efficiency resulted. A substantial reduction in retention aid dosage was also possible. Economic analysis showed net savings, resulting primarily from reduced loss of titanium dioxide to the sewer.

Frost (133) suggested a method of treating papermaking whitewater. Paper-machine whitewater is clarified and then exposed to UV light that causes certain dissolved solids, usually of a biodegradable organic nature, to polymerize into insoluble materials that can then be separated from the whitewater by conventional means. The whitewater is then recirculated.

Experience gathered during a 2-year operating period with a mill's effluent-clarification installation was reported by Nyaradi and Szalay (134). Data include evaluation of suspended solids and COD removal efficiencies. Solids coagulated by the addition of aluminum sulfate resulted in 67% removal efficiency and COD reduction averaged 82% (99% maximum). With proper pH control and adequate sedimentation time, the clarified effluent was suitable for recirculation in certain mill processes. Separate treatment of the resulting sludge was not justifiable; it is dewatered jointly with the pulp-mill effluent sludge.

The use of defoamers, pitch and resin dispersants, flotation and retention aids, and related surface-active pulp additives for removal of contaminants and entrapped gases from fiber suspensions was reviewed by Kolb (135).

Brendiner and Kargolis (136) obtained a U.S. Patent for the incorporation of a water-soluble or water-dispersible deinking chemical into a bale of waste paper. The chemical is a synthetic organic surfactant effective in dispersing ink present on the paper in the form of very small ink particles when the bale of waste paper is deinked and pulped in an aqueous alkaline bath. The surfactant can be a nonionic polyoxyethylene alcohol or alkyl phenol containing 1–50 moles of ethylene oxide adducted to an aliphatic alkanol having 8–20 carbon atoms or to an alkyl phenol having 8–12 carbons in the alkyl group. The surfactant can be applied to the bale by spraying the bale with an aqueous solution of the dispersed surfactant. Other treatment chemicals such as slimicides can be included in the treatment composition.

Takenaka et al. (137) treated pulp wastewater by the addition of calcium hydroxide in two steps in the presence of an anionic polymer coagulant to enlarge the floc size. Calcium hydroxide (3,000 mg/L) was added to Kraft pulp waste water with a COD of 900 mg/L followed by the addition of 2 mg/L Sanpoly 305, stirred, and then the second dose of 2,000 mg/L calcium hydroxide was added to the mixture. The settling rate was about twice as fast as that from the addition of a single coagulant dose.

The effect of water reuse on paper pulp mill whitewater properties was discussed by Lightsey and Hall (138). Results from whitewater recycling simulations are compared with results from actual reuse operations. The foaming tendency and foam stability of the whitewater are shown to increase as the rate of recycle increases. Foaming can be controlled by increasing the concentration of defoaming agents in the whitewater.

Mobius (139) reported that economies can be affected by physicochemical treatment of the water system and effluents, especially in small paper mills. Three possibilities are discussed: flocculation or adsorptive precipitation, adsorption onto pigments that become part of the paper, and ion-exchange with highly porous exchangers or absorbent resins.

Williams (140) presented an international survey of waste paper recycling in various countries, including Sweden, UK, Japan, USA, and Eastern and Western Europe. Various aspects of waste paper recycling are discussed, including major technological improvements, waste paper sources, economics (with suggestions for methods to increase profits), machinery available for processing and handling waste paper, and some encountered problems. Actual mill experiences were described. Handling and deinking methods, the use of hydrogen peroxide for upgrading waste paper, fiber recovery from laminated packaging materials, stock preparation methods, and coating of recycled paper are also discussed.

A regional system for purification and recycling of whitewater in three mills was developed at the Ukrainian Scientific & Technical Association of the Pulp & Paper Industry (141). In this system, whitewater from two paper mills, after suitable purification, was used as process water at the third board mill that produces coated multiply boxboard containing up to 85% waste paper stock. The system involves a multistage purification of effluents from the board mill for recycling, as well as utilization of sediments by drying and combustion or in production of constructional fiberboards. The system reduced the volume of effluents discharge into the river by 75%.

The foam separation of dispersed and coagulated titanium dioxide was investigated by Rubin and Haberkost (142), using anionic and cationic collector surfactants in a dispersed air flotation system. Aluminum sulfate and ethanol are recommended as the coagulating agent and the frother, respectively. Their research results demonstrated the feasibility of recovering titanium dioxide from aqueous dispersion using flotation techniques with anionic and cationic collectors. For all flotation systems studied by them, the titanium dioxide separation efficiencies were dependent upon proper conditions of pH, collector concentration, coagulant concentrations, and other solution and operating parameters.

At Lenox Institute of Water Technology, Krofta and Wang (143, 144) and Landin (56) investigated a nonfoaming DAF process for the treatment of whitewater and the recovery of titanium dioxide and fibers. Their laboratory testing results are presented in the following section.

7. DAF PROCESS FOR RECOVERY OF FIBER AND TITANIUM DIOXIDE

7.1. Experimental Investigation

The goal of the investigation was to remove paper fiber and titanium dioxide from a paper mill whitewater and subsequently produce paper from these recovered materials that did not have significantly altered optical properties. The investigations consisted of:

1. Batch jar tests
2. Batch DAF tests
3. Handsheet formation using a dynamic drainage jar

The ability of coagulants and polymers to flocculate the paper mill wastewater was tested in batch jar tests. Optimal polymer and coagulant dosages were determined. The flocculated whitewater was then subjected to a flotation test. The subnatant of the flotation test was observed and measured for turbidity to determine the ability of flotation to remove titanium dioxide and fiber from the whitewater. Handsheets were then made from the floated sludge. These handsheets were measured for light transmittance and titanium dioxide content to determine whether there was any degradation of optical properties in the paper made with the recovered materials.

Overall, simulation of the papermaking process was achieved by conducting jar tests (which simulated the chemical treatment of a waste whitewater), floating the whitewater (which simulated the flotation of a. waste whitewater in a saveall), collecting the floated sludge, deflocculating the sludge, reapplying a retention aid, and making a handsheet from the treated sludge (which simulated the recycling of the recovered materials in the papermaking process).

7.2. Jar and Flotation Tests

Overall, the purpose of the jar and flotation tests was to determine which chemicals could be used in a saveall to recover the titanium dioxide. Flocculation and flotation characteristics were noted and subnatant turbidities measured. The investigation tested all pressurization modes, full flow, partial flow, and recycle flow (145–147).

Pressurization mode. Full and partial flow modes showed poor flotation characteristics. The reason for this poor performance may have been due to operational problems associated with the pressurized sprayer used to introduce the pressurized fluid into the flotation cylinder. The fiber in the whitewater seemed to plug the outlet valve of the pressurization vessel. Because of this, at times the outlet would become almost entirely plugged and very little of the sample would be released. In other instances, the outlet would briefly plug up and then clear so that the sample would be discharged into the flotation cylinder turbulently, in spurts, not smoothly as it should be in laminar flow. This type of action may have greatly hindered the flotation performance.

Although most of paper mills in the country do use full flow flotation in savealls, it was not practical to continue the experiments under these conditions. Therefore, a decision was made to use recycle flow flotation, which avoids this plugging problem. The flotation characteristics of recycle flow flotation tests were good. Titanium dioxide concentration was reduced from 100 down to 60 mg/L, which indicates that flotation alone without chemical addition is capable of recovering a fair amount of titanium dioxide. The following chemical agents were then tested to determine their efficacy in titanium removal.

Turkey red oil. Turkey red oil was tested because it has the ability to decrease the bubble size of the released pressurized water. However, the Turkey red oil apparently did not have a noticeable effect.

Nalco 625. Nalco 625, a strongly anionic polymer, exhibited poor flotation characteristics and poor titanium dioxide recovery. This validates the fact that whitewaters possess a negative charge. A negatively charged polymer when introduced into a negatively charged solution would not be expected to produce flocculation. The like charges would repel one another and hinder flocculation (68).

Alum. The tests that involved alum showed very good results. Alum used in combination with sodium hydroxide and a polymer showed the best results. The polymers that seemed to work best in combination with alum and sodium hydroxide were the Nalco 85P208, a cationic polymer, and Nalco 2PD-462, an anionic polymer. These are high weight polymers and the ability of both cationic and anionic polymers to perform well seems to indicate the alum/sodium hydroxide reactions reduce the charge in the whitewater so that both are equally capable of retaining the titanium dioxide via the bridging mechanism.

Gendriv 162. Gendriv, a high charge, high molecular weight cationic polymer, showed an excellent ability to flocculate whitewater. This again supports the theory that whitewaters are indeed negatively charged.

Kymene 557. Kymene is a cationic polymer used in paper mills to improve paper wet strength and as a retention aid. However, it performed poorly as a flocculating agent. Flotation subnatant turbidities were no different from those of raw wastewater.

Starches. Starches worked well. Cato 215, an amphoteric starch, needed higher dosages to produce results similar to those of cationic starches (National 131 and 132). This makes sense because the amphoteric starch does not have the charge differential promoting flocculation, so more of it would have to be added to produce similar results.

XYZ. XYZ an amphoteric polymer obtained from a local paper mill (Berkshires, MA) did not exhibit good flotation characteristics. Because this is an amphoteric polymer, it does not have a charge differential promoting flocculation and is forming flocs via the bridging mechanism. Therefore, the flocs may be susceptible to shear, which could explain the poor flotation performance.

Berocell. Berocell 672 and 439 also preformed very poorly. Berocell 672 is a slightly anionic polyacrylamide polymer that is used as an anchoring substance for the Berocell 439, a nonionic PEO. Perhaps the negatively charged whitewaters inhibited the ability of anionic Berocell 672 to anchor onto the particles rendering Berocell 439 ineffective.

7.3. Chemical Selection

After performing the jar tests, it was necessary to narrow down the number of chemical combinations to be used for further testing. Three factors were considered in making this decision (56):

1. The ease of application of the chemical combination in the papermaking process
2. The potential for the flocculating mechanisms of the chemicals to be reversed
3. The ability of the chemicals to retain the titanium dioxide

Given these base conditions, the following chemicals and combinations there off were selected: Berocell 439 and 672, Gendriv 162, Starches, Kymene 557, and XYZ.

7.4. Controls

The next step in the investigation was to determine the ability of different mechanisms to break apart the sludge formed from the flotation of flocculated whitewater. The purpose of this is to redisperse titanium dioxide in the sludge and maximize the potential optical properties that the sludge would possess. This was measured by making handsheets with the deflocculated sludge and comparing their optical properties.

As a control, handsheets were made up from a well dispersed virgin titanium dioxide whitewater with no chemicals added. There was an upper limit to the amount of titanium dioxide that could be retained in the handsheet. This limit was at a titanium dioxide content of 5 g/m^2.

To increase the range of the control, two different experiments were conducted. The first increased the refining time (the amount of time that the paper fibers are beaten) and the second increased the amounts of paper fibers added.

7.5. Effects of Flocculated Whitewater on Paper

The basic premise of this investigation is that flocculated whitewaters have a detrimental effect on the optical properties of paper. It was believed that the recovery process, with flocculation occurring in the flotation saveall, was responsible for creating the flocculated whitewaters. To verify this hypothesis two tests were conducted.

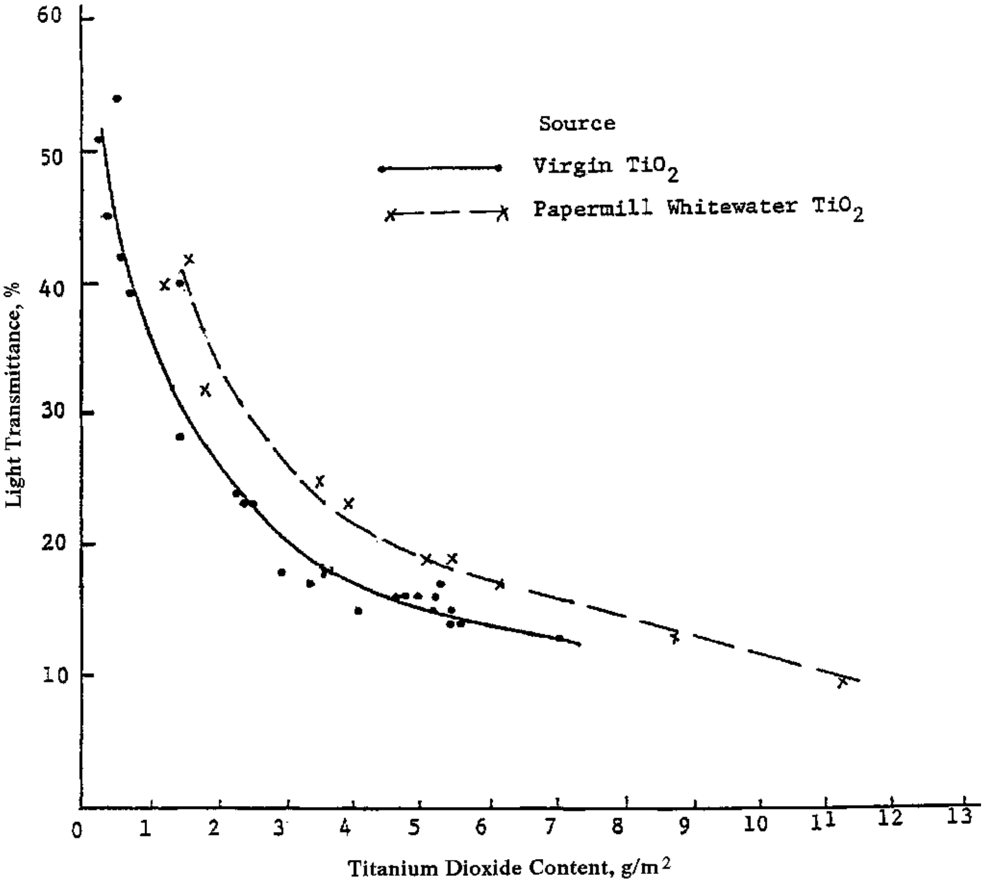

Fig. 7.8. Light transmittance as a function of titanium dioxide content.

The first test used a whitewater collected at a local paper mill. This whitewater was collected from the tray below the wire and was used as the source of titanium dioxide in the handsheets. This whitewater came from a stock that had been treated with XYZ retention aid. The second test simulated a paper mill whitewater treated with a retention aid by adding Gendriv 162 to a paper stock. The results of these two tests are shown in Fig. 7.8.

The handsheets that were produced from the whitewaters treated with a retention aid had degraded optical properties. At similar titanium dioxide concentrations, the whitewaters with the retention aid had higher light transmittance than virgin untreated whitewaters. This shows that the titanium dioxide in whitewater was pilled prior to its introduction to the saveall. Therefore, while the flocculation in the saveall may degrade the optical properties of titanium dioxide, the retention aid (at least in this instance) is also partially responsible for the degradation. Therefore, it is necessary to deflocculate the whitewaters to improve the optical properties of paper.

7.6. Deflocculation

Kymene 557, Berocell, Gendriv 162, and starch were tested for their effectiveness in deflocculation. Kymene and Berocell were found to be ineffective. Gendriv 162 sludge showed a little bit more promise. Both stewing and mechanical action produced handsheets that had lower titanium dioxide contents than the control. This may indicate that titanium dioxide was well dispersed by the deflocculating action and passed through the handsheet, reducing the titanium dioxide contents in the handsheets compared with control sheets. The data indicates that mechanical action had a greater ability to disperse titanium dioxide than stewing action.

The results of the starch deflocculation were the most promising of those tried. The three starches, Cato 215, National 131, and National 132, were deflocculated by stewing them in the presence of an enzyme, Tekatex, Tenase, or Enzeco. No matter which combination of starch and enzyme was used, in nearly every case the handsheet made with the deflocculated sludge had properties indicative of good titanium dioxide dispersion.

The properties that indicate good dispersion are that the titanium dioxide contents are lower in the deflocculated handsheets than the control. Because there is less of titanium dioxide retained in the sheet, the light transmittances accordingly increased above those of the control.

There did not appear to be a great amount of difference between the starches and their deflocculating capabilities. Paper made with the deflocced Cato sludge had an average titanium dioxide content of 1.5 g/m^2 and light transmittance of 31%. The values for National 131 and 132 sludges were 1.8 g/m^2 and light transmittance of 27%. Cato 215 was an amphoteric starch and this may explain why it seemed to disperse titanium dioxide a little better. The National starches had a charge associated with them. This charge may have helped hold the titanium dioxide in the sheet and resulted in the slightly higher titanium dioxide contents and corresponding lower light transmittance.

With respect to the deflocculating enzymes, a definite trend was noticed. It appears that the sludge deflocced with the Tekatex enzyme produced paper with the lowest titanium dioxide contents and highest light transmittance. Tekatex was followed closely by the Tenase and Enzeco enzymes. These data indicated that the Tekatex enzyme could be able to digest the starches more efficiently given the time allotted for stewing and the stewing temperature.

7.7. Papermaking System Simulation

Because of the enormous number of possible different combinations of retention aids, flotation aids, and deflocculating mechanisms that could be used in simulating the papermaking process, it was decided that the simulation should be conducted using the chemicals and methods that gave the best deflocculation results. As can be seen from the previous sections, the chemicals that produced the best deflocculation results were the starches when used in combination with an enzyme that digested the starch.

Because the handsheets made from the National 131 and 132 sludges possessed similar characteristics and because the deflocculating abilities of the Tenase and the Enzeco were similar, the papermaking simulation was conducted using the Cato 215 and National 132 as the flocculating agents and the Tekatex and Enzeco as the deflocculating agents. In this way, it was thought that a good range of flocculating/deflocculating characteristics would be achieved.

The simulation first attempted, used the XYZ from the local paper mill as a retention aid. This was selected because it was felt that it would be practical to try and use materials commonly used in the paper industry so that if a deflocculating system were ever introduced, there would be changes just for the deflocculating process rather than a great deal of change to the whole system.

The paper produced from the Cato 215 and National 132 sludges possessed similar characteristics, having average titanium dioxide content of 15.5 g/m^2 and light transmittance in the 6–8% range. The paper made with the sludges had lower light transmittance and higher titanium dioxide content than their respective controls to which no deflocculation was employed. This indicated that the deflocculation process did work because the optical properties of the deflocculated pigment were not impaired.

It appears that paper sheets made with the sludge deflocculated with the Enzeco enzyme have slightly higher titanium dioxide content than paper sheets deflocculated with the Tekatex enzyme. Again, this would seem to support the theory that the Tekatex enzyme is better able to deflocculate titanium dioxide because less of it is retained in the sheets. However, because a retention aid is being employed, the impact that the lesser amounts of titanium dioxide has on light transmittance is negligible.

Next a simulation was carried out that used starches as retention and flotation aids. In this case, when the floated sludge was subjected to deflocculating action, all of the flocculating chemicals would have the same deflocculating mechanism. National 132 was chosen to be the retention aid and Cato 215 was chosen to be the flotation aid because Cato seemed to be more susceptible to the deflocculating mechanisms and if used as the flotation aid it would be present in the greatest quantities. Because the deflocculation process takes about an hour, when National 132 was added as a retention aid just prior to sheet formation, it was felt that it would not be degraded by the enzymes present and could retain the titanium dioxide.

The paper produced using this simulation displayed good optical properties over a wide range of titanium dioxide concentrations. Light transmittance was lower than that of the control at similar titanium dioxide contents, which indicates that the deflocculating process was effective. Once again paper made from sludge deflocculated with Enzeco enzyme displayed higher titanium dioxide contents and lower light transmittance than paper deflocculated with the Tekatex enzyme. This again indicates that Tekatex may be a better deflocculator; however, in this instance it appears that less of the titanium dioxide was retained so that light transmittance increased. Perhaps, a different combination of starches should be tried to find the starch that is better able to retain titanium dioxide than the National 132 did here.

It is interesting to note that when these paper sheets made in the simulation are compared with the paper made initially with virgin titanium dioxide (see Fig. 7.9), the optical properties of the papers are very similar over a wide variety of titanium dioxide contents. This indicates that the whitewater of a paper mill can be dispersed and recycled into the system without greatly impairing the optical properties of the paper.

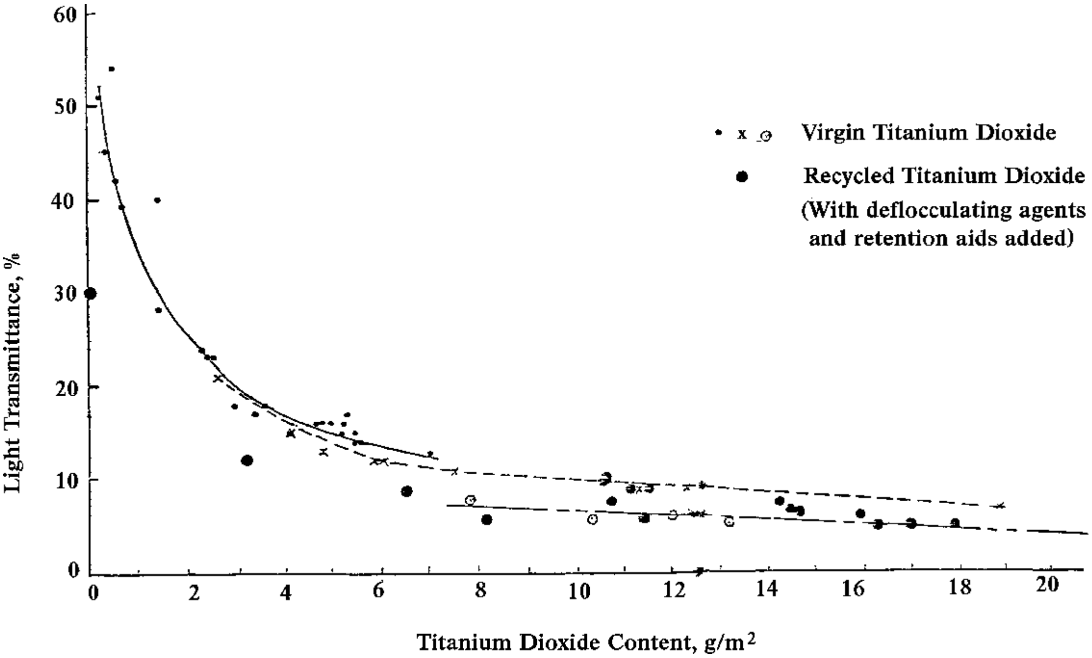

Fig. 7.9. Light transmittance as a function of titanium dioxide content.

7.8. Conclusions

1. The experiments conducted on whitewater collected from the tray below the wire at a paper mill indicate that the pigment in this whitewater is already agglomerated due to the action of the retention aid. The paper sheets produced using whitewater as a source of titanium dioxide showed degraded optical properties relative to sheets with the same content of virgin filler. This indicates that the DAF recovery process is not entirely responsible for degrading the optical properties of the pigment. In this case, the pigment had already been impaired prior to the recovery operations. Therefore, changing the recovery process alone will not be entirely effective in improving the optical properties of the recovered pigment. A system's approach is required.
2. Recycle pressurization mode best recovers the materials in whitewaters at 25–33% recycle flow.
3. The shear forces associated with full and partial flow pressurization modes seem to be responsible for poor flotation performance and recovery of materials.
4. Flotation processes using alum proved to be especially susceptible to shear forces involved in full or partial flow pressurization modes.
5. The paper fiber and titanium dioxide contained in a simulated whitewater can best be recovered by the addition of cationic polymer (Gendriv 162) or starches (Cato 215 and National 132). The required dosages were 2 mg/L of Gendriv 162 and 20 and 10 mg/L of Cato 215 and National 132 starches, respectively. These were recovered using a recycle flow DAF at 25% recycle flow rate.
6. In general, it can be concluded that the chemicals that will best recover titanium dioxide from the paper mill whitewaters are cationic chemicals. The polymers that worked best were of high molecular weight and not necessarily of high charge. Therefore, the mechanism that was most likely used to create the flocs was the bridging mechanism. It appears that there must have also

been some electrostatic bonding because mechanical action, which is usually capable of destroying the floc and degrading the bridging polymer, was ineffective.

7. Simulations indicated that the chemicals used to recover the paper fiber and titanium dioxide have an adverse effect on the optical properties of produced paper.
8. Mechanical action and chlorine addition were ineffective in deflocculating Kymene 557 sludges.
9. Enzyme digestion of starches effectively deflocculate pigment and fiber.
10. A system approach using a starch (National 132) as a retention aid, another starch (Cato 215) as a flotation aid, and an enzyme (either Enzeco or Tekalex) as a deflocculating agent followed by papermaking using National 132 as a retention aid could produce paper with unimpaired optical properties (148–153).

REFERENCES

1. OECD (2004) Draft emission scenario on pulp and paper industry – none-integrated paper mills. Environmental Exposure assessment, Environmental Directorate, Organization for Economic Co-operation and Development, ENV/JM/EEA(2004)7/2/REV, Gatineau, Quebec, Canada, Dec
2. European Commission (1996) Technical guidance document in support of commission directive 93/67/EEC on risk assessment for new notified substances and commission regulation, European Commission No. 1488/94 on risk assessment for existing substances, Part IV. Office for Official Publications of the European Communities, Luxembourg
3. Hynninen P, Luonsi A, Vuoriranta P (1986) Reduction of pulp and paper industry effluent loading. Water Sci Technol 18(3):109–126
4. European Commission (2001) Integrated Pollution Prevention and Control (IPPC). Reference document on best available techniques in the pulp and paper industry. European Commission, Office for Official Publications of the European Communities, Luxembourg
5. Repeta LE (1987) Comprehensive look at key stamp element. Am Philat 129–131, Feb
6. U.S. EPA (1995) Profile of the pulp and paper industry. EPA/310-R-95–015, US Environmental Protection Agency, Office of Compliance, Washington, DC, Sept
7. Whitney RP (1979) Chemistry of paper, paper – art and technology. World Print Council, San Francisco, CA, pp 36–44
8. Holton HH, Kutney GW (1985) Pulp with less pollution. Chemtech 15(9):568–571
9. U.S. EPA (1982) Development documentation for effluent limitation, guidelines, and standards for the pulp, paper, and paperboard industry – point source category. US Environmental Protection Agency, Washington, DC, pp 67–86, Oct
10. U.S. EPA (1984) Paper production – guidance manual for pulp, paper and paperboard and builder's paper and board mills pretreatment standards. US Environmental Protection Agency, Washington, DC, 2–5 July
11. Rauch J (2008) The Kline marketing guide to the paper and pulp industry. Charles H. Kline & Co., Fairfield, NJ, p 213, Dec
12. Ash M, Ash I (2001) Handbook of paper and pulp chemicals. Synapse Information Resources, Endicott, NY
13. UNIDO (1991) Case study No. 1, pulp and paper, United Nations Industrial Development Organization. Conference on Ecologically Sustainable Industrial Development, Copenhagen, Oct
14. Casey JP (1960) Pulp and paper, chemistry and chemical technology, 2nd edn, vol 2. Interscience Publisher Inc., New York, NY, pp 853–875
15. Ambery HR (1984) Sludge dewatering and disposal in the pulp and paper industry. J Water Pollut Control Fed 56(8):962–970

16. Bashaar YA (2004) Nutrients requirements in biological industrial wastewater treatment. Afr J Biotechnol 3(4):236–238
17. Gilbride KA, Fulthorpe RR (2004) A survey of the composition and diversity of bacterial populations in pulp and paper mill wastewater treatment systems. Can J Microbiol 50(8): 633–644
18. Baker CJO, Fulthorpe RR, Gilbride KA (2003) An assessment of variability of pulp mill wastewater treatment system bacterial communities using molecular methods. Water Qual Res J Can 38:227–242
19. Kirkwood A, Nalewajko C, Fulthorpe RR (2003) Physiological characteristics of cyanobacteria in pulp and paper waste treatment systems. J Appl Phycol 15:324–335
20. Milestone CB, Fulthorpe RR, Stuthridge T (2004) The behaviour of color during the biological treatment of pulp and paper wastewater. Water Sci Technol 50(3):87–94
21. Bragy R (1984) Paper mill effluent treatment. Effluent Water Treat J 23(10):435
22. Oikari A et al (1985).Ecotoxicological aspects of pulp and paper mill effluents discharged to an inland water system: distribution in water, and toxicant residues and physiological effects in caged fish. Aquat Toxicol 6(3):219–239
23. Dines RA, Wharfe JR (1985) Environmental impact of waste discharges to the swale. Environ Pollut 38(3):245–260
24. Crowther RA, Luoma ME (1985) Pattern recognition techniques to determine benthic invertebrate trophic and community responses to industrial input. Verhandlung Internationale Vereinigung Limnologie 22(4):2226–2231
25. Webb LJ (1985) Investigation into the occurrence of sewage fungus in rivers containing paper mill effluents – III. Removal of sewage fungus nutrients. Water Res 19(8):961–967
26. Webb LJ (1985) Investigation into the occurrence of sewage fungus in rivers containing paper mill effluents – IV. Growth in experimental channels dosed with effluents and pure compounds. Water Res 19(8):969–976
27. Tana J, Nikunen E (l986) Impact of pulp and paper mill effluent on egg hatchability of pike. Bull Environ Contam Toxicol 36(5):738–743
28. NY DEC (2002) Environmental self-assessment for the pulp and paper industry. New York State Department of Environmental Conservation, Albany, NY, Nov
29. Environment Canada (2003) Chemical releases from Canadian pulp and paper mills. Prepared for Environment Canada, Gatineau, Quebec by Crechem Technologies, Ottawa, Ontario in association with JANCO, Perth, Ontario, 7 July
30. McKague B, Reeve DW (2003) Analysis of plant sterols in pulp mill effluents and sludges. TAPPI international environment conference, Portland, OR, May 2003
31. Zhuang W, McKague B, Carey J, Reeve D (2004) Characterization of extractable organochlorine in fish downstream from bleached kraft pulp mills. Int J Environ Anal Chem 86(12):867–887
32. U.S. EPA (2010) An industry overview of pulp and paper mills. Enviro Science, US Environmental Protection Agency. http://es.epa.gov/techinfo/facts/facts
33. O'Rourke JT (1982) Water recycling in the pulp and paper industry in California. California Water Resources Control Board, Sacramento, CA, Technical Report, Jan 1982
34. Stevens WV (1976) White water system engineering. TAPPI J 59(2):71–74
35. MPM (2009) Environmental stewardship. Monadnock Paper Mills (MPM). Can be located at: http://www.mpm.com/about/environment.asp
36. Luskey HL, Drechsel ER (1983) Reuse of warm paper machine water pays off at Madison. Pulp Pap 57(9):46–47

37. Kolkov VL, Volkov VV (1980) System for water usage and effluent purification at the Leningrad board mill. Bumazh Prom 6:5 [Rus]; ABIPC 52:2879 (1981)
38. Scott JH Jr (1981) How to plan a vacuum pump seal water recovery system. TAPPI J 64(3):63
39. Krofta M, Guss DB, Wang LK (1985) Closing the water system on paper machines with a high-rate flotation clarifier. Tech. Paper No. LIR/09–85/175. Lenox Institute of Water Technology, Lenox, MA
40. Guss DB (1978) Closed water systems in mills using secondary fiber. TAPPI J 61(6):19–22
41. Panchapakesan B (2001) Optimizing white water system design improves runability, lowers operating cost, Paper Age, Apr 2001
42. Geller A, Gottsching L (1982) Closing water systems completely in the Federal Republic of Germany. TAPPI J 65(9):97
43. Wang LK, Wu Z, Shammas NK (2009) Trickling filters. In: Wang LK, Pereira NC, Hung YT and Shammas NK (eds) Biological treatment processes. Humana Press, Inc., Totowa, NJ, pp 371–458
44. Niemelä SL, Väätänen P (1983) Factors regulating the density of bacteria in process waters of a paper mill. J Appl Bacteriol 54(3):367–371
45. Gassinger J (1980) Use of calcium sulfate – effects on closed systems, ATIP Congress. Grenoble, 33d, p 18, 25–27 Mar [Fr]
46. Water and Agro-Industry (2009) Efficient water use in agro-based industries – pulp and paper. Water and Agro-Industry, India. http://www.waterandagroindustry.org/pulp_paper.htm
47. Bier TH, Mattison RJ (1974) Fiber recovery increases water reuse and reduces treatment costs. TAPPI J 57(4):66–70
48. U.S. EPA (1993) Development document for proposed effluent limitations guidelines and standards for the pulp, paper and paperboard point source category. United States Environmental Protection Agency EPA-821-R-93–019, Office of Water, Washington, DC
49. Ekono Inc (2005) Environmental performance, regulations and technologies in the pulp and paper industry. Strategic Study, Bellevue, WA, Aug
50. Allen DG, Reeve DW, Liss SN (2004) Minimizing the impact of pulp and paper mill discharges. Year Four Report, Prepared for Consortium Members, Pulp & Paper Centre, University of Toronto, Apr
51. UNEP (1987) Pollution Abatement and Control Technology (PACT). United Nations Environment Program, Publication for the Pulp and Paper Industry, UNEP Industry and Environment Information Transfer Series, Paris
52. UNIDO (1992) Draft pulp and paper industrial pollution guidelines. United Nations Industrial Development Organization, Vienna, Austria
53. World Bank (1998) Pollution prevention abatement: pulp and paper mills. Project Guidelines: Industry Sector Guidelines. Environment Department, Washington, DC, July
54. MIGA (1998) Environmental guidelines for pulp and paper mills. Multilateral Investment Guarantee Agency, Pollution Prevention and Abatement Handbook, World Bank, pp 489–495
55. Environmental Pollution Controls in the Taiwan Paper Industry (2010) Taiwan environmental enterprize database. Taiwan Green Productivity Foundation. http://www.environet.org.tw/e-04envr05–0111.asp
56. Landin M (1988) Treatment of paper mill whitewater for resource recovery and reuse. MS Thesis, Lenox Institute of Technology, Lenox, MA
57. Bachand JP, Hagerty GA (1981) Gravity straining of white water minimizes shower nozzle plugging. Pulp Pap 55(4):103

58. Hoinonoff EC, Rodmari CA (1981) Novel approach to automotive filtration. Proceedings of TAPPI paper synthetics conference, Chicago, 14–16 Sept 1981, pp 97–108
59. Ragnegaard S (1981) Method and filter for separating particles from a liquid suspension. PCT patent 359/81, Issued 19 Feb 1981. C1.BO1D37/02. Priority: Sweden application 6743/79, 13 Aug 1979
60. Fremont HA (1981) Method of removing fine suspended materials from effluent streams. US patent 4,303,533, Issued 1 Dec 1981. Filed US application 154800, 30 May 1980
61. Doshi MR, Trettin DR (1981).Ultrafiltration of colloidal suspensions and macromolecular solutions in an unstirred batch cell. I & EC Fundam 20(3):221–229
62. Tardif O, Hall ER (1997) Alternatives for treating recirculated newsprint whitewater at high temperatures. Water Sci Technol 35(2–3):57–65
63. New Logic International, Inc (1999) Application note: end of pipe effluent treatment for pulp and paper mill. Emeryville, CA. http://www.vsep.com, Jan 1999
64. Shammas NK, Chang CC, Wang LK (2006) Tertiary microscreening. In: Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical treatment processes. Humana Press, Inc., Totowa, NJ, pp 191–202
65. Chen JP, Mow H, Wang LK, Matsuura T (2006) Membranes filtration. In: Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical treatment processes. Humana Press, Inc., Totowa, NJ, pp 203–260
66. Hysek M (1981) Prevention of plugging of paper machine shower nozzles. Papir Celuloza 36(4):76–78 [Czech]
67. Shammas NK, Kumar IJ, Chang SY (2005) Sedimentation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Inc., Totowa, NJ, pp 279–430
68. Shammas NK (2005) Coagulation and flocculation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Inc., Totowa, NJ, pp 103–140
69. Carter CN, Sigler RG (1981) Clay/polymer vs. alum treatment in a solids contact clarifier for mill process water. TAPPI J 64(9):135–139
70. Doblanzki P et al (1981) Precipitation and flocculation as possible white water treatment. Wochbl Papierfabr 109(16):563–566, 31 Aug [Ger]
71. Golikova TG (1981) Method of purifying green or white liquor. U.S.S.R. patent 870,540, Issued 7 Oct 1981. Filed U.S.S.R. application 2866736/29–12, 8 Jan 1980
72. Nyaradi Z, Szalay A (1980) Results of paper mill effluent clarification at the Dunaujvaros paper mill. Papiripar 24(5):179 [Hung]
73. Svitellskii VP et al (1981) Method of treating aqueous-fibrous effluents from production of paper. U.S.S.R. patent 861,452, Issued 7 Sept 1981. Filed U.S.S.R. application 2095286/29–12, 6 Jan 1975
74. Wang LK, Fahey EM, Wu Z (2005) Dissolved air flotation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Inc., Totowa, NJ, pp 431–500
75. Wang LK (2006) Adsorptive bubble separation and dispersed air flotation. In: Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical treatment processes. Humana Press, Inc., Totowa, NJ, pp 81–122
76. Shammas NK, Wang LK, Hahn HH (2010) Fundamentals of wastewater flotation. In: Wang LK, Shammas NK, Selke WA, Aulenbach DB (eds) Flotation technology. Humana Press, Totowa, NJ
77. Krofta M, Wang LK (2000) Flotation engineering, 1st edn. Technical Manual No. Lenox/1–06–2000/368. Lenox Institute of Water Technology, Lenox, MA

78. Krofta M, Wang LK (1999) Flotation and related adsorptive bubble separation processes, 4th edn. Technical Manual No. Lenox 7–25–1999/348. Lenox Institute of Water Technology, Lenox, MA
79. Furukawa Y (1973) On the application of polyelectrolytes to white water treating by dissolved air flotation. Jpn TAPPI 27(8):384–393
80. Miyamae H (1981) Recovery of calcium carbonate in white water. Japan patent kokai 101,992/81, 14 Aug 1981. C1.D21F1/82. Filed Japan application 1373/80, 11 June 1980
81. Backaeva EM (1979) Wastewater treatment in the production of synthetic papers. Vodopollzoyanie, Ochistka Stochnykh Vod. Util. Osadkov 51–56 [Russ]
82. Gehr RI, Henry JG (1981) Upgrading the dissolved air flotation process. Mid Atlantic industrial waste conference, University of Delaware, 13 June 29–30, pp 386–395
83. Lewandowska K (1980) Separation and thickening of paper mill effluent suspended solids by flotation. Przeylad Papier 36(3):3 [Pol]; ABIPC 51:8714 (1981)
84. LIWT (1982) Laboratory Notes, Lenox Institute of Water Technology, Lenox, MA, Project Number R81PO1-SORG, May 1982
85. Wenta B, Hartman B (2002) Dissolved air flotation system improves wastewater treatment at Glatfelter. Pulp Paper 2002(3):2
86. Robinson JV (1976) Optical properties of paper as affected by wet end chemistry. TAPPI J 59(2): 77–82, Feb
87. Ducey MJ (1987) Coating and filler pigment market rides the industry production wave. Pulp Paper 1987(5):102
88. Scott WE (1987) Filler research studies improve papermaking applications. American Papermaker 12–14, May
89. Howard GJ (1983) The influence of polymers on the light scattering pf titanium dioxide pigment in paper. TAPPI J 66(6):87–91
90. Alince B, Lepoutre P (1981) Light-scattering of filled sheets: the effect of pigment dispersion. TAPPI J 64(11):117–118
91. Miller ML, Paliwal DC (1985) The effects of lumen – loading on strength and optical properties of paper. J Pulp Pap Sci 11(3):84–88
92. Frankle WE, Sheridan JL (1976) Value of first pass retention. TAPPI J 59(2):84
93. Scott WE (1986) Fines management and control in wet end chemistry. TAPPI J 69(11):30–34, Nov
94. Britt KW (1986) Observations on water removal in paper making. TAPPI J 69(7):76
95. Davison RW (1983) Mechanism of fine-particle retention in paper. TAPPI J 66(11):69–72
96. Ama JN (1974) Zeta potential and its application to filler retention. TAPPI J 57(12):97–100
97. Strazdins E (1984) Chemical aids can offset strength loss in secondary fiber furnish use. Pulp Paper 1984(3):73–77
98. Ford PA (1987) Possible ways of identifying and measuring the effect of disturbing substances on wet end chemistry. TAPPI papermakers conference proceedings, pp 147–151
99. Springer AM, Strutz MD (1982) A wet end optimization strategy for total water reuse. TAPPI J 65(3):139
100. Britt KW (1981) Interference in the use of retention aids. TAPPI J 64(11):55
101. Bozkov I (1981) Two-component polymer systems for increasing filler retention in paper. Zellstoff Papier 30(6):280–282, Nov/Dec [Ger]
102. Unanimous (1987) Procomp’s total system wet end approach. American papermaker 1987(5): 40–41, May

103. Waech TG (1983) Improving filler retention by adding filler after retention aid addition. TAPPI J 66(3):137–139, Mar
104. Sikora MD, Stratton RA (1981) The shear stability of flocculated colloids. TAPPI J 64 (9):97–101
105. Scbwalbe HC (1962) Fillers and loading, Chapter 3. In: Libby CE (ed) Pulp and paper science and technology, vol 2. McGraw-Hill, New York, NY, p 64
106. Uono M, Endo S, Kawano M, Kimura T (1980) Improvement of surface strength of paper. Kimura, Kyoritsu Research Institute of Organic Industry Ltd., Mitsubishi Paper Mfg. Co. Ltd., Japan patent Kokai 163,298/80, 19 Dec 1980, 6p, Cl.D21H3/78, Filed: Japan application 70,381/79, 5 June 1979
107. Kamphorst BJ (1981) Control of Total Ash, Titanium Dioxide, and Calcium Carbonate with Sentrol's 'Poly-Ash' Ash Sensor, CPPA Annual Meeting (Montreal), Preprints 67B, 27–30 Jan 1981, pp 187–190
108. Shibazaki K, Edagawa S (1981) Pigment-coated paper. Shira-ishi Industry Ltd., Japan patent Kokai 68,187/81, 8 June 1981, 6p, C1.D21H1/22, Filed: Japan application, 88,073/78, 13 June 1978
109. Smaine LH (1981) What the papermaker does to get opacity. TAPPI papermakers conference proceedings, P. H. Glatfelter Co., Chicago, 6–8 Apr 1981, pp 203–204
110. Olson RA (1980) Methods of making combined titanium dioxide and calcium carbonate and opaque paper containing the resulting combination. P. U. Glatfelter Co., Canada patent 1,085,564, Issued 16 Sept 1980, 10 claims, 20p. Cl.9–67, Filed: Canada application, 254,413, 9 June 1976, Priority: US application, 605,216 15 Aug 1975
111. Koppelman MH (1981) Effect of clay and titanium dioxide extenders on paper opacity. TAPPI papermakers conference proceedings, Chicago, 6–8 Apr 1981, p 197
112. Vasil'eva EI, Trukhtenkova NE, Reznikova PP (1976) Retention of titanium dioxide and red ferric hydroxide pigment in neutral and weakly alkaline media. Sb. Tr. VNII Tsellyu1-Bumazh, Prom (Issled. Oblasti Khim. Tekhnol, Proizvod, Bumagi Kartona) 69:34–41 [Russ]
113. Jaycock MJ, Nazir BA (1978) Deposition of fillers on cellulose surfaces. SCI, symposium on deposition and filtration of particles from gases and liquids. Society of Chemical Industry, London, pp 171–181
114. Kock V, Luciani M (1979) Increasing retention on the machine: contribution to the solution of problems with papermaking effluents. Imballagio 283:118–121, 141 [Ital]
115. Itoh Oil Mfg. Co. Ltd. (1980) Manufacture of amide amines. Japan patent Kokat 118,925/80, 12 Sept 1980. 3p. Cl.C08G73/00 Filed: Japan application 26,010/79, 6 Mar 1979, from: C.A. 94, no. 6, abstr., 32, 336, 9 Feb 1981
116. Linck E (1980) Reflections on theory of waste paper dispersion. Allg Papier-Rundschau 24/25:724–726, 20 June 1980 [Ger]
117. Raczynska Z (1980) Optimization of filler retention by chemical additives. Zellstoff Papier 29(5):206–212, Sept/Oct 1980 [Ger]
118. Trombetta JC (1980) Importance of retention aids to paper making efficiency. ATIPCA 19(1):32, 34–36, 38, Feb/Mar 1980 [Span]
119. Lobach W, Kolb G, Lehmann W, Cramm G, Muller F, Muszik J, Bayer AG (1981) Urea group-containing polyamines as well as their manufacture and use as retention aids. German patent 2,925,567, Dos 22 Jan
120. Pelton RH, Allen LH, Nugent HM (1960) Factors affecting the effectiveness of some retention aids in newsprint pulp. Svensk Papperstid 83(9):251–258

121. Dyer DA, Meyer H, Nelson RW (1981) Retention dynamics for small particles on cylindrical fibers (2) experimental verification of a model simulating particle retention. Paperi Puu 63 (1):11–12, 14–16
122. Parker PE (1981) Dysco, a modular dynamic simulator for the pulp and paper industry. Proceedings of TAPPI annual meeting, Chicago, 2–5 Mar 1981, pp 215–219; Tappi 64(3):97–101, Mar 1981
123. Britt KW (1981) Paper sheet formation: observations concerning retention. TAPPI J 64(5):53–55
124. McKenzie AW, Davies GW (1971) The Structure and properties of paper – the retention and optical effects of titanium dioxide. Appita 25(1):32–39
125. Wang LK, Rivero de Aguilar JC, Wang MHS (1979) Pulp and paper mill wastewater, Part I: management and planning aspects. J Environ Manage 8:13–24
126. Wang MHS, Wang LK, Rivero de Aguilar JC (1979) Pulp and paper mill wastewater, Part II: environmental control aspects. J Environ Manage 8:25–42
127. Schirtzinger MM (1979) Paper mill water treatment and reuse system for zero discharge. Proceedings of industrial waste conference, vol 34. Purdue University, pp 594–599
128. Guss DB (1980) Clarification of alkaline deinking effluents. Proceedings of the technical association of the pulp and paper industry, pp 177–180. TAPPI, www.tappi.org.
129. Guss DB (1978) Closed water systems in mills using secondary fiber. TAPPI J 61(6):19–22
130. Brecht WH, Dalpke L, Borner F (1973) Investigation of closed water systems in another waste paper processing paper plant. Technical Report, Institute of Papermaking, Technical University, Darmstadt, Germany, pp 113–119
131. Hashimoto T, Teranishi K (1980) Treatment of reclaimed paper. Japan patent Kokai 76,184/80, 9 June 1980, 6p. C1.D21B1/32. Filed: Japan application 148,293/78, 29 Nov 1978
132. Stratton RA, Swanson JW (1980) Mill trial of the enzyme treatment of starch-containing broke. Proceedings of TAPPI papermakers conference Atlanta, 14–16 Apr 1980, pp 151–159
133. Frost AW III (1980) Method of treating papermaking whitewater. U.S. patent 4,221,634, Issued 9 Sept 1980, 5 claims, 10p., Cl.162/l90, Filed US application 13,088, 21 Feb 1979
134. Nyaradi Z, Szalay A (1980) Results of paper-mill effluent clarification at the Danaujvaros Paper Mill. Papirpar 24(5):179–183 [Hung]
135. Kolb W (1980) Purification and deaeration of paper pulps with chemical aids. Allg Papier-Rundschau 9(218):220, 5 Mar [Ger]
136. Bendiner B, Margolis BI (1980) Baled WASTE paper product containing a deinking chemical. US patent 4,229,493, Issued 21 Oct 1980, 11 claims 4p., Cl.428/2, Filed: US application 34,685, 30 Apr 1979
137. Takenaka M, Yano K, Hosokawa S, Fukutake S, Nojima K (1980) Treatment of pulp waste water. Japan patent Kokai 35,965/80, 13 Mar 1980, 3p. Cl.CO2F1/52. Filed: Japan application 110,105/78, 6 Sept 1978
138. Lightsey GR, Hall WB (1979) Control of foaming in pulp and paper mill white water. Mississippi State University, NTIS Report PB80–112741, Oct
139. Mobius H (1980) Possibilities of physicochemical treatment of circulating and waste Waters. Wochb1, Papierfabr 108(16):617–620, 31 Aug [Ger]
140. Williams W (1980) Recycling in the 80's: Paper [magazine] sees strong potential for profit and for problems as well, Paper, 193, 12, 32–34, 38, 40–42, 44, 46–48, 52, 54, 56, 58, 60, 62, 66, 68–69, 73–74, 76, London, 23 June 1980
141. Volkov VV, Kovaleva VL (1980) System for water usage and effluent purification at the Leningrad board mill. Bumazh Prom 6:5–6, June [Russ]

142. Rubin AJ, Haberkost DC (1973) Coagulation and flotation of colloidal titanium dioxide. Sep Sci 8(3):363–373
143. Krofta M, Wang LK, Wu BC (1983) Recovery of titanium dioxide and secondary fibers from whitewater. Technical Report. U.S. Department of Commerce, National Technical Information Service, Springfield, VA, June
144. Krofta M, Wang LK (1983) Recent advances in titanium recovery filler retention and whitewater treatment. Technical Report, LIR/06–83/1. U.S. Department of Commerce, National Technical Information Service, Springfield, VA, June
145. Wang LK, Hung YT, Shammas NK (eds) (2005) Physicochemical treatment processes. Humana Press, Totowa, NJ, 723
146. Wang LK, Hung YT, Shammas NK (eds) (2006) Advanced physicochemical treatment processes. Humana Press, Inc., Totowa, NJ, 690
147. Wang LK, Hung YT, Shammas NK (eds) (2007) Advanced physicochemical treatment technologies. Humana Press, Inc., Totowa, NJ, 710
148. Wang LK, Wang MHS, Suozzo T, Dixon RA, Wright TL, Sarraino S (2009) Chemical and biochemical technologies for environmental infrastructure sustainability. 2009 National engineers week conference, Albany Marriott, Albany, NY, 5–6 Feb 2009
149. Wang LK, Guss D, Krofta M (2010) Kinetics and case histories of activated sludge secondary flotation systems. In: Handbook of advanced industrial and hazardous wastes treatment. CRC Press, Boca Raton, FL, pp 1155–1190
150. Shammas NK (2010) Waste management in the pulp and paper industry. In: Handbook of advanced industrial and hazardous wastes treatment. CRC Press, Boca Raton, FL, pp 857–912
151. Gale R (2005) Environmental costs at a Canadian paper mill: a case study of environmental management accounting (EMA). J Cleaner Prod 1–15
152. White A, Savage D, Dierks A (1995) Environmental accounting: principles for the sustainable enterprise. 1995 TAPPI international environmental conference, Atlanta Georgia, 7–10 May 1995. TAPPI J, www.tappi.org
153. U.S. EPA (2006) A specialty paper mill. Environmental Accounting Project, US Environmental Protection Agency, Washington, DC

8

Ozone–Oxygen Oxidation Flotation

Lawrence K. Wang and Nazih K. Shammas

CONTENTS

Abstract Oxyozosynthesis is a pressurized ozone–oxygen oxidation flotation process, which involves the use of ozone and oxygen as the oxidation agents for stabilization of wastes in a pressurized reactor to expedite the oxidation process. The wastes can be either a wastewater stream or a sludge stream (biosolids stream). Since the oxidation reactions occur under high pressure, the ozone and oxygen gases are forced to dissolve in the aqueous phase although these gases are also converted mainly into carbon dioxide gas after the chemical reactions. Subsequent release of the oxidized waste stream to a flotation reactor results in efficient water–solid separation and solids concentration due to the release of previously pressurized CO_2 and O_2 bubbles into atmosphere pressure. Dissolved air flotation (DAF) can be added to Oxyozosynthesis for expediting the water–solid separation process. This chapter introduces two Oxyozosynthesis process systems: (a) Oxyozosynthesis sludge management system and (b) Oxyozosynthesis wastewater reclamation system. The engineering topics cover the process descriptions, ozone formation and generation, ozonation requirements and equipment, ozonation, oxygenation, disinfection, stabilization, oxidation flotation, process performance, design criteria, and case history.

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Key Words Oxyozosynthesis • sludge treatment • wastewater treatment • biosolids treatment • ozonation • oxygenation • oxidation • disinfection • stabilization • pressurized reactor • dissolved gas flotation • dissolved air flotation • DAF • ozone–oxygen oxidation flotation.

1. INTRODUCTION

Increasing populations and improving standards of living are placing increasing burdens on water resources. The preservation of our limited natural water supplies and, in the not too distant future, the necessity for direct recycling of water in some parts of the world will demand improved technology for the removal of contaminants from wastewater.

The contaminants in wastewater are many and continually varying and they are not well characterized according to chemical species. Commonly, the level of organic contamination is expressed by biological oxygen demand (BOD), chemical oxygen demand (COD), or total organic carbon (TOC). Ozone and oxygen are powerful oxidants, which can oxidize many contaminants in wastewater and sludge biosolids. Ozone is more powerful than oxygen, but it is an unstable material, which must be generated at the point of use.

Ozone has been used for disinfecting drinking water in European countries for many years. It has also been used for treating some special industrial wastes, notably for removing cyanides and phenols. Since 1980, ozone started to be used for wastewater, industrial wastes, and sludge treatment on a large scale (1–6). Oxidative purification and disinfection with ozone as a tertiary wastewater treatment or sludge treatment has a number of inherent advantages:

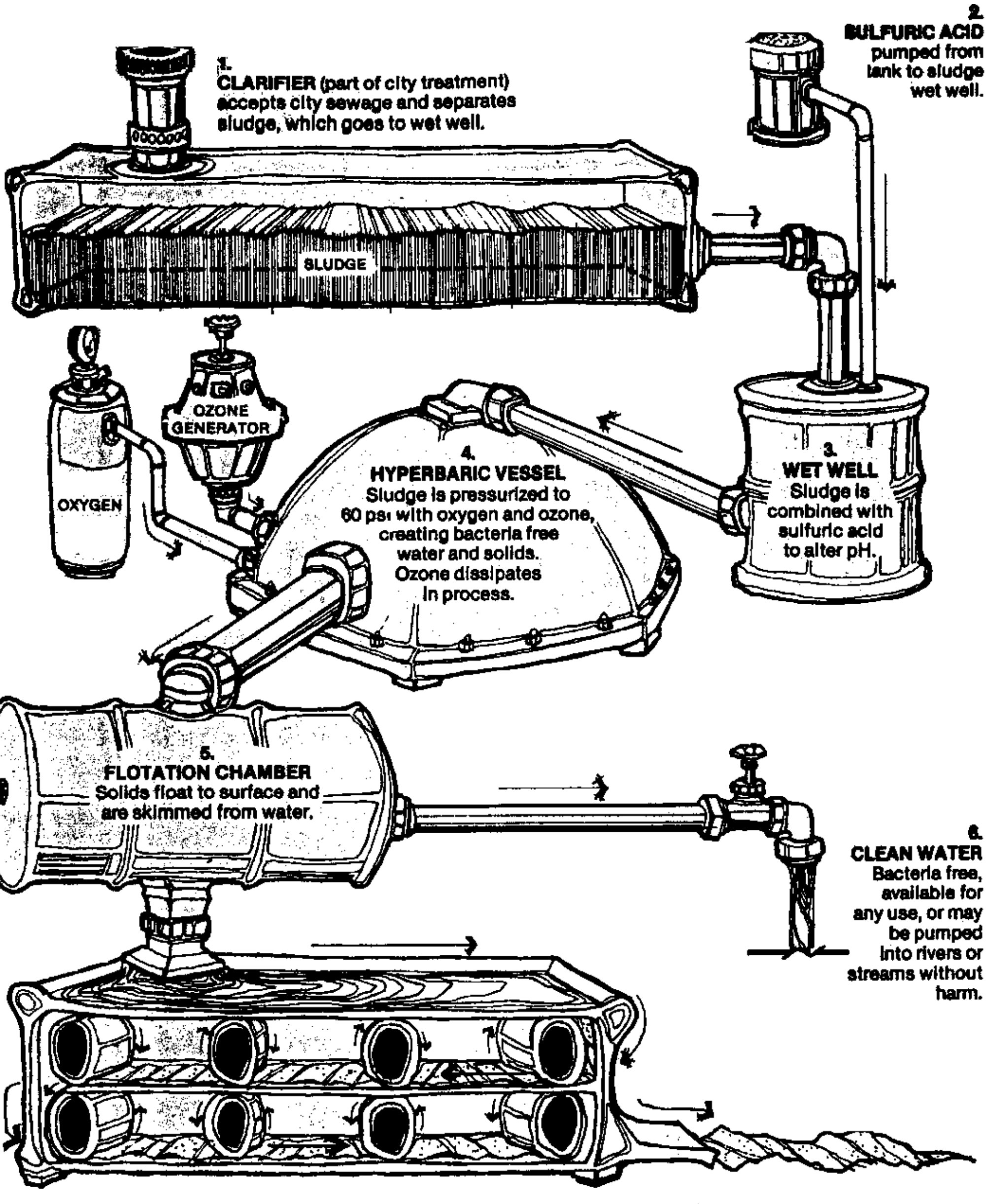
(a) Reduction in BOD and COD
(b) Reduction of odor, color, turbidity, and surfactants
(c) Pathogenic organisms are destroyed
(d) The treatment products are beneficial
(e) The effluent water has a high dissolved oxygen (DO) concentration

The relative high cost of ozone generation requires a high ozone-utilization efficiency if ozone treatment is to be economically competitive. A principal disadvantage to the use of ozone in waste treatment is its cost. However, recent advances in ozone generation have rendered the ozonation process more competitive.

This chapter deals with two newly developed oxygenation–ozonation (Oxyozosynthesis) systems for wastewater and sludge treatment. Each treatment scheme consists of a wet well for flow equalization and pH adjustment, a hyperbaric reactor for oxygenation and ozonation, a flotation clarifier for degasification and solid–water separation, and a filter belt press for final sludge dewatering. Special emphasis is placed on theory, kinetics, and disinfection effect of ozonation and oxygenation (7–12).

1.1. *Oxyozosynthesis Sludge Management System*

As shown in Figs. 8.1 and 8.2, the new sludge management system consists of the following unit operations and processes: sludge production from clarifiers, flow equalization



1\. **CLARIFIER** (part of city treatment) accepts city sewage and separates sludge, which goes to wet well.

2\. **SULFURIC ACID** pumped from tank to sludge wet well.

3\. **WET WELL** Sludge is combined with sulfuric acid to alter pH.

4\. **HYPERBARIC VESSEL** Sludge is pressurized to 60 psi with oxygen and ozone, creating bacteria free water and solids. Ozone dissipates in process.

5\. **FLOTATION CHAMBER** Solids float to surface and are skimmed from water.

6\. **CLEAN WATER** Bacteria free, available for any use, or may be pumped into rivers or streams without harm.

7\. **BELT PRESS** dries mud-like solids which emerge as a dry, paper type fuel called "croal" (compressed residual oxyozosynthesis altered litter).

8\. **CROAL** is a dry, inert fuel which burns like wood or soft coal at over 7500 BTU.

Fig. 8.1. General view of oxygenation–ozonation (Oxyozosynthesis™) system.

and pH adjustment in a wet well, oxygenation–ozonation in a hyperbaric reactor vessel (Fig. 8.3), flotation, dewatering in a belt press, and resource recovery of final product as fuel or for land application.

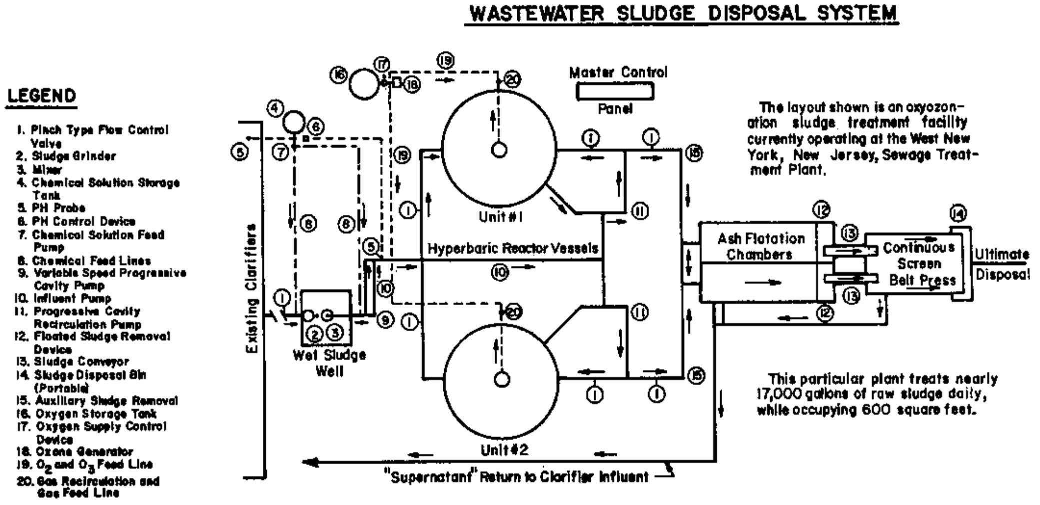


Fig. 8.2. Flow diagram of Oxyozosynthesis™ sludge management system.

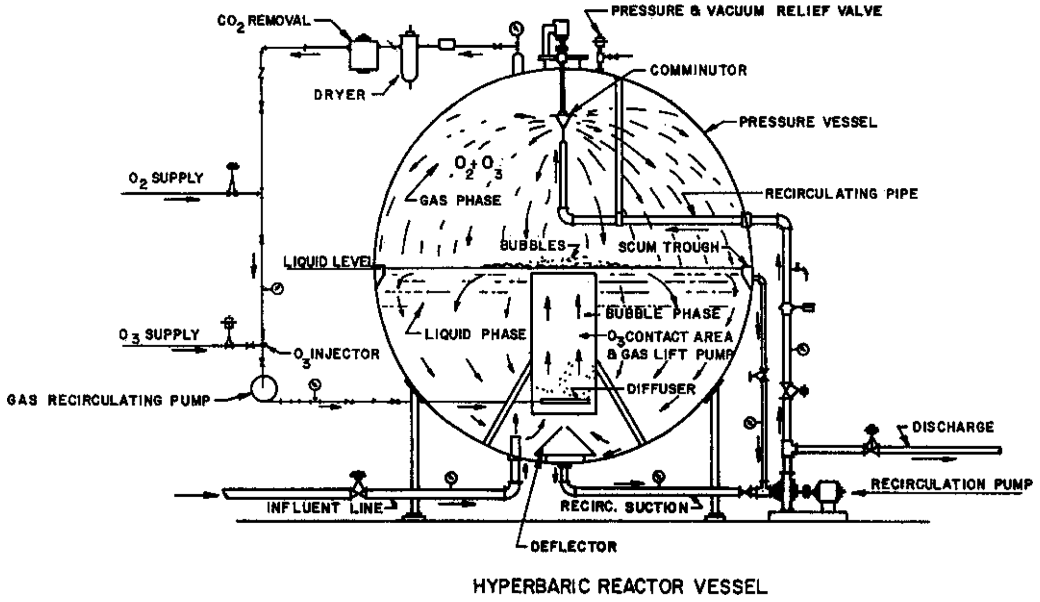


Fig. 8.3. The hyperbaric reactor vessel.

A full-scale Oxyozosynthesis sludge management system was installed at the West New York Sewage Treatment Plant, West New York, NJ, USA. The plant treats domestic wastewater flow of 10 MGD and produces 22,000 gpd of primary sludge. Primary raw sludge is pumped from sumps located at the bottom of the primary sedimentation clarifiers by means of two positive displacement pumps to a sludge grinder, then to the wet well. As the wet well is filled with grinded sludge, a 10% sulfuric acid solution is added to adjust the pH to a 3.5–4.0 value by a chemical metering pump. A mechanical mixer and a pH meter are mounted on the wet well for proper mixing and pH monitoring, respectively. Following acidification, the sludge is pumped by a progressive cavity pump to one of the two batch-operated hyperbaric reactor vessels, each capable of treating 1,500 gallons of sludge in 90 min by oxygenation and ozonation. To start up each reactor vessel, the pressure in the reactor is built up to 40 psig with liquid oxygen first and then up to 60 psig with ozone. There are two operational modes:

(a) Continuous oxygenation–ozonation:
After the startup with oxygen and ozone, ozone is continuously fed into the reactor for a total of 90 min. The pressure is maintained at 60 psig by bleeding off (or recycling) the excess gas.

(b) Noncontinuous oxygenation–ozonation:
After the startup with oxygen and ozone, ozone is shut off to let the reactor be isolated and maintained as such for 90 min.

During the 90 min contact time in the oxygenation–ozonation reactor, pathogenic bacteria, viruses, total suspended solids, and volatile suspended solids in the sludge are significantly reduced. The reactor effluent is then released (at a flow rate of approximately 1,500 gallons per 90 min) into an open flotation unit where dissolved oxygen, ozone, and carbon dioxide gases come out of solution and form tiny bubbles, which adhere to the residual suspended solids causing them to float and get thickened at the top of the unit. The flotation unit is equipped with revolving paddles (or scoops) that transport these floating solids onto a subsequent filter belt press for sludge dewatering. The subnatant liquor is recycled to the head of the sewage treatment plant for further treatment with the incoming wastewater flow.

The filter belt press produces a dry high-nutrient sludge cake with low metal content and high BTU value. The sludge cake can be recycled by spreading on agricultural land, reused as a fuel source, or disposed off in landfill. The dry sludge can also be reused as secondary fiber in paper manufacturing or as raw material for building blocks.

1.2. Oxyozosynthesis Wastewater Reclamation System

As shown in Fig. 8.4, the new wastewater reclamation system consists of the following unit operations and processes: wastewater collection and preliminary treatment (bar screens and grit chambers), flow equalization and pH adjustment in a wet well, oxygenation–ozonation in a hyperbaric reactor vessel, dissolved gas flotation (DGF), and filtration.

A pilot-scale Oxyozosynthesis wastewater reclamation system was installed at the Lenox Institute of Water Technology, Lenox, MA, USA. The pilot plant treats a wastewater flow of 6 gpm and produces small amount of sludge. Raw wastewater is pumped from sumps located at the bottom of the grit chambers by means of positive displacement pumps to a wet well. As the wet well is being filled with the raw wastewater, a 10% sulfuric acid solution is added to adjust the pH to a 3.5–4.0 value by a chemical metering pump. A mechanical mixer and a pH meter are mounted on the wet well for proper mixing and pH monitoring, respectively.

From the wet well, a progressive cavity pump delivers the acidified wastewater to a batch-operated hyperbaric reactor vessel capable of treating 100 gallons of wastewater in

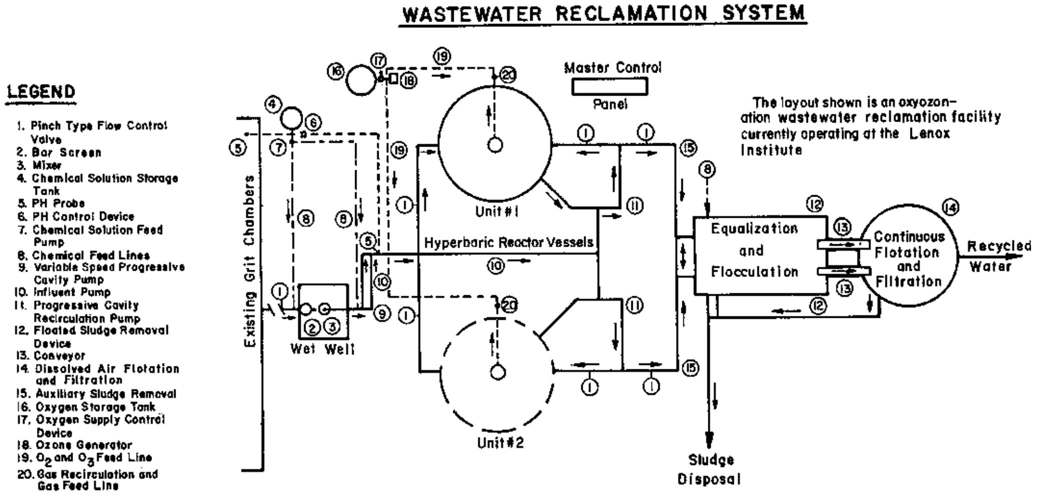


Fig. 8.4. Flow diagram of Oxyozosynthesis wastewater reclamation system.

30–60 min depending on the characteristics of the wastewater. To start up the reactor vessel, the pressure in the reactor is built up to 40 psig with liquid oxygen first and then up to 60 psig with ozone. There are two operational modes:

(a) Continuous oxygenation–ozonation:
After the startup with oxygen and ozone, ozone is continuously fed into the reactor for a total of 30–60 min. The pressure is maintained at 60 psig by bleeding off (or recycling) the excess gas.

(b) Noncontinuous oxygenation–ozonation:
After the startup with oxygen and ozone, ozone is then shut off to let the reactor be isolated and maintained as such for 30–60 min.

During the 30–60 min contact time in the oxygenation–ozonation reactor, pathogenic bacteria, viruses, total suspended and volatile suspended solids, phenols, cyanides, manganese, etc. in wastewater are all significantly reduced. The reactor effluent is released into a DGF unit where flocculant(s) can be added and the dissolved gases come out of aqueous phase forming tiny bubbles, which adhere to the flocs and residual suspended solids causing them to float at the top of the unit. Heavy metals, iron, phosphate, humic acids, hardness, toxic volatile organics, etc. all react with the flocculant(s) to form insoluble flocs that are floated. The flotation unit is equipped with revolving paddles (or scoops) that transport these floating solids onto a subsequent filter belt press for final sludge dewatering. A dual-media filter further polishes the subnatant clarified water.

The filter effluent quality is not far from that of potable water, having extremely low color, turbidity, suspended solids, hardness, iron, manganese, trihalomethane precursor (humic acid), heavy metal, volatile organics, phenol, cyanide, etc. The product water is suitable for reuse for industrial and agricultural purposes. Further treatment of the final filter effluent by adsorption on activated carbon is optional.

2. DESCRIPTION OF PROCESSES

2.1. Ozonation and Oxygenation Process

Ozone gas is sparingly soluble in water. The solubility of ozone in water increases with its increasing partial pressure, decreasing water pH, and decreasing temperature. Oxidation rate, however, increases with increasing temperature. For economic operation of the hyperbaric oxygenation–ozonation reactor, it is operated at room temperature and pressure in the range of 40–60 psig, and the influent liquid sludge pH is reduced with sulfuric acid down to a value in the range of 3.5–4.0.

The addition of oxygen at 40 psig and ozone at 60 psig ensures proper partial pressures for solubilizing both oxygen and ozone gases in the sludge. Both dissolved oxygen and ozone act to chemically oxidize reducing pollutants found in the liquid sludge, thus reducing BOD and COD, which results with the formation of oxygenated organic intermediates and end products. Ozonation–oxygenation treatment also reduces color and odor in waste sludge.

Because there is a wide range of ozone reactivity with the diverse organic content of wastewater, both the required ozone dose and reaction time are dependent on the quality of the influent to the ozonation process. Generally, higher doses and longer contact times are required for ozone oxidation reactions than are required for wastewater disinfection using ozone. Ozone tertiary treatment may eliminate the need for a final disinfection step. Ozone breaks down to elemental oxygen in a relatively short period of time (its half-life is about 20 min). Consequently, it must be generated on site using either air or oxygen as the feed gas. Ozone generation utilizes a silent electric arc or corona through which air or oxygen passes and yields ozone in air/oxygen mixture, the percentage of ozone being a function of voltage, frequency, gas flow rate, and moisture. Automatic devices are commonly applied to control and adjust the ozone generation rate.

>For sludge treatment or wastewater reclamation, it is a developing technology. Recent developments and cost reduction in ozone generation and ozone dissolution technology make the process very competitive. A full-scale application is currently in the demonstration stage at the West New York Sewage Treatment Plant, West New York, NJ. If oxygen-activated sludge is employed in the system, ozone treatment may be even more economically attractive, since a source of pure oxygen is available facilitating ozone production.

For poor quality wastewater or sludge with extremely high COD, BOD, and/or TOC contents ($>$300 mg/L), ozone treatment can be economical only if there is adequate pretreatment. The process will not produce any halogenated hydrocarbons. Table 8.1 shows the reduction of overall COD, BOD, and TOC, achieved in the U.S. EPA controlled tests after a 90 min contact time with ozone oxidation. Beyond the 70% COD removal level, the oxidation rate is significantly slowed. In laboratory tests, COD removal never reaches 100% even at a high ozone dose of 300 mg/L.

As a disinfectant with common dosages of 3–10 mg/L, ozone is an effective agent for deactivating common forms of bacteria, bacterial spores, and vegetative microorganisms found in wastewater as well as eliminating harmful viruses.

Table 8.1
Effectiveness of ozone as an oxidant (Source: U.S. EPA)

Ozone dosage (mg/L)	COD (mg/L)		BOD_5 (mg/L)		TOC (mg/L)	
	Influent	Effluent	Influent	Effluent	Influent	Effluent
50	318	262	142	110	93	80
100	318	245	142	100	93	77
200	318	200	142	95	93	80
325	318	159	142	60	93	50
50	45	27	13	7	20.5	15.5
100	45	11	13	3	20.5	9
200	45	5.5	13	1.5	20.5	5

Table 8.2
Effectiveness of ozone as a disinfectant (Source: U.S. EPA)

Source	Influent	Dose (mg/L)	Contact time (min)	Effluent residual
U.S. EPA	Secondary effluent	5.5–6.0	≤ 1	<2 fecal coliforms/100 mL
U.S. EPA	Secondary effluent	10	3	99% inactivation of fecal coliform
U.S. EPA	Secondary effluent	1.75–3.5	13.5	<200 fecal coliforms/100 mL
U.S. EPA	Drinking water	4	8	Sterilization of virus
WNYSTP	Primary sludge	NA	60	Over 99% inactivation of fecal coliform
SIT/LI	Secondary sludge	NA	60	Over 99% inactivation of fecal coliform

Additionally, ozone acts to chemically oxidize materials found in the wastewater and sludge, forming oxygenated organic intermediates and end products. Further, ozone treatment reduces wastewater color and odor. Ozone disinfection is applicable in cases where chlorine disinfection may produce potentially harmful chlorinated organic compounds. If oxygen-activated sludge is employed in the system, ozone disinfection is economically attractive, since a source of pure oxygen is available facilitating ozone production. Ozone disinfection, however, does not form a residual that will persist and can be easily measured to assure adequate dosage. Ozonation may not be economically competitive with chlorination under nonrestrictive local conditions.

Easily oxidizable wastewater organic materials consume ozone at a faster rate than disinfection; therefore, effectiveness of disinfection is inversely correlated with effluent quality but directly proportional to ozone dosage. When sufficient concentration is introduced, ozone is a more complete disinfectant than chlorine. Results of disinfection by ozonation have been reported by various sources, which are summarized in Table 8.2.

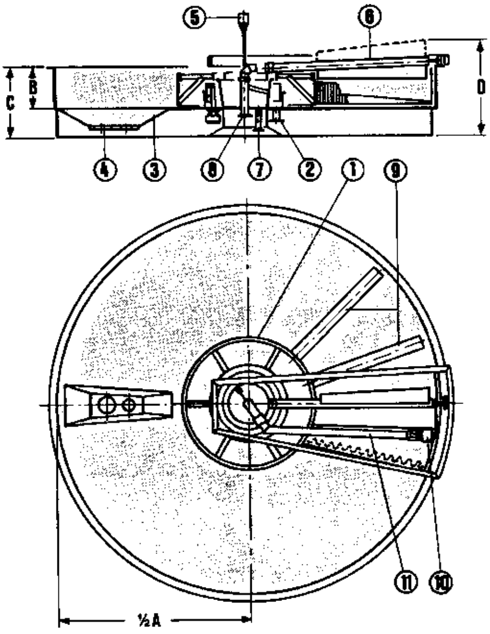
2.2. *Flotation Process*

Dissolved gas flotation is mainly used to remove suspended and colloidal solids by flotation resulting from the decrease in their apparent density. The influent feed liquid can be raw water, wastewater, or liquid sludge.

The flotation system consists of four major components: gas supply, pressurizing pump, retention tank, and flotation chamber. According to Henry's law, the solubility of gas in aqueous solution increases with increasing pressure. A pressurizing pump is used to saturate the feed stream with gas at pressures several times the atmospheric pressure (25–70 psig). The pressurized feed stream is held at this high pressure for about 0.5–3.0 min in a retention tank (hyperbaric vessel) designed to provide the required time for dissolution of gas into the treatment stream. Following the retention vessel, the stream is released back to atmospheric pressure in the flotation chamber. Most of the pressure drop occurs downstream from a pressure-reducing valve and in the transfer line between the retention vessel and the flotation chamber so that the turbulent effect of depressurization is minimized. The sudden reduction in pressure in the flotation chamber results in the release of microscopic gas bubbles (average diameter 80 μm or smaller) that attach themselves to the suspended and colloidal particles present in water. This results in an agglomeration, which due to its entrained gas gives a net combined specific gravity less than that of water whose consequence is the flotation phenomenon. The vertical rising rate of gas bubbles ranges between 0.5 and 2.0 ft/min. The floated materials rise to the surface of the flotation chamber where they are continuously scooped by specially designed flight scrapers or other skimming devices. The surface sludge layer or float can in certain cases attain a thickness of several inches and be relatively stable. The layer thickens with time, but undue long delays in removal will cause release of particulates back to the liquid. The clarified effluent is usually drawn off from the bottom of the flotation chamber, which can be recovered for reuse or for final disposal. Figures 8.5 and 8.6 illustrate up-to-date DGF systems using single cell and double cell, respectively. The flotation system is known as dissolved air flotation (DAF) if only air is used. In the Oxyozosynthesis system, the dissolved gases include oxygen, ozone, carbon dioxide, and air.

The retention time in the flotation chamber is usually short about 3–5 min depending on the characteristics of process water and the performance of the flotation unit. DGF units with such short retention times can treat water, wastewater, or sludge at an overflow rate of 3.5 gpm/ft^2 for a single unit and up to 10.5 gpm/ft^2 for triple stacked units. A comparison between a DGF clarifier and a sedimentation tank shows that (13):

(a) DGF floor space requirement is only 15% of the sedimentation tank.
(b) DGF volume requirement is only 5% of the sedimentation clarifier.
(c) The degrees of clarification of a DGF is similar to that of a sedimentation tank using the same flocculating chemicals.
(d) The operational cost of the DGF clarifier is slightly higher than that for the sedimentation unit, which is offset by the considerably lower cost for financing the installation.
(e) DGF clarifiers are usually prefabricated using stainless steel. This results with lower erection cost, better flexibility in construction, and ease of possible future upgrade compared to the in-situ constructed heavy concrete sedimentation tanks.



1 ROTATING CENTER SECTION
2 CLARIFIED WATER OUTLET
3 SETTLED SLUDGE SUMP
4 SETTLED SLUDGE OUTLET
5 ROTARY CONTACT
6 SPIRAL SCOOP
7 FLOATED SLUDGE OUTLET
8 UNCLARIFIED WATER INLET
9 CLARIFIED WATER EXTRACTION PIPES
10 GEAR MOTOR
11 DISTRIBUTION DUCT

A DIAMETER of SUPRACELL
B DEPTH of SUPRACELL TANK
C DEPTH of SUPRACELL TANK with BOTTOM SUPPORT
D MINIMUM OVERALL HEIGHT of SUPRACELL

TYPE		DIMENSIONS						FLOW		
A ft	A mm	B in	B mm	C in	C mm	D in	D mm	m^3/min	US GPM	m^3/h
8	2400	23.5	600	33	850	45	1150	0,56	148	34
10	3200	23.5	600	33	850	49	1250	1,00	263	60
12	3900	25.5	650	35	900	51	1300	1,50	394	90
16	4500	25.5	650	37	950	57	1450	2,00	525	120
18	5500	25.5	650	37	950	58	1480	3,00	789	180
20	6100	25.5	650	37	950	61	1560	3,65	961	219
22	6700	25.5	650	37	950	62	1580	4,40	1160	264
24	7200	25.5	650	37	950	63	1600	5,08	1340	305
27	8100	25.5	650	37	950	67	1700	6,44	1695	386
30	9000	25.5	650	37	950	71	1820	7,95	2090	477
33	10000	25.5	650	37	950	72	1840	9,80	2580	588
36	11000	25.5	650	37	950	73	1860	11,87	3125	712
40	12200	26	660	38	960	76	1920	14,60	3840	876
44	13400	27	685	39	985	78	1980	17,60	4630	1056
49	14800	27	685	39	985	82	2070	21,50	5660	1290
56	16800	27	685	39	985	87	2200	27,70	7290	1662

Fig. 8.5. A single-cell high rate dissolved air flotation system (Supracell).

Currently used DGF units are more reliable, have excellent performance for sludge thickening, and require less land area than gravity thickeners. However, the gas released to the atmosphere may strip volatile organic material from the sludge. The volume of sludge requiring ultimate disposal or reuse may be reduced, although its composition will be altered if chemical flotation aids are used. U.S. EPA data from various air flotation units indicate that solids recovery ranges from 83 to 99% at solids loading rates of 7–48 lb/ft^2/day. A summary of U.S. EPA data that illustrate the excellent performance of DAF for thickening various types of sludges is shown in Table 8.3.

DAF is also an excellent process for solids separation in water treatment and wastewater reclamation (14–17). DAF is an integral part of the Oxyozosynthesis Wastewater Reclamation System. A bird's view of the advanced DAF unit with built-in chemical flocculation and filtration (Sandfloat) is shown in Fig. 8.7. The influent raw water or wastewater enters the inlet at the center, near bottom and flows through a hydraulic rotary joint and an inlet distributor into the rapid mixing section of the slowly moving carriage. The entire moving

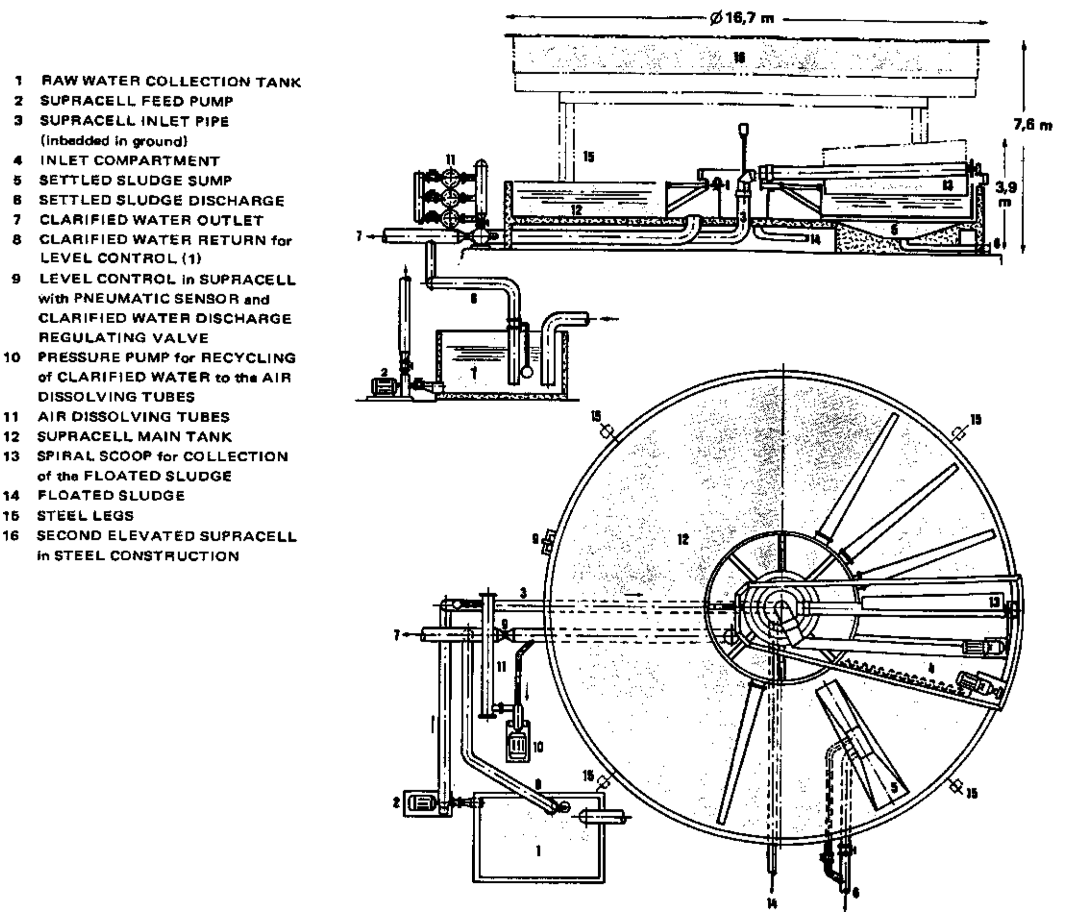


Fig. 8.6. A double-cell high rate dissolved air flotation system (Supracell).

carriage consists of rapid mixer, flocculator, air dissolving tube, backwash pump, sludge discharge scoop, and sludge recycle scoop. From the rapid mixing section, the water enters the hydraulic flocculator for gradually building up the flocs by gentle mixing. The flocculated water moves from the flocculator into the flotation tank clockwise with the same velocity as the entire carriage including the flocculator, which is moving counter clockwise simultaneously. The flocculator effluent velocity is compensated by the opposite velocity of the moving carriage, resulting in a “zero” horizontal velocity of the flotation tank influent. The flocculated water thus stands still in the flotation tank for optimum clarification. At the outlet of the flocculator, clarified or recycled water stream with microscopic air bubbles is added to the flotation tank to float the insoluble flocs and suspended matters to the water surface. The float (scum/sludge) accumulated at the top of the unit is scooped off by a sludge discharge scoop and discharged into the center sludge collector where there is a sludge outlet to an appropriate sludge treatment facility. The bottom of the Sandfloat is composed of multiple

Table 8.3
Sludge thickening by dissolved air flotation (Source: U.S. EPA)

	Feed solids conc. (%)	Loading rate W/o polymer (lb/ft^2/day)	Loading rate W/ polymer (lb/ft^2/day)	Float solids conc. (%)
Primary + WAS	2.0	20	60	5.5
Primary + (WAS + $FeCl_3$)	1.5	15	45	3.5
(Primary + $FeCl_3$) + WAS	1.8	15	45	4.0
WAS	1.0	10	30	3.0
WAS + $FeCl_3$	1.0	10	30	2.5
Digested primary + WAS	4.0	20	60	10.0
Digested primary + (WAS + $FeCl_3$)	4.0	15	45	8.0
Tertiary, alum	1.0	8	24	2.0

sections or wedges of sand filter and clear well. The clarified flotation effluent passes through the sand filter downward and enters the clear well. Through the circular hole underneath each sand filter section, the filter effluent enters the center portion of the clear well where there is an outlet for the Sandfloat effluent. The filter sections are backwashed sequentially.

For the wastewater reclamation plant, DAF is an important process unit. Filtration is used for final polishing of the plant effluent. Table 8.4 presents the U.S. EPA data on removal of various classical pollutants, toxic heavy metals, and toxic organics by flotation. For more information on the DAF process, the reader is referred to Refs. (18, 19).

2.3. *Filter Belt Press*

The filter belt press or simply the belt press is used for sludge dewatering. Filter belt presses consist of an endless filter belt that runs over a drive and guide roller at each end like a conveyor belt. Several rollers support the filter belt along its length. Above the filter belt is a press belt that runs in the same direction and at the same speed; its drive roller is coupled with the drive roller of the filter belt. The press belt can be pressed on the filter belt by means of a pressure roller system whose rollers can be individually adjusted horizontally and vertically. The sludge to be dewatered is fed on the upper face of the filter belt and is continuously dewatered between the filter and press belts. After having passed the static pressure zone, further dewatering is achieved by the superimposition of shear forces to expedite the dewatering process. The supporting rollers of the filter belt and the pressure rollers of the pressure belt are adjusted in such a way that the belts and the sludge between them describe an S-shaped curve. Thus, there is a parallel displacement of the belts relative to each other due to the differences in the radii. After further dewatering in the shear zone, the sludge is removed by a scraper.

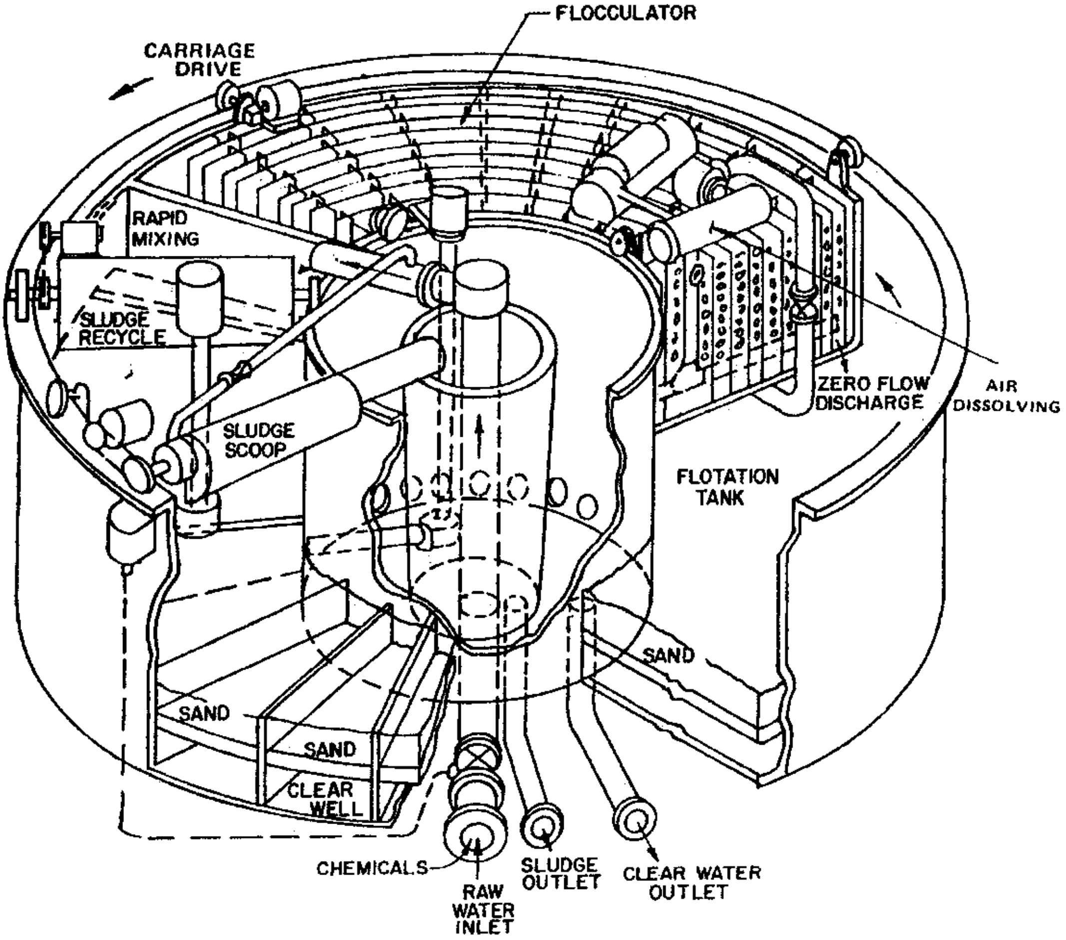


Fig. 8.7. Bird's view of a flocculation/flotation/filtration package unit (Sandfloat).

Some units consist of two stages where the initial draining zone is on the top level followed by an additional lower section wherein pressing and shearing occur. A significant feature of the belt filter press is that it employs a coarse mesh, relatively open weave, metal medium fabric. This is feasible because of the rapid and complete cake formation obtainable when proper flocculation is achieved. Belt filters do not need vacuum systems and do not have the sludge pickup problem occasionally experienced with rotary vacuum filters. The belt press can handle the hard-to-dewater sludges more readily. The produced low cake moisture permits incineration of primary/secondary sludge combinations without auxiliary fuel. A large filtration area can be installed in a minimum of floor area. To avoid penetration of the filter belt by sludge, it is usually necessary to coagulate the sludge (generally with synthetic, high polymeric flocculants). The sludge treated by ozonation, however, does not need any flocculants for sludge conditioning.

Table 8.4
Removal of various pollutants, toxic heavy metals, and organics by flotation (Source: U.S. EPA)

Pollutant	Date points		Effluent concentration		Removal efficiency (%)	
	Pilot scale	Full scale	Range	Median	Range	Median
Classical pollutants (mg/L)						
BOD_5		9	140–1,000	250	4–87	68
COD		12	18–3,200	1,200	8–96	66
TSS		12	18–740	82	6–98	88
Total phosphorus		6	<0.05–12	0.66	50–>99	98
Total phenols		10	<0.001–23	0.66	3–>94	12
Oil and grease		11	16–220	84	57–97	79
Toxic pollutants (μg/L)						
Antimony		9	ND–2,300	20	4–95[a]	76
Arsenic		7	ND–18	<10	8–>99	45
Xylene		3	ND–1,000	200	95–>99	97
Cadmium		9	BDL–<72	3	0–>99	98[a]
Chromium		12	2–620	200	20–99	52
Copper		12	5–960	180	9–98	75
Cyanide		7	<10–2,300	54	0–<62	10
Lead		13	ND–1,000	70	9–>99	98
Mercury		8	BDL–2	BDL	33–88	75
Nickel		12	ND–270	41	29–>99	73
Selenium		3	BDL–8.5	2		NM
Silver		5	BDL–66	19		45
Thallium		3	BDL–50	14		NM
Zinc		11	ND–53,000	200	12–>99	89
Bis (2-ethylhexyl) phthalate		8	30–1,100	100	10–98	72
Butyl benzyl phthalate		5	ND–42	ND	97–>99	>99
Carbon tetrachloride		3	BDL–210	36		75
Chloroform		6	ND–24	9	20–>99	58
Dichlorobromomethane		1		ND		>99
2, 4-Dichlorophenol		1		6		NM
Di-*n*-butyl phthalate		6	ND–300	20	0–>99	97
Diethyl phthalate		1		ND		>99
Di-*n*-octyl phthalate		6	ND–33	11	61–>99	78
N-nitrosodi phenylamine		1		620		66
N-nitroso-di-*n*-propyiamine		1		84		NM
2-Chlorophenol		1		2		NM
2, 4-Dimethylphenol		2	ND–28	14		>99
Pentachlorophenol		5	5–30	13		19
Phenol		8	9–2,400	71	0–80	57
2, 4, 6-Trichlorophenol		1		3		NM

(*Continued*)

Table 8.4
(Continued)

Pollutant	Date points		Effluent concentration		Removal efficiency (%)	
	Pilot scale	Full scale	Range	Median	Range	Median
Benzene		3	5–200	120		NM
Chlorobenzene		1		57		NM
Dichlorobenzene		2	18–260	140		76
Ethylbenzene		7	ND–970	44	3–>99	65
Toluene		6	ND–2,100	580	10–>99	39
Fluoranthene		2	0.5–<10	5.2		NM
Fluorene		1		14		NM
Naphthalene		9	ND–840	96	33–>99	77
Pyrene		2	0.3–18	9.2		0
Anthracene/phenanthrene		5	0.2–600	10	45–>98	81
2-Chloronaphthalene		1		17		0

Blanks indicate data not available.
BDL below detection limit, *ND* not detected, *NM* not meaningful.
[a] Approximate value.

The process reliability is considered to be excellent. Over 1 year of trouble-free operation has been achieved at the West New York Sewage Treatment Plant. Table 8.5 shows performance data collected at the WNYSTP. The last two entries in the table represent the primary sludge at the WNYSTP and the secondary sludge that was collected from a nearby secondary treatment plant, which were oxidized by oxygenation–ozonation before entering the belt press for dewatering.

2.4. *Performance of Oxyozosynthesis Sludge Management System*

The sludge management system consists of a pH adjustment unit, an innovative reactor for oxygenation–ozonation under moderate pressure (40–60 psi), DGF for sludge thickening, and an advanced filter belt press for sludge dewatering. The system's overall mechanical reliability is excellent. Tables 8.6 and 8.7 document the operational data at the West New York Sewage Treatment Plant (20). It is shown that the resulting cake is low in heavy metals and toxic organics and meets the requirements of the U.S. Environmental Protection Agency (40 CFR part 503 regulations) (21) and the NJ Department of Environmental Protection for sludge disposal. The ozone-treated sludge cake has low volatile solids content, high suspended solids consistency, and high fuel value (over 7,500 BTU/lb dry sludge) and is nonoffensive, odor free, and almost coliform free. Besides, the ozone-treated sludge can be thickened easily by flotation and subsequently dewatered by the filter belt press without any additional chemicals. The product sludge cake can be disposed of safely in a sanitary landfill site, spread on land for crop production, or could be reused as an ideal RD fuel.

Table 8.5
Belt press performance (Source: U.S. EPA)

Feed solids (%)	Secondary: primary ratio	Polymer dosage[a]	Pressure (lb/in.^{2}g)[b]	Cake solids (%)	Solids recovery (%)	Capacity[c]
9.5	100% primary	1.6	100	41	97–99	2,706
8.5	1:5	2.4	100	38	97–99	2,706
7.5	1:2	2.7	25–100	33–38	95–97	1,485
6.8	1:1	2.9	25	31	95	898
6.5	2:1	3.1	25	31	95	858
6.1	3:1	4.1	25	28	90–95	605
5.5	100% secondary	5.5	25	25	95	546
5.6	100% primary	None	NA	39–43	>97	NA
3.8	100% secondary	None	NA	25	>95	NA

[a] pounds per ton dry solids.
[b] pounds per square inch, gauge.
[c] pound dry solids per hour per foot.

Table 8.6
Heavy metal contents of dewatered filter-belt-press cake[a] (Source: U.S. EPA)

Heavy metals mg/kg dry sludge	West NY sludge cake	NJ DEP limits for land application	U.S. EPA ceiling limits[b] for land application	U.S. EPA High-quality limits[c] for land application
Cadmium	3	25	85	39
Chromium	14	1,000	3,000	1,200
Copper	447	1,000	4,300	1,500
Nickel	9	200	420	420
Lead	126	1,000	840	300
Zinc	192	2,500	7,500	2,800

[a] The Oxyozosynthesis system hyperbaric unit was operated at pH = 4 and contact time = 90 min.
[b] Absolute value of any single concentration (40 CFR part 503 regulations, U.S. EPA, 1994).
[c] Monthly average values (40 CFR part 503 regulations, U.S. EPA) (23).

The flotation unit uses the pressurized gases in the hyperbaric reactor vessel for water sludge separation. The pressurized gases include oxygen, ozone, and carbon dioxide. Under optimum operation, all gaseous ozone should disappear and the flotation process should release mainly oxygen and carbon dioxide. Since supplemental air is not needed in sludge flotation, a significant cost-saving in sludge thickening is achieved.

The side streams from the flotation unit and belt press, which contain low concentrations of suspended solids and no harmful microorganisms, are recycled to the head of the treatment plant for reprocessing. The suspended solids, BOD, COD, and TKN of the recycle liquors are significantly lower than that produced from aerobic digestion, anaerobic digestion, and thermal treatment processes. Therefore, there will not be any adverse effect on the biological

Table 8.7
Toxic organic compounds in dewatered filter-belt-press cake* (Source: U.S. EPA)

Toxic organics (mg/kg dry sludge)	U.S. EPA limitations	WNY dewatered sludge cake
Aldrin	0.10	<0.001
Chlordane	0.10	<0.001
Dieldrin	0.10	<0.001
Endrin	0.10	<0.001
Heptachlor	0.10	<0.001
Heptachlor epoxide	0.10	<0.001
Lindane	0.10	<0.001
Methoxychlor	0.25	<0.001
Mirex	0.25	<0.001
p, p′ – DDT	0.25	<0.001
p, p′ – DDE	0.25	<0.001
p, p′ – TDE (DDD)	0.25	<0.001
Toxaphene	1.0	<0.001
PCB	0.50	<0.001

*Note:
Sources: West New York Sewage Treatment Plant U.S. Environmental Protection Agency.
Oxyozosynthesis process' Hyperbaric unit was operated at pH = 4, detention time = 90 min.
1 mg/kg dry sludge = 1 ppm on dry weight basis.

wastewater treatment system if the side streams are recycled. pH adjustment may be needed if the ratio of low pH recycle liquor flow to the plant influent flow is high.

The heavy metal content in the recycle liquors will not be high if the wastewater treatment plant treats only municipal sewage. In industrial areas where heavy metals could settle with the sludge by chemical precipitation or biological assimilation, many of these heavy metals will become soluble and present in the recycle liquor if the pH of influent sludge is to be lowered to 3–4 before entering the hyperbaric reactor for oxidation. In this case, two remedies are possible:

(a) Operating the hyperbaric reactor without acidification. This implies a lower ozonation efficiency, or
(b) Operating the flotation unit with chemical additions for both pH adjustment and heavy metals flotation. This is the perfect solution for removing the heavy metals and maintaining high ozonation efficiency in the hyperbaric reactor.

In summation, the Oxyozosynthesis Sludge Management System is a very promising and sound engineering development (22). It will be extremely competitive under the following conditions:

(a) Ocean dumping is not allowed, which is the case in the US.
(b) Federal and State regulations for disposal of sludge on land are very stringent whereby the treated sludge must be stabilized and rendered safe for cropland disposal.

(c) Incineration, which creates some air pollution, is not allowed in urban areas with many high-rise buildings.
(d) Wet air oxidation, which creates some odor problems, is not allowed in urban areas or cannot be afforded in rural areas.
(e) Distance is too far to transport sludge to another plant or site for disposal.
(f) There are engineering demonstration grants available encouraging testing and/or using innovative sludge management technology.

2.5. *Performance of Oxyozosynthesis Wastewater Reclamation System*

The major components of the Oxyozosynthesis Wastewater Reclamation system (refer to Fig. 8.4) are two hyperbaric oxygenation–ozonation reactors (see Fig. 8.3) and a Sandfloat flotation–filtration package unit (see Fig. 8.7). The full-scale hyperbaric reactors have a capacity of 22,000 gpd (20, 23). The package unit consists of chemical flocculation, dissolved gas flotation (DGF), and rapid sand filtration with a full-scale plant capacity of 1 MGD that was installed in the Town of Lenox, MA for water treatment demonstration (24).

The aim of this combined system is to convert municipal wastewater to a reusable water meeting the water quality criteria indicated in Table 8.8 for reclaimed water reuse in apartment complexes (25). The ultimate goal is to renovate wastewater for reuse as a potable water supply that meets the U.S. Environmental Protection Agency Drinking Water Standards (26).

Table 8.8
Water quality criteria for reclaimed water use in apartment complexes

Item	Unit	Criteria
Odor		Nonexistence
Color	Unit	<10
Turbidity	Unit	<5
TDS	mg/L	<1,000
SS	mg/L	<5
pH	Unit	5.8–8.6
COD	mg/L	<20
BOD_5	mg/L	<10
PO_4^{3-}	mg/L	<1.0
MBAS	mg/L	<1.0
Coliform	count/mL	Nonexistence
General bacteria	count/mL	<100
Residual chlorine	mg/L	>0.2
TOC	mg/L	<15

3. FORMATION AND GENERATION OF OZONE

3.1. Formation of Ozone

The conversion of oxygen (O_2) into ozone (O_3) requires the rupture of the very stable O_2 molecules. Since the breaking of the oxygen–oxygen bond requires a great deal of energy, only very energetic processes can accomplish it. In an electric discharge through an oxygen stream, collisions occur between electrons and oxygen molecules. A certain fraction of these collisions occur when the electrons have sufficient kinetic energy to dissociate the oxygen molecule,

$$O_2 + e^- \rightarrow 2[O] + e^- \tag{1}$$

Each of the oxygen atoms may subsequently form a molecule of ozone,

$$[O] + 2O_2 \rightarrow O_3 + O_2 \tag{2}$$

Collisions capable of dissociating oxygen molecules also occur when oxygen is bombarded with a high-speed alpha or beta particles coming from radioactive processes or with the cathode rays brought out through the thin metal foil window of the Coolidge tube.

The dissociation of oxygen, with subsequent formation of ozone, may also be brought about by the absorption of ultraviolet (150–190 nm) or gamma radiation, or even thermal dissociation; for instance if oxygen which has just been heated to a very high temperature (over 3,000°C) is suddenly quenched with liquid oxygen, a certain amount of ozone is found.

The energetic processes necessary for producing ozone molecules are also capable of destroying them. Ozone can be dissociated according to Eq. (3):

$$O_3 \rightarrow O_2 + [O] \tag{3}$$

This would not matter, of course, if it were always formed again by reaction of Eq. (2). Unfortunately there is another reaction,

$$[O] + O_3 \rightarrow 2O_2 \tag{4}$$

The higher the ozone concentration, the higher the rate for ozone destruction, so that whatever method is used for producing ozone, the concentration cannot be increased beyond a limiting value, at which the rates of formation and destruction are equal.

Ozone can also be made from water by electrolysis. Under special conditions (high current density, low temperature, adding the correct amount of sulfuric or perchloric acid to the water, etc.), the anode gases may consist of a mixture of oxygen and ozone. The reaction shown as Eq. (5) is more endothermic (207.5 kcal) than the reaction shown as Eq. (6) (34.1 kcal); therefore, it is difficult to carry out, and poor ozone yields are usually obtained:

$$3H_2O \rightarrow O_3 + 3H_2 \tag{5}$$

$$1.5O_2 \rightarrow O_3 \tag{6}$$

The yields and maximum concentrations attainable by these different processes vary considerably, as seen in Table 8.9. It should be noted that maximum energy yields could only be obtained by operating ozone generation at much less than the maximum ozone concentrations.

Table 8.9
Energy yield and maximum ozone concentration attainable by various generation methods

Methods	Energy yield (g/kWh)	Ozone concentration
Electric discharge in oxygen	Up to 150	Up to 6 vol%
Electrolysis of water	Up to 12	Up to 20%
Photochemical		
1,850–2,537 Å	Up to 25	Up to 0.25%
1,400–1,700 Å		Up to 3.5%
Radiochemical		
Using O_2 gas	220	60 ppm
Using liquid O_2	108	5 mol%
Thermal	56	0.33 mol%

3.2. *Generation of Ozone*

The two technologies for generating ozone that have found practical application are the silent electric discharge and the photochemical methods. The latter is only used where small quantities of ozone and very low concentrations are desired. In practically all other laboratory and industrial applications, the electric discharge method is used.

The instability of ozone with respect to decomposition back to oxygen dictates the need for an on-site production facility. This in turn dictates the need for a cost efficient, space efficient, low maintenance installation if ozone is to be applied in wastewater and/or sludge treatment applications. In recent years, great strides have been taken in providing equipment and technology for such installations (27–30).

Figure 8.8 shows the principal elements of a corona discharge ozone generator (31, 32). A pair of large-area electrodes is separated by a dielectric about 1–3 mm in thickness and an air discharge gap approximately 3 mm wide. When an alternating current (AC) is applied across the discharge gap with voltages between 5 and 25 kV in the presence of an oxygen containing gas, a portion of the oxygen is converted to ozone.

The excitation and acceleration of stray electrons within the high-voltage AC field cause the electrons to be attracted first to one electrode and then the other. At sufficient velocity, these electrons split some oxygen molecules into free radical oxygen atoms, as shown in Eq. (1). The free radical oxygen atoms then combine with other oxygen molecules to form ozone according to Eq. (2).

The decomposition of ozone back to oxygen, Eq. (3) is accelerated with increasing temperature and moisture so that all generators must have a cooling device for heat removal and a drying device for moisture removal from the feed gas. For optimization of ozone generation, the following practical engineering requirements should be met:

(a) For prevention of ozone decomposition, heat removal should be as efficient as possible.
(b) For dielectric material and electrode protection, the gap should be constructed so that the voltage can be kept relatively low while maintaining reasonable operating pressures.

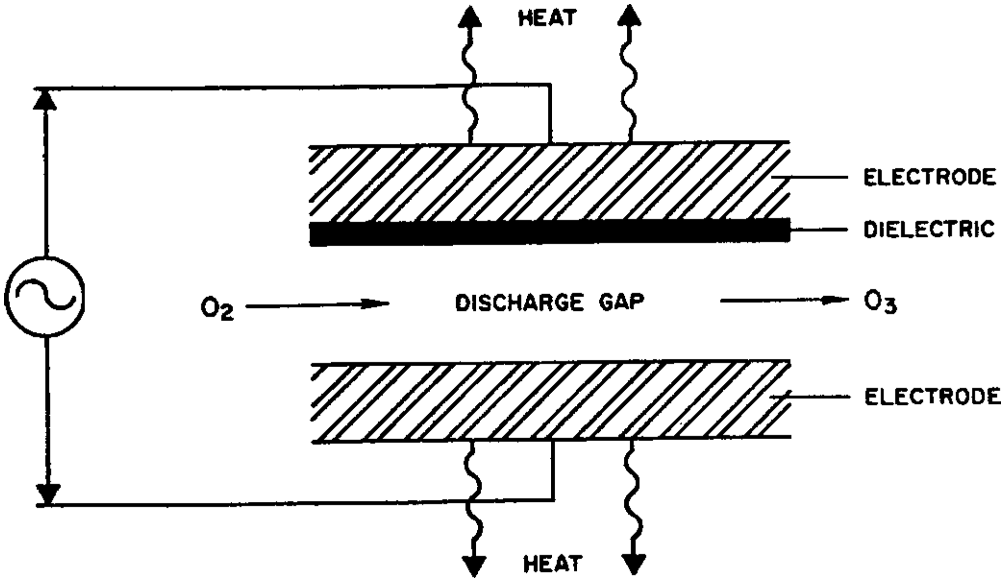


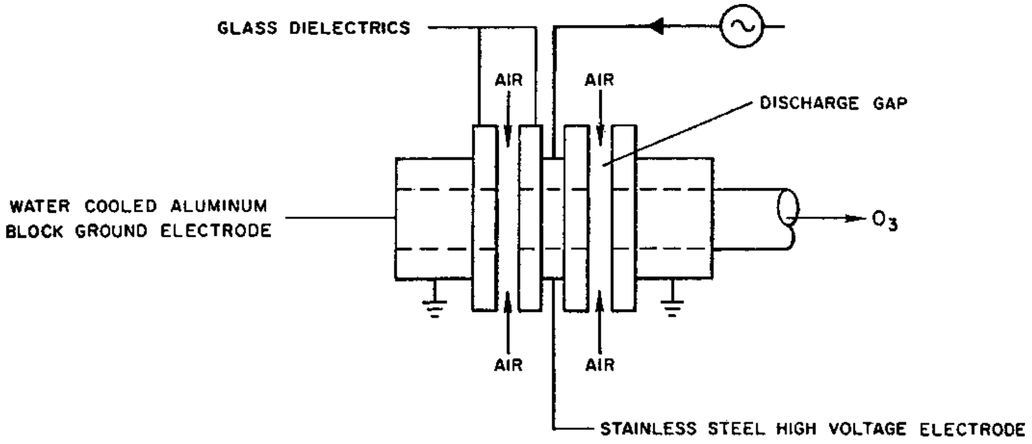
Fig. 8.8. Cross-section view of principal elements of a corona discharge ozone generator (Source: U.S. EPA).

(c) For high-yield efficiency, a thin dielectric material with a high dielectric constant, such as glass, should be used.
(d) For prolonged generator life and reduced maintenance problems, high-frequency AC should be used. High frequency is less damaging to the dielectric surfaces than high voltage.

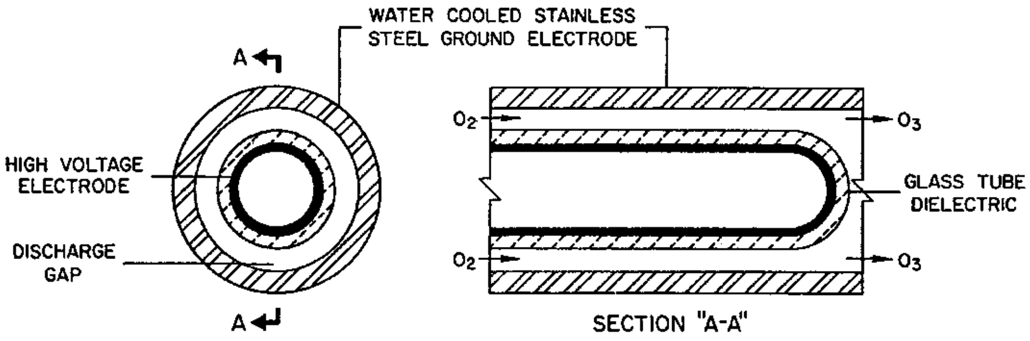
There are three basic types of commercial ozone generators (refer to Fig. 8.9). The characteristics and power requirements for the generators are given in Table 8.10. In addition to the generator's ozone yield per unit area of electrode surface, the concentration of ozone from the generator is regulated by:

(a) Adjusting the flow rate of feed gas
(b) Adjusting the voltage across the electrodes, and/or
(c) Selecting a suitable feed gas

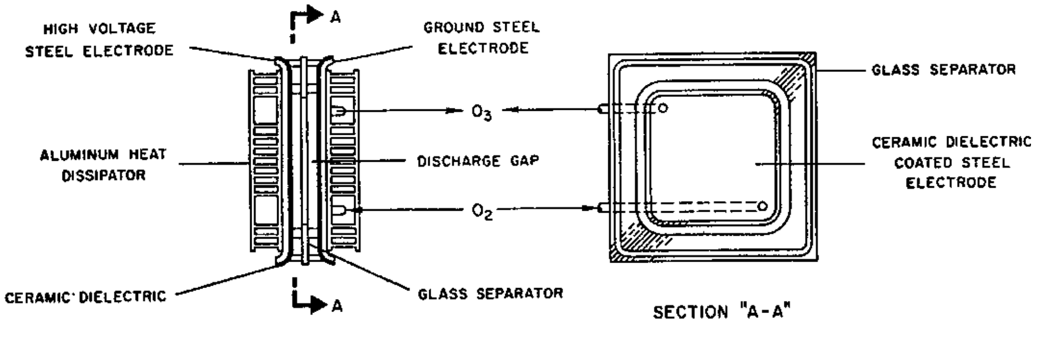
For reasons of economics, it is advisable to feed oxygen or oxygen-enriched air (instead of ordinary air) to the ozone generators. However, for an electronic ozone generator using the latest semiconductors for power generation and titanium oxide ceramic electrodes for ozone generation, feeding ordinary air is common. This type of generators can deliver an ozone concentration of 2% by weight from predried air at 4.5 kWh per pound of ozone. This new ozone generation technology renders the cost of ozonation competitive with the cost of chlorine oxidation. Table 8.11 presents some comparative data in ozone technology. It is important to recognize that the low operating voltage (6.5 kV) of the titanium oxide ceramic electrode insures longer life and minimum maintenance.



Otto Plate Type Generator Unit



Tube Type Generator Unit



Lowther Plate Generator Unit

Fig. 8.9. Types of ozone generators.

Table 8.10
Comparison of conventional ozone generators (Ozonators)

Typical Ozonator operating characteristics	Type of Ozonator		
	Otto	Tube	Lowther
Feed	Air	Air, oxygen	Air, oxygen
Dew point of feed (°F)	−60	−60	−40
Cooling	Water	Water	air
Pressure	0	3–15	1–12
Discharge gap (in.)	0.125	0.10	0.05
Voltage (kV peak)	7.5–20	15–19	8–10
Frequency (Hz)	50–500	60	2,000
Dielectric thickness (in.)	0.12–0.19	0.10	0.02
Power requirements[a]			
Air feed	10.2	75–10.0	6.3–8.8
Oxygen feed	–	3.75–5.0	2.5–3.5

[a] Note: kWh/lb of ozone at 1% concentration.

4. REQUIREMENTS FOR OZONATION EQUIPMENT

Basically, an ozonation system consists of (33):

(a) Feed gas equipment
(b) Ozone generators, and
(c) Ozone contactors

4.1. *Feed Gas Equipment*

Conventional ozone generators are fed either with predried air or pure oxygen. The reason for the use of pure oxygen is primarily to increase the ozone concentration from 1 to 2% by weight. This factor represents a 2–3 times higher sterilizing and oxidative power. Since new electronic generators do not have any appreciable gain when fed with pure oxygen, it is therefore recommended that only predried air be used.

For air preparation, equipments are required for air compression, air filtration, and air-drying:

(a) Air compression: Oil-free compressor should be specified. Over 15 HP screw-type compressors are recommended due to their extended life. The compressor rating should be up to 100 psi.
(b) Air filtration: Prefilter, after-filter, and after-cooler are integral parts to be supplied and mounted on the compressor. Smaller size compressors up to 5 HP are mounted on air receiver tank of appropriate size.
(c) Air drying: Predried air at −60°F dew point is required to deliver 98% of the rated ozone capacity. Refrigerated or heated air dryers are capable of delivering a maximum of −50°F dew point and they are subject to failure. Only heatless air dryers should be specified. A pressure

Table 8.11
Comparative data in ozone technology (Source: U.S. Ozonair Corp)

Comparative data in ozone technology	
Electronic ozone generators	Conventional ozone generators
I. Air preparation Oilless compressor and heatless air dryer Dryness of air: −60°F dew point Ozone production in relation to dryness of air: 98%	I. Air preparation Refrigerated Dryness of air: −60 to −40°F dew point Ozone production in relation to dryness of air: 70–85%
II. Air requirements per lb of ozone: 10.69 scfm at 80 psi	II. Air requirements per lb of ozone: 20 scfm
III. Power requirements per lb of ozone: 4.035 kWh	III. Power requirements per lb of ozone: 10–12 kWh
IV. Energy saving per lb of ozone: Air: 2.13 kWh Power: 6.965 kWh Total: 9.095 kWh	IV.
V. Ozone concentration from predried air: 1.6–2% by weight which represents two to three times higher sterilizing and oxidative power as compared to 1%.	V. Ozone concentration from predried air: Maximum of 1% on the average
VI. Ozone producing electrodes Material: titanium oxide ceramic Dielectric strength: $e = 85$ Dielectric constant: >15 kV/mm	VI. Ozone producing electrodes Material: glass Dielectric strength: $e = 25$ Dielectric constant: <10 kV/mm
VII. Operating voltage: 6,500 V	VII. Operating voltage: 12–16,000 V on the average
VIII. Probable failure in relationship to high voltage: 0.35%	VIII. Probable failure in relationship to high voltage: 8%
IX. Physical size of ozone generator: 19 lbs/day 30 ft^3 Weight: 380 lbs	IX. Physical size of ozone generator: 19 lbs/day 60 ft^3 Weight: 2,000 lbs

regulator is required to control an appropriate pressure for the ozone generator in the range of 10–20 psi. A moisture indicator (colorimetric) should be mounted after the air dryer. The required amount of air is usually based on a maximum flow rate of 10.7 ft^3/min/lb of produced ozone.

4.2. *Ozone Generators*

Previously, the specifications called for conventional ozone generators to have glass electrodes with transformers rated at 16,000 V. Many design engineers have specified two identical ozone generators (one as standby), especially for larger installations.

New ozone generators are being designed for a constant ozone production and constant ozone concentration. Independently wired modules control the ozone output. The specifications are currently written along the following lines (34–36):

(a) Ozone generator: The capacity is specified as weight of ozone per unit time such as lb/h or lb/day (kg/h or kg/day)
(b) Ozone concentration from predried air: Minimum 1.6% by weight
(c) Air requirements at −60°F dew point: Maximum 10.7 ft^3/min/lb of ozone. Air pressure supplied to generator is 15 psi.
(d) Overall design: Modular. Each module wired and controlled from the front panel or by remote control
(e) Power consumption: Not more than 4.5 kWh per pound of ozone produced.
(f) Power requirements: 220 V AC, 50 or 60 cycles
(g) Operating Voltage: Maximum 7 kV
(h) Control: Front panel pushbuttons (Start/Stop); power indicating light; air flow meter; DC ammeter; and AC voltmeter.
(i) Ozone resistant materials: All parts, components, tubing and piping in direct contact with ozone shall be of ozone-resistant materials.

4.3. *Ozone Contactors*

It is essential to have efficient mass transfer of ozone into the liquid. The widely used diffuser system can transfer a maximum of 65–70% of the ozone into solution. The balance of ozone (30–35%) is collected as an exhaust gas and burned. Several recently developed ozone contactors are being marketed with ozone transfer efficiency of more than 95% (37, 38).

(a) In-line contactor for water treatment (Fig. 8.10): The in-line contactor consists of venture-type ejector and two or more built-in static mixers. It is mounted directly in the water supply line. One or several contactors may be used and grouped into a single manifold. The maximum diameter of the contactor is 3 in. with a minimum of 40 ft of pipe run after the contactor. A minimum water pressure of 30 psi is required upstream of the contactor to accommodate the 40% pressure loss in the contactor itself. Depending on the degree of contamination, it is possible in some instances to supersaturate with dissolved ozone only part of the flow and then mix it with the untreated water flow.
(b) Film layer purifying chamber (FLPC) contactor for water treatment (Fig. 8.11): The basic principle is the reverse of that for bubbling. Contaminated water is emulsified (sprayed) into a powerful ozone concentration. The net result is that up to 1.5 mg/L of ozone is dissolved almost instantly in the water (compared to 0.5 mg/L concentration in ozone bubbling). FLPC-treated

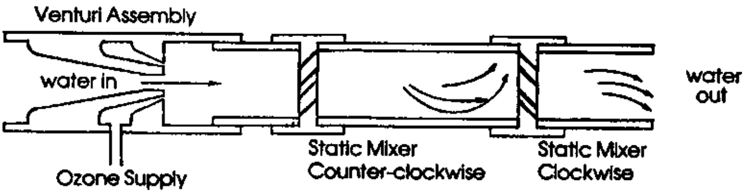
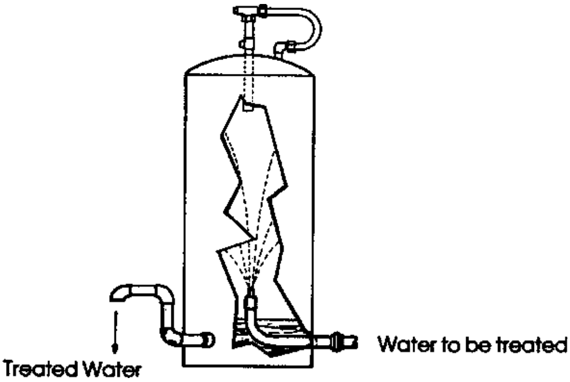


Fig. 8.10. In-line ozone contactor.

Fig. 8.11. Film layer purifying chamber (FLPC) ozone contactor.



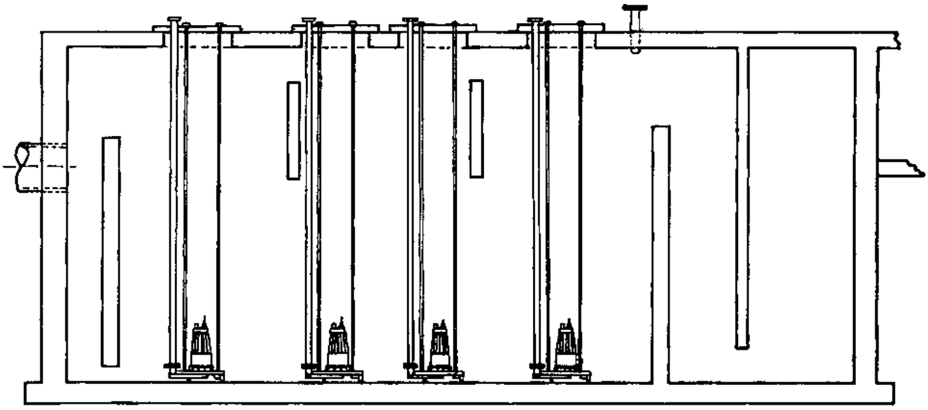


Fig. 8.12. Multicompartment turbine ozone contactor.

water is discharged under gravity following a retention period of 2–4 min in the tank under an influent water pressure of 30 psi.

(c) Turbine contactor for wastewater treatment (Fig. 8.12): The turbine contactor is used for wastewater treatment where the ozone contact time has to be extended. Mass transfer of 10–12 lb of oxygen per horsepower as compared to 2–3 lb with an average aerator. Ozone transfer of 99–100% can be achieved. For efficient wastewater treatment, one to four turbines may be used in an oxidation ditch depending on the effluent contamination and the flow. A multicompartment contactor where the effluent is introduced into fresh ozone residual, approximately 20% greater treatment effect will be obtained compared to treating the effluent in one single compartment.

(d) Diffuser contactor for water and wastewater treatment (Fig. 8.13): Disinfection and some chemical oxidation processes are mass-transfer-rate limited, while others are chemical-reaction-rate limited. Diffuser contactors are designed as part of an overall system to optimize the tradeoffs between ozone transfer and the contact time required for achieving a specific treatment objective. Systems are designed for a minimum ozone transfer of 90% and a typical disinfection contact time of 15 min. Both the influent upward velocity and the effluent downward velocity

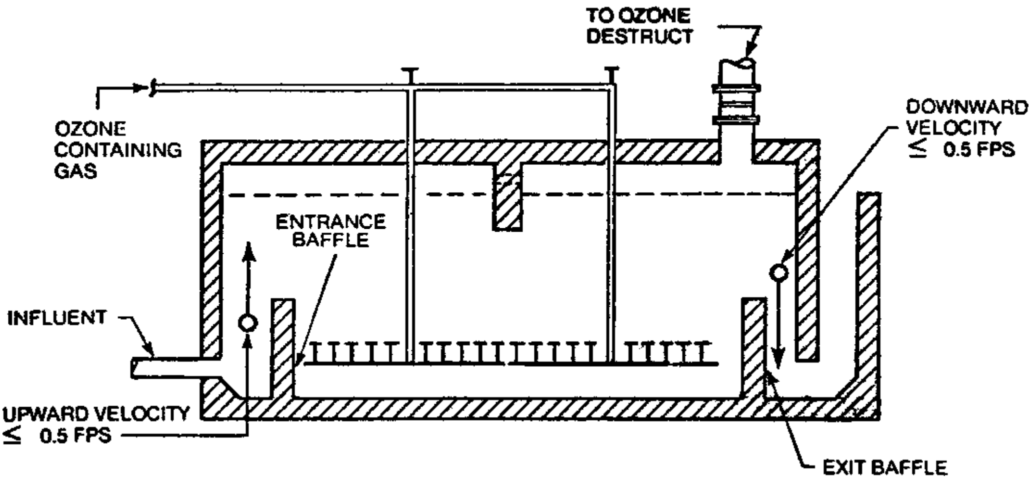


Fig. 8.13. Diffuser ozone contactor.

should be less than or equal to 0.5 ft/s. Extensive pilot plant and modeling studies, considering such factors as diffuser type, size and porosity and arrangement in relation to mass transfer, mixing, baffling, wall effects and materials of construction, have led to the currently recommended designs.

(e) Hyperbaric vessel for both wastewater and sludge treatment (Fig. 8.14): This innovative ozone–oxygen contactor is a combination of conventional diffuser contactor, film layer purifying chamber contactor, and turbine contactor. It is an advanced contactor, which is suitable for wastewater effluent and sludge treatment. Oxygen is first pumped into the hyperbaric vessel until a pressure of 40 psig is reached. Ozone is then pumped into a small compartment in the reactor through a gas diffuser, eventually making its way into the second main compartment of the reactor. Part of the wastewater or sludge is recycled by a recirculation pump and emulsified (sprayed) into the powerful ozone–oxygen concentration zone near the top of the reactor with the aid of a comminutor. A film layer is thus created for efficient gas transfer.

5. PROPERTIES OF OZONE

Ozone is an unstable, colorless gas and condenses to a dark blue liquid. It has a characteristic odor to which it owes its name, derived from the Greek word “ozein,” to smell. The odor of ozone in the vicinity of an electrical machine is well known. It is generally encountered in dilute form in a mixture with air or oxygen. Ozone is formed photochemically in the earth’s stratosphere but, at ground levels, it exists only at great dilution. It is produced commercially from air or oxygen by a form of electric discharge. It is a potent germicide and powerful oxidant in both inorganic and organic reactions. With unsaturated organic compounds ozone adds to the carbon–carbon double bond, forming ozonides. Decomposition of these ozonides almost always results in cleavage at the double bond, a property, which has been used for structural analysis and in the commercial preparation of chemicals.

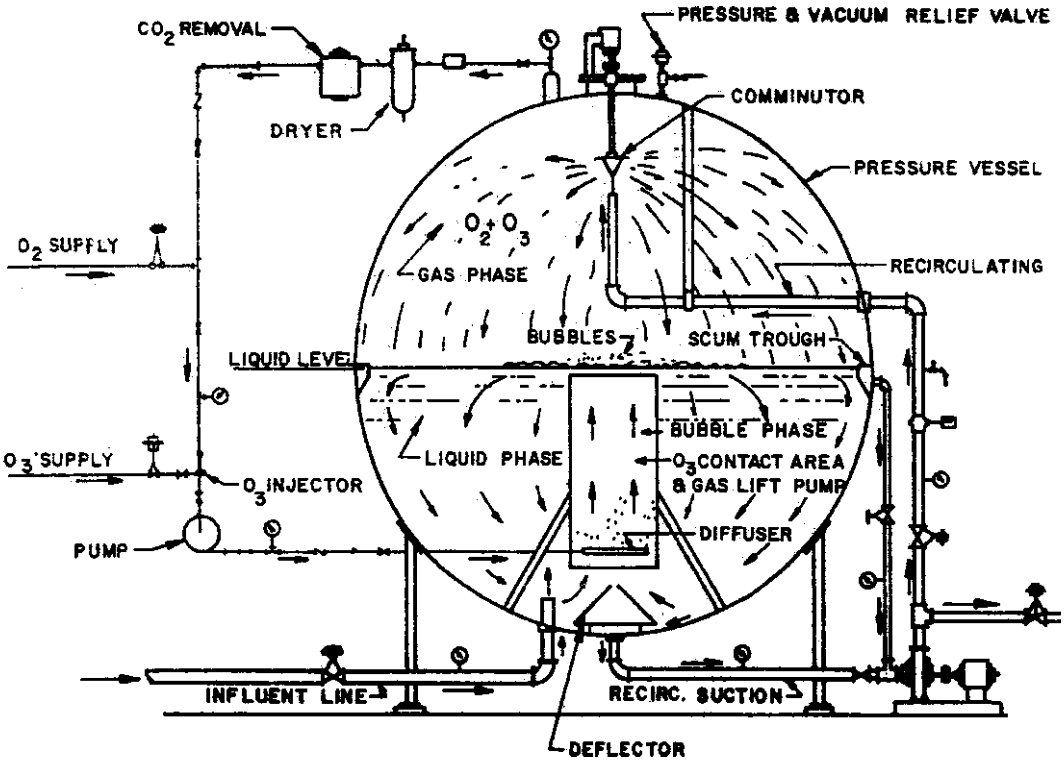


Fig. 8.14. Pressurized oxygen–ozone contactor (hyperbaric reactor vessel).

At ordinary temperatures and the concentrations it is normally produced, the color is not noticeable unless the gas is viewed through considerable depth. At −112°C, ozone condenses to a dark blue liquid. Liquid ozone is easily exploded, as are concentrations of ozone–oxygen mixtures above 20% ozone, in either the liquid or the vapor state. Explosions may be initiated by minute amounts of catalysts or organic matter, shocks, electric sparks, sudden changes in temperature or pressure, etc.

Ozone has strong absorption bands in the infrared, the visible, and the ultraviolet. The absorption maximum at 253.7 nm is particularly strong and affords a convenient means of measuring ozone concentrations in the stratosphere, as well as in laboratory and industrial measurements. Other properties of ozone are given in Table 8.12.

Liquid ozone is reported to be miscible in all proportions with the following liquids: $CClF_3$, CCl_2F_2, CH_4, CO, F_2, NF_2, and OF_2; forms two-layer systems with the following liquids: CF_4, N_2, and O_2; and ozone solutions in $CClF_3$ (chlorotrifluromethane) (about 105 g/L) have been prepared commercially in small cylinders. It is necessary to refrigerate these cylinders (−75°C) to minimize the decomposition of ozone at higher temperatures.

The limited miscibility of ozone in oxygen is of practical importance because the dense, oxygen-rich layer, which settles to the bottom, is easily exploded. The mutual solubility of the

Table 8.12
Properties of pure ozone

Parameters		Data
Melting point, °C		-192.5 ± 0.4
Boiling point, °C		-111.9 ± 0.3
Critical temperature, °C		-12.1
Critical pressure, atm		54.6
Critical volume, cm^2/mol		111
Density and vapor pressure of liquid		
Temperature (°C)	*Density (g/cm^3)*	*Vapor pressure (torr)*
−183	1.574	0.11
−180	1.566	0.21
−170	1.535	1.41
−160	1.504	6.73
−150	1.473	24.8
−140	1.442	74.2
−130	1.410	190
−120	1.378	427
−110	1.347	865
−100	1.316	1,605
Density of solid ozone, g/cm^3, at 77.4 K		1.728
Viscosity of liquid, cP		
At 77.6 K		4.17
At 90.2 K		1.56
Surface tension, dyn-cm		
At 77.2 K		43.8
At 90.2 K		38.4
Parachor[a] at 90.2 K		75.7
Dielectric constant, liquid, at 90.2 K		4.79
Dipole moment, debye		0.55
Magnetic susceptibility, cgs units		
Gas		0.002×10^{-6}
Liquid		0.150
Heat capacity of liquid from 90 to 150 K		$C_p = 0.425 + 0.0014(T - 90)$
Heat of vaporization, kcal/mol		
At −111.9°C		3,410
At −183°C		3,650
Heat and free energy of formation		
	ΔH_f (kcal/mol)	*ΔG_f (kcal/mol)*
Gas at 298.15 K	34.15	38.89
Liquid at 90.15 K	30.0	
Hypothetical gas at 0 K	34.74	

[a] $M\gamma^{1/4}(D - d)$ where M = molecular weight; γ = surface tension; D = liquid density; d = vapor density.

Table 8.13
Solubility of ozone in water

Temperature (°C)	Bunsen coefficient	Henry's law coefficient, H × 10^{-4}
0	0.49	3.95
5	0.44	3.55
10	0.375	3.0
20	0.285	2.29
30	0.20	1.61
40	0.145	1.17
50	0.105	0.85
60	0.08	0.64

two liquids decreases when the temperature is reduced. Thus, liquid ozone and oxygen are completely miscible above 93.2 K (at which temperature the total pressure is 1.25 atm) but at 90.2 K (the atmospheric pressure boiling point of liquid O_2), there is a separation into two layers, containing 17.6 and 67.2 mol% ozone, respectively. At still lower temperatures the separation becomes even more pronounced.

Ozone gas is sparingly soluble in water, and more so in other liquids, especially at low temperatures. The solubility of ozone in water is given in Table 8.13.

$$B = \frac{\text{Concentration of ozone in liquid}}{\text{Concentration of ozone in gas, reduced to STP}}, \tag{7}$$

where B is the Bunsen coefficient of solubility and H is Henry's constant, mol/atm (mole fraction of ozone in solution/partial pressure of ozone in gas, in atm).

The preparation of saturated ozone solutions is difficult to achieve because of the great tendency of ozone to react or to undergo decomposition. The thermal decomposition of ozone has been extensively studied in the temperature range 80–500°C. The mechanism is as shown in Eqs. (8)–(10).

$$O_3 + M \rightarrow O_2 + [O] + M \tag{8}$$

$$O_2 + [O] + M \rightarrow O_3 + M \tag{9}$$

$$[O] + O_3 \rightarrow 2O_2, \tag{10}$$

where M is a third element, O_2, O_3, N_2, He, or whatever is present. This leads to the rate expression shown in Eq. (11).

$$-\,d(O_3)/dt = 2k_1k_3(O_3)^2/k_2O_2, \tag{11}$$

where k_1, k_2, and k_3 are rate constants.

Since the thermal decomposition of ozone is not a first order process, the half-life of the ozone varies inversely with its initial concentration and directly with the oxygen concentration. Typical values are given in Table 8.14 (39).

Table 8.14
Uncatalyzed thermal decomposition of ozone in ozone–oxygen mixtures (39)

Temperature (°C)	$\frac{k_2}{2k_1k_3}$	Half-life for indicated initial concentration[a]			
		5 wt% 3.333 vol%	2 wt% 1.333 vol%	1.0 wt% 0.667 vol%	0.5 wt% 0.333 vol%
120	22.4	11.2[b]	28[b]	56[b]	112[b]
150	1.40	41.8	104.5	209	418
200	0.030	0.9	2.2	4.5	9.0
250	0.00133	0.04	0.10	0.20	0.40

[a] Half-life = $(k_2/2k_1k_3)$ (100/vol% O_3) in seconds.
[b] In minutes.

Numerous substances can catalyze the decomposition of ozone. The reaction with N_2O_5 proceeds according to the mechanism shown in Eqs. (12)–(15).

$$N_2O_5 \rightarrow NO_2 + NO_3 \tag{12}$$

$$NO_2 + NO_3 \rightarrow N_2O_5 \tag{13}$$

$$NO_2 + O_3 \rightarrow NO_3 + O_2 \tag{14}$$

$$2NO_3 + 2NO_2 \rightarrow 4NO_2 + O_2 \tag{15}$$

As long as any ozone remains, the N_2O_5 is regenerated so that the net effect is the decomposition of ozone. This process was studied at 20°C and 400°C, and may be of some importance in the case of ozone generated from air since air always contains traces of N_2O_5.

At room temperature, the decomposition of ozone apparently depends on surface reactions. A half-life of 20–100 h may be expected in clean vessels of glass, stainless steel, or other inert materials. Many solids catalyze the decomposition of ozone. The activity of such catalysts depends on subdivision, crystal structure, presence or absence of moisture, etc. Preparations of iron oxide have been made that are extremely active in decomposing ozone.

In aqueous solutions, the decomposition of ozone is much more rapid than in the gaseous state. It is catalyzed by the hydroxyl ion. The initial reaction is shown in Eq. (16),

$$O_3 + OH^- \rightarrow O_2 + [HO_2] \tag{16}$$

followed by the reactions shown by Eqs. (17)–(20).

$$O_3 + [HO_2] \rightarrow 2O_2 + OH^- \tag{17}$$

$$O_3 + OH^- \rightarrow O_2 + [HO_2] \tag{18}$$

$$2[HO_2] \rightarrow O_3 + H_2O \tag{19}$$

$$[HO_2] + [HO] \rightarrow O_2 + H_2O \tag{20}$$

Table 8.15
Comparison of the solubilities of ozone, chlorine, and oxygen

Gas	Solubility by water temperature (mg/L)			
	0°C	10°C	20°C	30°C
Oxygen				
At 100%	70.5	54.9	44.9	38.2
At 21%	14.8	11.5	9.4	8.0
Ozone				
At 100%	1,374.3	1,114.9	789.0	499.6
At 4%	55.0	44.6	31.6	20.0
Chlorine				
At 100%	14,816.5	9,963.4	7,263.6	5,688.8
At 99.8%	14,789.4	9,943.5	7,249.1	5,677.4

Ozone is more soluble in water than oxygen, but because of a much lower available partial pressure, it is difficult to obtain a concentration of more than a few milligrams per liter under normal conditions of temperature and pressure.

A comparison of the solubilities of ozone, chlorine, and oxygen by water temperature and gas concentration is presented in Table 8.15. A mathematical model describing dissolved oxygen concentration can be found elsewhere (40). The dissolved oxygen concentration is a function of water temperature, pressure, and chloride concentration.

In 1981, Hill et al. (41) performed ozone absorption in a pressurized bubble column (7.7 m tall and 5.25 cm inside diameter), which was operated in a semi-batch mode with gas pressures up to 791 kPa (100 psig) and water temperatures ranging from 20 to 40°C. Also in 1981, Roth and Sullivan (42) reviewed and investigated the solubility of ozone in water under various pH values and water temperatures. Their reviewed data are presented in Table 8.16 and Eq. (21) is a mathematical model fitting their experimental data:

$$H = 3.84 \times 10^{7}[\mathrm{OH}^{-}]^{0.035}\exp(-2{,}428/T), \qquad (21)$$

where H is Henry's Law constant, atm/mole fraction of ozone; $[\mathrm{OH}^{-}]$ is the hydroxide concentration, g mol/L; and T is the temperature, K.

Ozone supposedly decomposes in water, but this is probably due to its strong oxidizing ability rather than simple decomposition. Ozone is much more soluble in acetic acid, acetic anhydride, dichloroacetic acid, chloroform, and carbon tetrachloride than it is in water. More technical information on ozonation can be found elsewhere (43–62).

It should be noted that HO_2 and HO in Eqs. (16)–(20) are free radicals, which are formed when ozone decomposes in aqueous solutions. The two free radicals have great oxidizing power, and in addition to disappearing rapidly (Eq. (20)), may react with impurities or pollutions present in solution, such as metal salts, organic substance, hydrogen, hydroxide ions, etc. It is believed that the free radicals formed by the decomposition of ozone in water are the principal reacting species (58).

Table 8.16
Ozone solubility in water (42)

Investigator	Temperature (°C)	*H*, atm/mol fraction
Kawamura (110)	5.0	2,880
	10.0	3,400
	20.0	4,610
	30.0	6,910
	40.0	9,520
	50.0	13,390
	60.0	18,980
Kawamura (110)		
7.57 N H_2SO_4	20.0	7,420
2.02 N H_2SO_4	20.0	5,810
1.01 N H_2SO_4	20.0	5,350
0.18 N H_2SO_4	20.0	4,770
0.11 N H_2SO_4	20.0	4,770
Kirk-Othmer (111)	0.0	2,530
	5.0	2,820
	10.0	3,330
	20.0	4,370
	30.0	6,210
	40.0	8,550
	50.0	11,770
Li (112)		
pH 2.2	25.0	7,840
pH 4.1	25.0	7,600
pH 6.15	25.0	9,000
pH 7.1	25.0	9,400

6. DISINFECTION BY OZONE

Smith and Bodkin (43) compared the bactericidal action of ozone and chlorine at varying values of pH. Ozone, over a wide pH range, was many times as effective as chlorine. At a temperature of 27.5°C and pH values of 5.0 and 6.0, ozone affected sterility of a 1-L sample containing 8×10^5 bacteria/mL in 5 min. At pH 7.0, 8.0, and 9.0, the sterilization time was 7.5 min. The ozone concentration varied from 0.13 to 0.20 mg/L. In contrast, the concentration of chlorine required to sterilize as rapidly as ozone varied from 2.7 mg/L at pH 5.0, to 7.9 mg/L at pH 8.0.

Leiguarda et al. (44) presented a detailed account of the bactericidal action of ozone in both pure and river waters. Varying amounts of ozone were added to pure water free from ozone demand, and the water was inoculated with dilute suspensions of *E. coli* or *Clostridium perfringens*. Samples were taken at various time intervals to determine the concentration of ozone and the number of bacteria present. The effects of temperature and pH on bactericidal action were also investigated. The results indicated that in water initially containing 10^4 *E. coli*/mL and 0.12 mg/L ozone, at pH 6.0 and maintained at a temperature of 10°C, no viable bacteria were found after 5 min; the ozone content had decreased to 0.09 mg/L. At pH 8.0 and higher temperatures, the efficiency was not significantly affected by temperature but was slightly greater at pH 6.0 than at pH 8.0. In addition, tests were made on the effects of ozone on the naturally occurring bacterial flora of river water. The ozone demand of this water was high, and tests were made using 1–6 mg/L of ozone. There were sizable reductions in the number of bacteria even when the amount of ozone added was insufficient to satisfy the ozone demand of the water. All organisms were destroyed when, after a contact period of 5 min, 0.08 mg/L of residual ozone was present. Similar results were obtained in experiments with river water samples that were coagulated, settled, and subsequently inoculated with *E. coli*. A total kill of vegetative forms of *C. perfringens* occurred within 5 min when 0.12 mg/L ozone was initially added to water containing 1.4×10^4 bacteria/mL. In water containing *C. perfringens* in concentrations of 2×10^3 spores/mL, at a pH of 6.0 and maintained at a temperature of 24°C, no viable spores were found after a contact period of 15 min with 0.25 mg/L of ozone, or after 2 min with 5 mg/L. At pH 8.0, bactericidal efficiency was reduced. Spores were not affected by 0.25 mg/L of ozone even after 120 min.

In a symposium on the sterilization of water, Whitson (45) reported that ozonation effected microorganism removal and improved water filterability, color, taste, and odor. Bernier (46), while comparing the bactericidal efficiencies of chlorine and ozone, asserted that ozone was the far superior disinfectant, being considerably faster than chlorine and not as notably affected by external factors such as pH and temperature.

Bringman (47) observed that 0.1 mg/L of active chlorine required 4 h to kill 6×10^4 *E. coli* cells in water, whereas 0.1 mg/L of ozone required only 5 s. When the temperature was raised from 22 to 37°C, the ozone inactivation time decreased from 5 to 0.5 s. Wuhrmann and Meyrath (48) carried an investigation of the kinetics of ozone disinfection. During each experiment, the ozone concentration was kept constant by continuously bubbling air–ozone through the test solution. The results indicated that ozone disinfection was mainly a function of contact time, ozone concentration, and water temperature. These investigations revealed that the contact time with ozone necessary for 99% destruction of *E. coli* was only one-seventh that observed with the same concentration of hypochlorous acid. The death rate for spores of *Bacillus* species was about 300 times greater with ozone than with chlorine.

Hann (49) presented a detailed review of the differences between chlorination and ozonation as determined by other workers. It is reported that ozone disinfection was found to be somewhat more expensive. Turbidity interfered with its use, and organic demand had to be satisfied before germicidal action was effective.

Scott and Lesher (50) postulated a mode of action of ozone on *E. coli* based on experimental data. The primary attack of ozone was thought to be on the cell wall or membrane of bacteria, probably by reaction with the double bonds of lipids, and that cell lysis depended on the extent of that reaction. Bringman (47) reported that the mode of action of ozone differed from that of chlorine. He concluded that chlorine selectively attacked and destroyed certain enzymes, whereas ozone acted as a general protoplasmic oxidant. Christensen and Giese (51) suggest that the primary locus of activity of ozone was the bacterial cell surface. Barron (52) hypothesized that the primary bactericidal activity of ozone was the oxidation of sulfhydryl groups on enzymes. Murray and coworkers (53) at the University of Western Ontario, recognizing that the outermost layer of gram-negative organisms is a lipoprotein followed by a lipopolysaccharide layer, surmised that these layers would be first subject to attack by ozone. They concluded that the attack by ozone on the cell wall results in a change in cell permeability eventually leading to lysis.

Smith (54) stated that under experimental conditions where there were less than 1% survivors of *E. coli* and *Streptococcus faecalis* after 60-s exposure to 0.8 mg/L ozone, the unsaturated fatty acids (mainly C_{16} and C_{18} monoenoic acids) of the cell lipids were oxidized in the same time interval. The lipids present in bacteria are largely confined to the cytoplasmic membrane. Thus, the mechanism of disinfection of ozone is still open to question.

At the Eastern Sewage Works in the London Borough of Redbridge, Boucher and his associates (55, 56) conducted experiments on microstraining and ozonation of wastewater effluents. Using an ozone dose of 10–20 mg/L most organisms were killed, although a sterile effluent was never obtained. Chlorine followed by ozone produced better results. In his conclusion, Boucher commented: “Chlorination as an additional treatment to ozonation has not produced any advantage except to destroy most of the few organisms that sometimes survive ozonation. This is not considered a sufficient advantage in view of its many known disadvantages for effluent treatment, namely, the production of chloro-derivatives which may be toxic to fish and other aquatic life or which may produce persistent tastes, difficult to remove by subsequent waterworks treatment, and the possibility of rapid after growth of microorganisms in a receiving river and all its attendant problems.”

Huibers et al. (57) determined that ozone treatment of effluents from secondary wastewater treatment plants could provide product water, which is within the US requirements for chemical and bacteriological quality of potable water. Virtually all color, odor, and turbidity were removed. Oxygen-consuming organic materials, measured as COD, were reduced to less than 15 mg/L. Bacteriological tests revealed that no living organisms remained.

In Los Angeles County, California, a well-oxidized secondary effluent was treated with ozone for disinfection (62). It was found that 50 mg/L of ozone was required to meet the California requirement of 2.2 total coliforms per 100 mL. To achieve the 200 counts of fecal coliform per 100 mL, the ozone requirement was 10 mg/L. It was also found that the removal of suspended solids down to 1 mg/L greatly improved the efficiency of ozone treatment. This study further revealed that to achieve excellent disinfection, the COD should be less than 12 mg/L and the nitrite should be less than 0.15 mg/L. The minimum required ozonation contact time was reported to be 10 min.

The kinetics of disinfection has been investigated by Morris (63). His concept of the lethality coefficient for a given disinfectant is presented below:

$$L = \ln(100)/Ct = 4.61/Ct, \tag{22}$$

where L is the lethality coefficient, $(\text{mg/L})^{-1}\ \text{min}^{-1}$; C is the residual concentration of disinfectant, mg/L; and t is the time in minutes for 99% microorganism destruction (2-log destruction).

Table 8.17
Relative efficiency of ozone disinfection (pH = 7, temperature = 10–15°C)

Organism	L^{a}	C^{b}
Escherichia coli	500	0.001
Streptococcus faecalis	300	0.0015
Polio virus	50	0.01
Endamoeba histolytica	5	0.1
Bacillus megatherium (spores)	15	0.03
Mycobacterium tuberculosam	100	0.005

[a] L, lethality coefficient [(mg/L)$^{-1}$ min^{-1}].
[b] C, residual concentration of disinfectant [mg/L].

Table 8.18
Comparison of lethality coefficients for ozone and chlorine

Agent	Enteric bacteria	Amoebic cysts	Viruses	Spores
O_3	500	0.5	5	2
$HOCl$ as Cl_2	20	0.05	1.0 up	0.05
OCl^- as Cl_2	0.2	0.0005	0.02	0.0005
NH_2Cl as Cl_2	0.1	0.02	0.005	0.001

Table 8.17 indicates the effectiveness of ozone for disinfection of various bacteria and viruses at pH 7 and temperature of 10–15°C. Table 8.18 further illustrates that in comparison with various forms of chlorine, ozone is a much more powerful disinfectant against enteric bacteria, amoebic cysts, viruses and spores by factors of 10–100. The disinfection efficiency of ozone does not seem to be affected significantly within the normal pH range of 6–8.5. Table 8.19 further presents the oxidation potentials of nine strong chemical disinfectants among which ozone has the highest oxidation potential. This makes ozone the strongest disinfectant as well as the strongest oxidizing agent. The exact effect of temperature on ozone disinfection is still unknown. It is known, however, that the higher the water temperature, the lower the efficiency of ozone mass transfer, which might translate to lower disinfection efficiency.

In summation, the advantages of using ozone for disinfection include but are not limited to:

(a) Ozone is a better virucide than chlorine.
(b) Ozone removes color, odor, and taste (such as phenolic compounds).
(c) Ozone oxidizes iron, manganese sulfides, etc.
(d) Ozone oxidizes organic impurities or pollutants in water.
(e) Ozone increases the dissolved oxygen content in water or wastewater.

Table 8.19
Oxidation potential of chemical disinfectants

Disinfectants	Chemical reactions	Oxidation potentials (E° volts)
Ozone	$O_3 + 2H^+ + 2e^- \rightarrow O_2 + H_2O$	2.07
Permanganate	$MnO_4^- + 4H^+ + 3e^- \rightarrow MnO_2 + 2H_2O$	1.67
Hypobromous acid	$HOBr + H^+ + e^- \rightarrow 0.5Br_2 + H_2O$	1.59
Chlorine dioxide	$ClO_2 + e^- \rightarrow ClO_2^-$	1.50
Hypochlorous acid	$HOCl + H^+ + 2e^- \rightarrow Cl^- + H_2O$	1.49
Hypoiodous acid	$HOI + H^+ + e^- \rightarrow 0.5I_2 + H_2O$	1.45
Chlorine gas	$Cl_2 + 2e^- \rightarrow 2Cl^-$	1.36
Bromine	$Br_2 + 2e^- \rightarrow 2Br^-$	1.09
Iodine	$I_2 + 2e^- \rightarrow 2I^-$	0.54

7. OXIDATION BY OZONE

7.1. *Ozone Reaction with Inorganics*

Potassium ozonide, KO_3, can be prepared at low temperatures by ozone treatment of dry KOH, the superoxide KO_2, or the metal itself dissolved in liquid ammonia as shown in Eqs. (23)–(25).

$$3O_3 + 3KOH \rightarrow KOH \cdot H_2O + 2O_2 + 2KO_3 \tag{23}$$

$$O_3 + KO_2 \rightarrow O_2 + KO_3 \tag{24}$$

$$O_3 + K \rightarrow KO_3 \tag{25}$$

This reaction will not occur in an aqueous medium because KO_3 immediately decomposes in the presence of water, probably by the reactions shown in Eqs. (26a)–(26c).

$$KO_3{}^+ + H_2O \rightarrow K^+ + HO_3 + OH^- \tag{26a}$$

$$HO_3 \rightarrow O_2 + [OH] \tag{26b}$$

$$4[OH] \rightarrow 2H_2O + O_2 \tag{26c}$$

The ozonides NaO_3 and $(CH_4)_4NO_3$ have also been prepared from ozone. However, they also would not be produced in an aqueous medium because of their decomposition in water, similar to that shown for KO_3. These ozonides are ionic crystals containing the O_3 ion.

The reaction of ozone with ammonia has been studied in the dry gaseous state, in liquid ammonia, in carbon tetrachloride solution, and in aqueous solution. The reaction is extremely fast, and the end product is always ammonium nitrate. The reaction is shown in Eq. (27).

$$2NH_3 + 4O_3 \rightarrow NH_4NO_3 + 4O_2 + H_2O \tag{27}$$

By carrying the reaction out at very low temperatures, the formation of the red ammonium ozonide, NH_4O_3 has been demonstrated. This compound decomposes rapidly to ammonium nitrate, oxygen, and water as shown in Eq. (28).

$$4NH_4O_3 \rightarrow 2NH_4NO_3 + O_2 + 4\ H_2O \tag{28}$$

Ammonium salts do not react again with ozone.

The reaction of ozone with the lower oxides of nitrogen NO, NO_2, N_2O_3, and N_2O_4, is extremely rapid leading to the formation of nitrogen pentoxide, N_2O_5, as shown in Eqs. (29)–(32).

$$2NO + O_3 \rightarrow N_2O_5 \tag{29}$$

$$6NO_2 + O_3 \rightarrow 3N_2O_5 \tag{30}$$

$$3N_2O_3 + 2O_3 \rightarrow 3N_2O_5 \tag{31}$$

$$3N_2O_4 + O_3 \rightarrow 3N_2O_5 \tag{32}$$

By the combined action of O_3, NO_2, and ClO_2 gases, nitronium perchlorate, NO_2ClO_4, can be formed as shown by Eq. (33). This is a white solid with low vapor pressure and strong oxidizing properties.

$$3NO_2 + 3ClO_2 + 2O_3 \rightarrow 3NO_2C1O_4 \tag{33}$$

In aqueous solutions, nitrites are oxidized to nitrates as shown by Eq. (34).

$$O_3 + NO_2{}^- \rightarrow NO_3{}^- + O_2 \tag{34}$$

This reaction has been used for the quantitative determination of ozone.

Ozone reacts rapidly with hydrogen sulfide, H_2S. In dry gas mixtures, the only reaction product appears to be SO_2, but the amount of ozone consumed per mole of H_2S has not been established with certainty. The reaction in water solution has not been adequately studied but there are reports that colloidal sulfur is among the products.

In the gas phase, ozone and sulfur dioxide, SO_2, react only slowly. In aqueous solutions, sulfates are produced. The reaction is pH dependent and complicated by induced oxidation of sulfites by oxygen, which is generally present along with the ozone. Thus, in sodium bisulfite solutions, ozone catalyzes the reaction between bisulfite and oxygen, this effect becoming more and more pronounced, the more dilute the ozone. In sufficiently dilute ozone, as many as 60 atoms of oxygen are consumed per molecule of ozone supplied. Similar observations have been made in the oxidation of aqueous SO_2 solutions.

Ozone liberates iodine from iodide solutions. The amount of iodine liberated per mole of ozone depends on the pH, concentration, temperature, and perhaps other factors. One mole of ozone liberates 1.0 mol of iodine, or its equivalent, in alkaline solutions; 1.1–1.3 mol of iodine at pH 7.0, and 2.5–3 mol of iodine in concentrated HI solutions. Ozone also oxidizes bromides to bromine as shown in Eq. (35).

$$O_3 + 2Br^- + H_2O \rightarrow Br_2 + 2OH^- + O_2 \tag{35}$$

Chlorides are only oxidized in acid solutions and the reaction is quite slow.

Ozone oxidizes the cyanide ion (CN^-) to cyanate (CNO^-) as shown in Eq. (36), in the first stage reaction, then the cyanate is oxidized further by ozone and converted to bicarbonate, nitrogen, and oxygen as shown in Eq. (37).

$$CN^- + O_3 \rightarrow CNO^- + O_2 \tag{36}$$

$$3CNO^- + 3O_3 + H_2O \rightarrow 2HCO^- + N_2 + 3O_2 \tag{37}$$

Thiocyanates (CNS^-) are oxidized to cyanide as indicated in Eq. (38).

$$CNS^- + 2O_3 + 2OH^- \rightarrow CN^- + SO_3{}^{2-} + 2O_2 + H_2O \tag{38}$$

If the addition of ozone is continued, then the cyanide ion is oxidized to cyanate and the sulfite ion is oxidized to sulfate as shown in Eq. (39).

$$CN^- + SO_3{}^{2-} + 2O_3 \rightarrow CNO^- + SO_4{}^{2-} + 2O_2 \tag{39}$$

Finally, the cyanate ion (CNO^-) can be oxidized to harmless bicarbonate, nitrogen and oxygen according to Eq. (37).

Argentic (Ag^{2+}) salts can be produced by treating $AgNO_3$ solutions with ozone as shown in Eq. (40).

$$Ag^+ + 2O_3 \rightarrow Ag^{2+} + 3O_2 \tag{40}$$

Ferrous (Fe^{2+}) salts are oxidized to ferric (Fe^{3+}) salts. In dilute H_2SO_4 solution, the reaction is as shown in Eq. (41).

$$2Fe^{2+} + O_3 + 2H^+ \rightarrow 2Fe^{3+} + O_2 + H_2O \tag{41}$$

The reaction for the oxidation of ferrocyanide, $Fe(CN)_6{}^{4-}$ to ferricyanide, $Fe(CN)_6{}^{3-}$ proceeds according to Eq. (42). The engineering significance of this reaction is for its usefulness in the treatment of wastewater produced by the photoprocessing industry (32).

$$2Na_4Fe(CN)_6 \cdot 10H_2O + O_3 \rightarrow 2Na_3Fe(CN)_6 + O_2 + 9H_2O + 2NaOH \tag{42}$$

This review of the reactions of ozone with inorganic pollutants in water and wastewater has failed to demonstrate that stable inorganic ozonides can be produced in aqueous solution and it is concluded that inorganic ozonides would not be a problem if ozone were used as the disinfectant for water or wastewater.

For practical water or wastewater treatment, ozone oxidizes inorganic impurities by straight chemical oxidation reaction. The following are examples.

(a) Ozone reacts rapidly to oxidize ferrous ion (Fe^{2+}) into ferric ion (Fe^{3+}). Ferric ion can then be removed as insoluble ferric hydroxide at high pH, or can coprecipitate with phosphate ion for both iron and phosphorus removals.

(b) Ozone rapidly oxidizes manganous (Mn^{2+}) into insoluble manganese dioxide or soluble permangante ($MnO_4{}^-$). The permanganate is also an oxidizing agent. Stoichiometrically, 0.94 mg/L of potassium permanganate will further oxidize 1 mg/L of ferrous ion; or 1.92 mg/L of potassium permanganate will further oxidize 1 mg/L of manganous ion. Eventually permanganate ion also converts into insoluble manganese dioxide in the aforementioned oxidation–reduction reaction.

(c) Ozone can break down organometallic complexes of both iron and manganese, which usually defy the conventional oxidation processes for iron and manganese removal from potable water.

(d) Ozone readily oxidizes sulfides and sulfites to stable sulfates, and nitrites to stable nitrates.

(e) Bromides and chlorides can be oxidized by ozone to bromine (Br_2) and chlorine (Cl_2), respectively although these reactions are slow and dependent upon the concentration of reactants.

(f) The oxidation of iodides (I) to iodine (I_2) is the basis for the standard method used in the determination of ozone concentration (64).

(g) The ammonium ion (NH_4^+) is apparently not attacked under normal pH values in wastewater treatment. So there is no waste of ozone oxidizing capacity with ammonia nitrogen if present in a waste stream. However, ammonia is oxidized completely to nitrate by ozone if the wastewater pH is and remains alkaline. The molar ratio of ozone consumed per ammonia oxidized is about 12 to 1 (65).

(h) In the process of treating photoprocessing water, silver is recovered electrolytically, then the spent bleach baths of iron ferrocyanide complexes are ozonated. Ferrocyanide in the spent liquor is oxidized to ferricyanide, which is its original form. Thus, the bleach is regenerated for reuse by the photoprocessor (see Eq. (42)).

(i) Ozone may replace chlorine in the treatment of industrial wastewaters containing cyanide. Ozone oxidation takes place in multistages according to Eqs. (36)–(39). Ozonation of cyanide ions and dyes in aqueous solutions is documented in Refs. (66, 67).

7.2. *Ozone Reaction with Organic Material*

The exact mechanism for the chemical processes taking place when water or wastewater is subjected to treatment by ozone and oxygen is still under investigation. In general, part of ozone in the reactor oxidizes carbonaceous substances in water or wastewater, thus producing carbon dioxide and oxygen, as shown in Eq. (43).

$$2O_3 + C(\text{Organic}) \rightarrow CO_2 + 2O_2 \tag{43}$$

The above reaction is oxidation reaction, and the carbon dioxide and oxygen are oxidation products. The remaining amount of available ozone reacts with organic substances yielding various intermediate and end products. The reaction is termed ozonolysis reaction, and the end products are termed ozonolysis products.

In ozonolysis reactions, ozone reacts readily with unsaturated organic compounds, (–C=C– or –C≡C–), adding all its three oxygen atoms at a double bond or a triple bond. The resulting compounds are termed ozonides. Decomposition of ozonides generally results in a rupture at the position of the unsaturated bond, causing the formation of simpler organic substances, such as ketones, aldehydes, acids, etc.

A typical reaction of ozone is its addition to the carbon–carbon bond of an ethylenic compound (68). This is illustrated by Eq. (44) in Fig. 8.15.

The resulting ozone–olefin compound is known as an ozonide, as discussed before. Decomposition of the ozonide gives a mixture of oxygenated products containing carbonyl compounds. This is shown by Eq. (45) in Fig. 8.15. Ozonides are not isolated as such, because of their unstable and explosive nature, but are employed for the production of other chemical

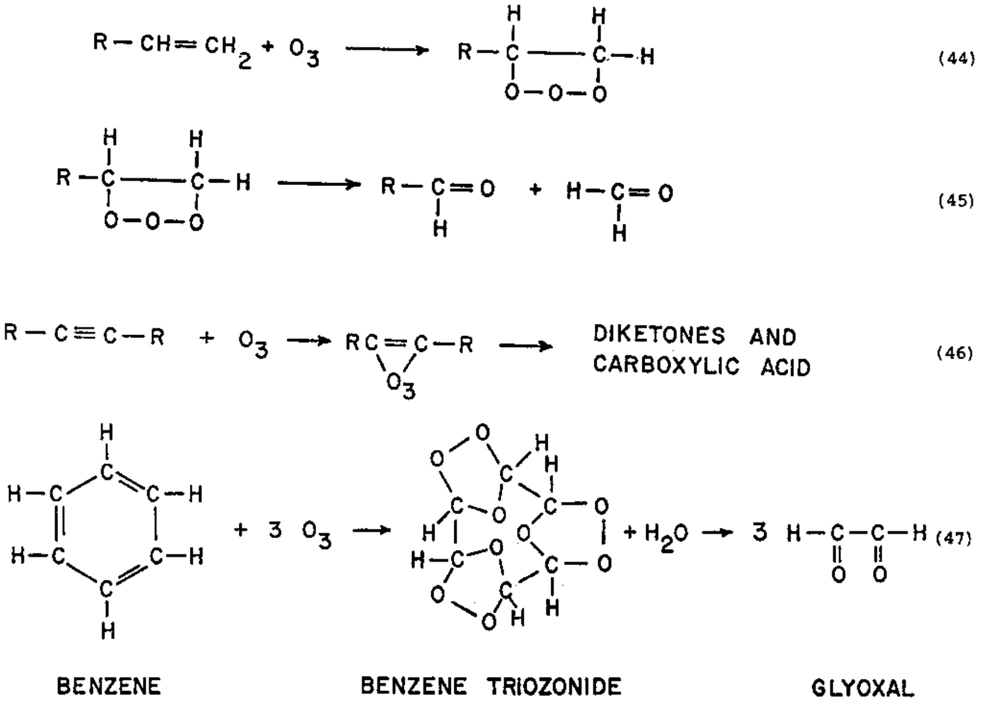


Fig. 8.15. Ozone reactions with organics – Eqs. (44)–(47) (68).

compounds. Useful products in good yields are obtained when the ozonides are reduced to produce carbonyl compounds or oxidized to produce carboxylic acids.

Ozone also adds to the carbon–carbon triple bond of acetylenic compounds as shown in Eq. (46) of Fig. 8.15. Very few detailed studies of the reaction have been made. The usual products isolated are diketones and carboxylic acids.

Ozone adds very slowly to benzene. Each benzene molecule can add three molecules of ozone and yields 3 mol of glyoxal, Eq. (47) in Fig. 8.15. Methyl-substituted benzenes react more rapidly. Hexamethyl benzene reacts several thousand times more rapidly than benzene. Hydrolysis of the ozonide products produce the carbonyl compounds usually obtained in ozonolysis reactions. Equation (48) in Fig. 8.16 illustrates how 2 mol of methyl-substituted benzene react with 6 mol of ozone yielding 3 mol of glyoxal, 1 mol of diacetyl, and 2 mol of z-methylglyoxal (31, 68).

In polynuclear aromatic compounds, the various carbon bonds and atoms have different reactivities. The reaction with ozone is more complex, and the composition of the products is difficult to predict. Oxidation at a carbon atom may, at times, predominate over ozone addition to a carbon–carbon double bond. While some aromatic compounds may add ozone rapidly and form ozonides, others may be oxidized to give quinones. Frequently, aromatic compounds react in both ways and the reaction mixture contains both oxidation and ozonolysis products.

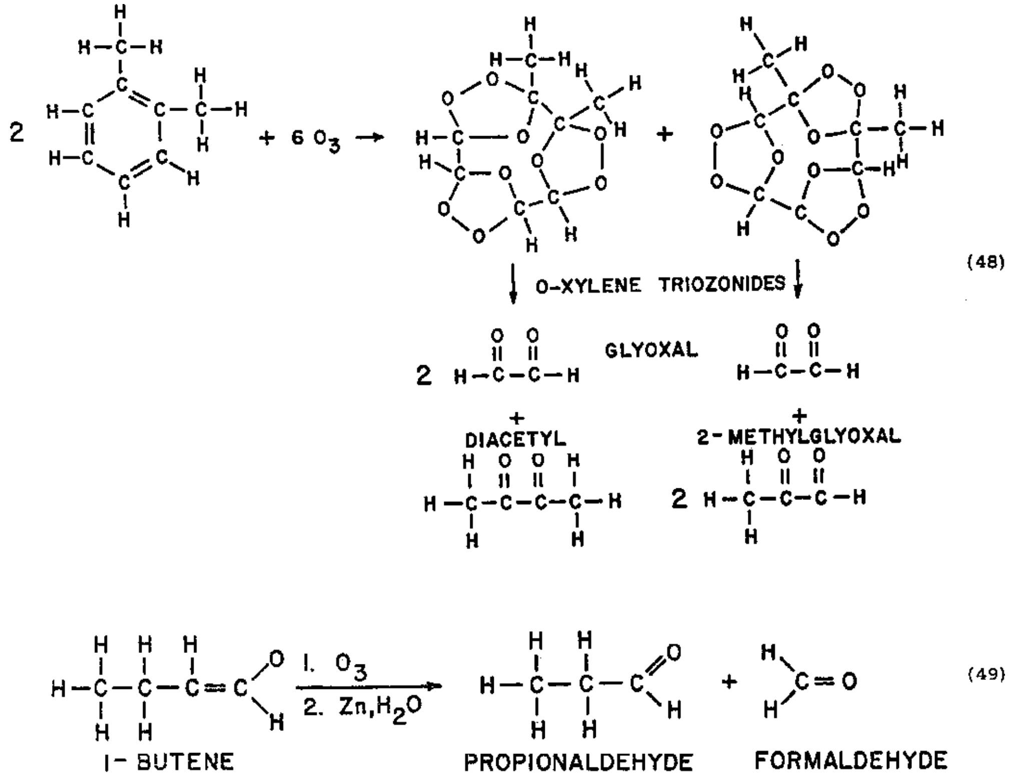


Fig. 8.16. Ozone reactions with organics – Eqs. (48) and (49) (31, 68).

Saturated hydrocarbons react very slowly with ozone at room temperature. However, at elevated temperatures, the reaction proceeds quite rapidly. Peroxides, ketones or aldehydes, alcohols, and acids are formed as the reaction products. Ethers are oxidized by ozone at the carbon next to the ether oxygen. Therefore, esters are found among the oxidation products. Lactones are produced by the reaction of ozone and cyclic ethers. Ozonation of cyclic formals produce carbonates.

Organic sulfides are oxidized by ozone through sulfoxides, RSOR′, to sulfones, RSO_2R'. The intermediate sulfoxide may be isolated. Primary and secondary amines are only degraded by ozone but tertiary amines form tertiary amine oxides. Organic phosphates may be prepared by ozone oxidation of phosphites, and phosphine oxides are formed from phosphines.

Besides the ozonolysis and oxidation reactions where stoichiometric amounts of ozone are reacted, there are catalytic reactions where experimental conditions determine the amount of ozone used. The preparation of peroxyacids from aldehydes is one of these reactions. Ozone is only a catalyst or initiator of the oxidation. In the production of cumene hydroperoxide intermittent ozonation of cumene is used.

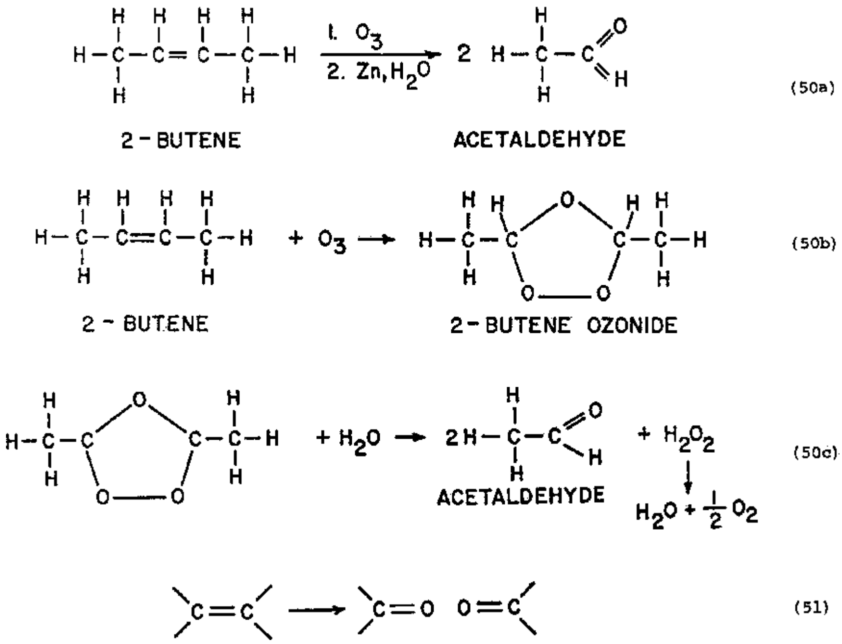


Fig. 8.17. Ozone reactions with organics – Eqs. (50)–(51) (31).

Ozonolysis followed by hydrolysis is reliable, though at times dangerous due to the unstable and explosive nature of ozonides, which search for the double bond in organic compounds. This ozonolysis/hydrolysis reaction sequence can be illustrated by the difference in reaction products obtained by the reaction of ozone with 1-butene and 2-butene as shown by Eq. (49) in Fig. 8.16 and Eq. (50a) in Fig. 8.17. Usually ozonized oxygen, containing up to 15% ozone, is passed at room temperature into a solution of the unsaturated compound. The ozonide formed is hydrolyzed either in the presence of a reducing agent to obtain aldehydes and ketones or with hydrogen peroxide in acetic acid solution to get carboxylic acids (31).

The decomposition of an ozonide can also be effected by catalytic hydrogenation. The over-all reaction is a breaking of the double bond with two carbonyl groups appearing in its place as represented by Eq. (51) in Fig. 8.17.

Ozonides, like most substances with the peroxide (O–O) bonds, are very unstable and may explode violently and unpredictably. Ozonation must, therefore, be carried out with due care and caution. The ozonides are usually not isolated but are destroyed by hydrolysis with water to yield carbonyl compounds that are generally quite easy to isolate and identify. The ozonation of 2-butene followed by hydrolysis to form acetaldehyde is an example of this, as shown by Eqs. (50b) and (50c) in Fig. 8.17.

Very few detailed studies have been made about the chemical pathways involved in ozonation of organic substances in water. In most studies in aqueous media, a cosolvent, a water emulsion, or a suspension has been employed.

Pryde (69) has ozonized methyl oleate and methyl lineoleate in water media and decomposed the peroxidic ozonolyses products to aldehydes and/or carboxylic acids under various conditions. Criegee and Lohaus (70) has synthesized a peroxide from ozonolysis of cyclic sulfone in the presence of water.

Sturrock (71) has ozonized the aliphatic 9, 10 bond of phenanthrene in an aqueous *t*-butyl alcohol medium and obtained a dialdehyde. Ozonolysis of acetylenic compounds (C=C) in aqueous media have not been studied but presumably peroxides would be produced that readily decompose to carboxylic acids.

Ozonation of aromatic compounds appears to involve both 1,3-dipolar cycloaddition at a carbon–carbon bond to give ozonolysis products and electrophilic ozone attack at individual carbon atoms (68). In regard to ease of ozone attack, the unsubstituted benzene ring is much less reactive than an olefinic double bond (68). Polycyclic aromatics, such as phenanthrene, anthracene, and naphthalene, fall in between in reactivity (68). Alkyl and other substituents, which activate for electrophilic attack facilitate ozone attack while those which deactivate for electrophilic attack drastically decrease the rate of ozone attack on the aromatic nucleus (68). Benzene (72) and its homologs (68), however, react to give the ozonolysis products as shown by Eq. (47) (Fig. 8.15) and Eq. (48) (Fig. 8.16).

Considerable study has been given to the removal of phenolic wastes from water (73). Phenols are more reactive with ozone than most aromatics, and phenol itself has been oxidized to carbon dioxide, formic acid, glyoxal, and oxalic acid (74). Eisenhauer (73, 75) has carried out a detailed study of the reaction of ozone with phenol in water solutions and has identified catechol and *o*-quinone as intermediary products. However, he did not establish that the reaction went solely through these intermediates. Muconic acid was assumed to be the next intermediate, followed by further ozonolysis of this unsaturated substance (73). Ozonation of other phenols and napththols have also been shown to occur readily (76–79).

The ozonation of polycyclic hydrocarbons has been studied extensively (68, 80, 81), although most of the work has been done in nonaqueous media. Most aromatic and aliphatic unsaturated heterocycles readily react with ozone (68). An exception is the pyridine ring, which reacts very slowly. Various organic substances with a nucleophilic atom in their structure are readily oxidized by ozone (68).

Various amino acids and proteins have been ozonized in water solution, but the ozone attack appears to have occurred at sulfur (cystine), aromatic, or heterocyclic unsaturated carbon–carbon bonds rather than nitrogen (82).

When reactive groupings are not present in organic molecules, ozone attack on carbon–hydrogen bonds becomes possible. Such reaction occurs readily with aldehydes (83–85), ethers (86, 87), alcohols (88), and hydrocarbons (89, 90) or hydrocarbon groupings (91) having secondary or tertiary carbon–hydrogen bonds. Through these reactions, aldehydes are converted to carboxylic acids; primary and secondary alcohols to carborylic acids, aldehydes, or ketones; ethers to alcohols and esters; and hydrocarbons to alcohols and ketones. There appears to be general agreement that these ozonation reactions involve a hydrotrioxide intermediate. However, the exact mode of formation of the intermediate and how it is converted to products is not clear.

The ozonation of ethers has recently been carried over to acetals, including sugar glycosides, to yield esters (92). Evidence is also available about the ozonation of sugar alcohols and of polysaccharides in aqueous medium (93), including the degradation of wood pulp (94–96). A simple carbon–hydrogen bond ozonation, which has been performed in water solution, is that of malonic acid (97). The methylene group (CH_2) was converted to an alcohol and a ketone function. Oxalic acid and carbon dioxide were also produced.

Because ozonides are active oxygen compounds, they could be used as oxidizing agents, polymerization catalysts, bleaching agents, and germicides. But their instability makes it difficult to prepare them in good yields and to use them safely in reactions. Ozonides or ozonolysis products have at times exploded on standing.

Commercially, ozonides are not handled as such, but serve only as intermediates to more stable products. The reduction of some organic ozonides will produce aldehydes in good yields and oxidation will produce carboxylic acids. Thermal composition of an ozonide will produce a mixture of aldehydes, acids, peroxy compounds, and some other by-products. The nature of solvents determines what ozonolysis products will be obtained. In nonpolar hydrocarbon solvents, ozonides will be formed. In more polar solvents, a mixture of ozonides, peroxides, aldehydes, and acids will be produced.

Ozonolysis products are thermally unstable. The reaction must be maintained within a specific temperature range to prepare these compounds. Since the ozone addition reaction is highly exothermic, reaction vessels must be cooled to maintain the desired reaction temperature.

Amines and amino acids may be prepared by reductive amination of oxonides or ozonolysis products. Ozone adds three oxygen atoms to the double bond. Therefore, further oxidation of the ozonide is required to give 2 mol of acids. Oxidation with air or oxygen will give satisfactory results in most cases. Some ozonides, however, may be more difficult to oxidize, and in these cases, oxidation with peroxyacids is required.

Humic acid is a major precursor for trihalomethane (THM) formation. Glaze et al. (98) have reported on the ability of ozone to destroy humic acid. Guirguis et al. (99) confirmed that ozone makes organic compounds better adsorbed by activated carbon.

Prengle et al. (100) reported that ozone plus UV light could reduce an organic pesticide, malathion, to carbon dioxide and water and simultaneously could reduce the TOC in water. Likewise, Richard (101) found that ozone could degrade two other pesticides, parathion and marathion, to simple phosphoric acid.

8. OXYGENATION AND OZONATION SYSTEMS

8.1. Oxygenation Systems

The use of pure oxygen or oxygen-enriched air instead of air alone can improve upon many conventional water and waste treatment technologies. Some of the developments in this regard include the following (102–109):

(a) Oxygenated activated sludge process for wastewater treatment and/or nitrification
(b) Autothermal thermophilic oxygen digestion process for sludge treatment

(c) Dissolved oxygen flotation process for iron and manganese removal from water
(d) Oxygenation–ozonation process for sludge management and wastewater reclamation
(e) Improved ozone generation technology using pure oxygen or oxygen-enriched air

Potential sources of supply for oxygen include on-site oxygen generation plants, transport of liquid oxygen to the site, and use of an oxygen gaseous pipeline supply.

On-site oxygen generation systems are the most economical and desirable form of oxygen supply for the aforementioned five applications, provided the plant is large enough (i.e., at least 1 MGD) to economically handle the capital cost for such installation.

A liquid oxygen supply system is useful for small plant's operation, or as back-up oxygen supply and peak load equalization for plants of any size. Although the unit oxygen cost is generally high, the small plants could find this to be a good option because of the saving of cost for capital investment. A pipeline oxygen supply system is practical if the treatment plant is in the vicinity of an oxygen generation facility.

There are two basic oxygen generation systems:

(a) The traditional cryogenic air separation (CAS) process for the large size plants, and
(b) The pressure-swing adsorption (PSA) process for the somewhat smaller and more common plant sizes.

The standard CAS process (Fig. 8.18) involves the liquefaction of air followed by fractional distillation to separate it into its components (mainly nitrogen and oxygen). The entering air is first filtered and compressed. It is then fed to the reversing heat exchangers, which perform the dual function of cooling and removing the water vapor and carbon dioxide by freezing these mixtures out onto the exchanger surfaces. This process is accomplished by periodically switching or "reversing" the feed air and the waste nitrogen streams through identical passes of the exchangers to regenerate their water vapor and carbon dioxide removal capacity. The air is next processed through "cold end gel traps" which are adsorbent beds, which remove the final traces of carbon dioxide as well as most of the hydrocarbons from the feed air. It is then divided into two streams, one of which feeds directly to the "lower column" of the distillation unit and the other is returned to the reversing heat exchangers and partially warmed to provide the required temperature difference across the exchanger. This second stream is then passed through an expansion turbine and fed into the "upper column" of the distillation unit. An oxygen-rich liquid exits from the bottom of the "lower column" and the liquid nitrogen from the top. Both streams are then subcooled and transferred to the upper column. In this column, the descending liquid phase becomes progressively richer in oxygen until what collects in the condenser reboiler is the oxygen product. This oxygen stream is continually recirculated through an adsorption trap to remove all possible residual traces of hydrocarbons. The nitrogen exits from the top portion of the "upper column" and its heat is exchanged with the oxygen product to recover all available refrigeration and to regenerate the reversing heat exchangers as discussed above.

The PSA system uses two (or more) adsorbent vessels to provide a continuous and constant flow of oxygen gas. Figure 8.19 shows a PSA system with three adsorbers. In operation, the feed air is compressed by a nonlubricated compressor. This compressed air is separated into oxygen- and nitrogen-rich streams as it flows through one of the adsorbent

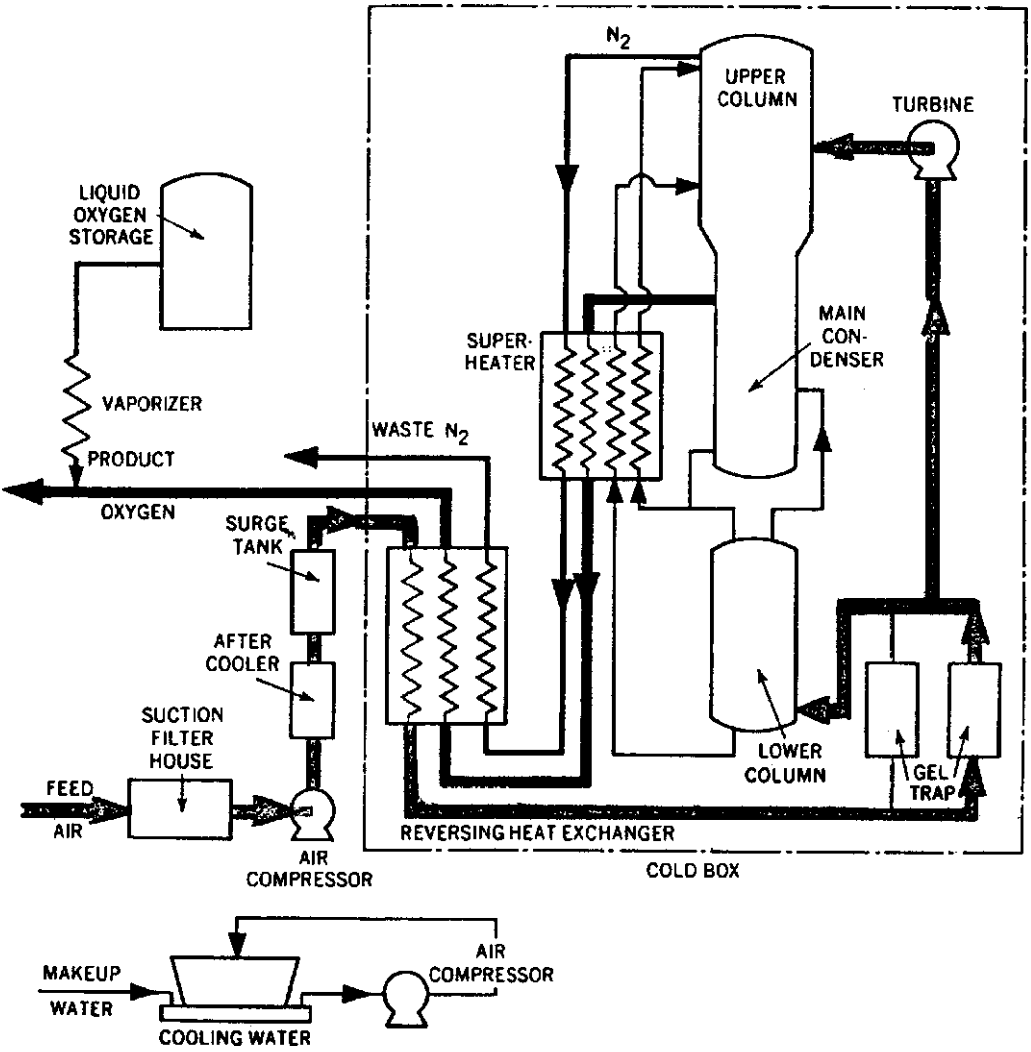


Fig. 8.18. Cryogenic air separation system for oxygen production (Source: Union Carbide Corp.).

vessels. The adsorbent is a granular material (molecular sieve), which attracts and traps (adsorbs) the carbon dioxide, water, and nitrogen gas, producing a relatively high purity oxygen product. While one bed is adsorbing, the other beds are in various stages of regeneration. The PSA oxygen generator operates on a pressure swing, an adsorption concept in which the oxygen is separated from the feed air by adsorption at high pressure and the adsorbent is regenerated by blow down to low pressure. The process operates on a repeated cycle that has two basic steps, adsorption and regeneration. During the adsorption step, feed airflow through one of the adsorbent vessels until the adsorbent is partially loaded

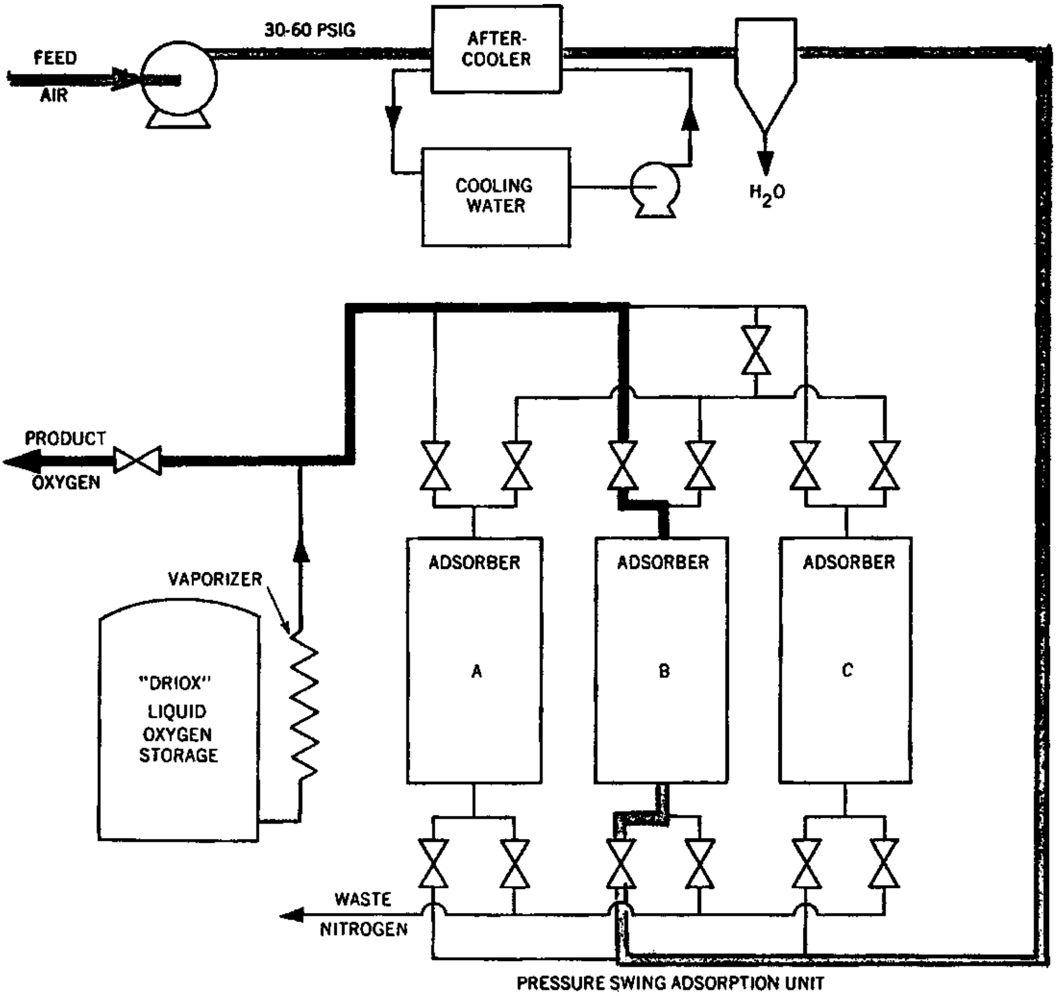


Fig. 8.19. Pressure swing adsorption system for oxygen production (Source: Union Carbide Corp.).

with impurity. At that time, the feed airflow is switched to another adsorber and the first adsorber is regenerated. During the regeneration step, the impurities (carbon dioxide, water, and nitrogen) are cleaned from the adsorbent so that the cycle (adsorption–generation) can be repeated.

Regeneration of the adsorber is carried out in three basic steps:

(a) The adsorber is depressurized to atmospheric pressure to remove some impurities from the adsorbent and to make it easy to remove the remaining impurities.
(b) The adsorber is purged with product oxygen to clean the remaining impurities.
(c) The adsorber is repressurized to adsorption pressure and is again ready to separate the feed air.

8.2. Ozonation Systems

Generally there are four basic ozonation systems used in water and waste treatment. Figures 8.20–8.23 illustrate the four systems. When the least cost basic system has been arrived at, there remains only the contactor that must be designed to finalize the ozone treatment system. For details and more information on ozonation technology, monitoring, and control instrumentation, the reader is referred to Refs. (102–113).

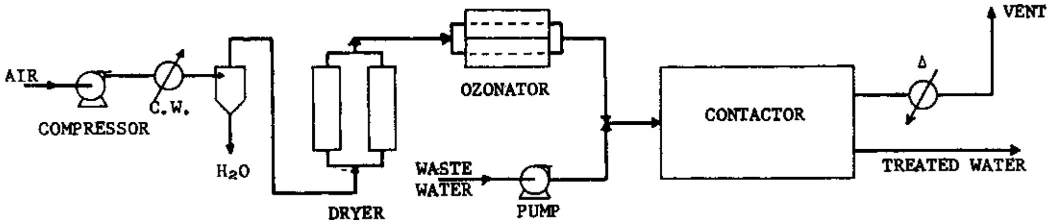


Fig. 8.20. Open-loop ozonation system using air (Source: W.R. Grace & Co.).

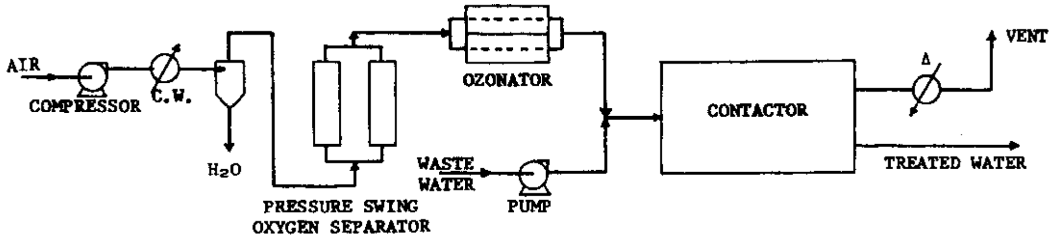


Fig. 8.21. Open-loop ozonation system using oxygen-rich air (Source: W.R. Grace & Co.).

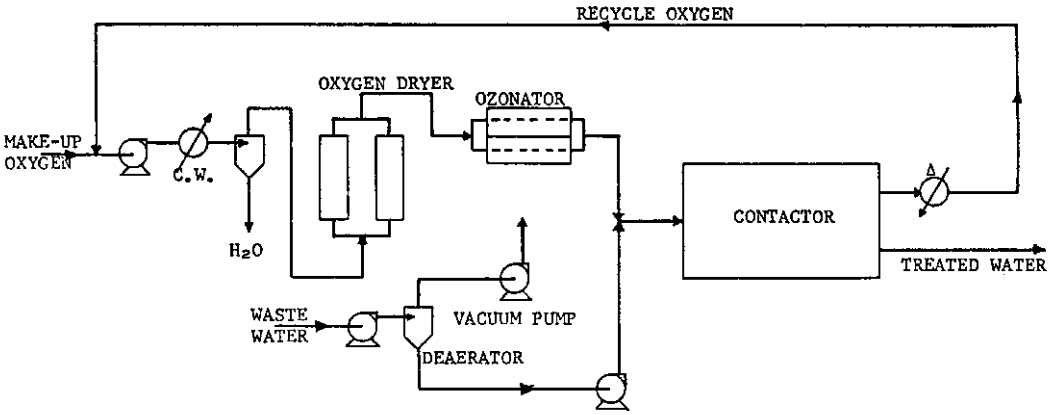


Fig. 8.22. Closed-loop ozonation system using oxygen (Source: W.R. Grace & Co.).

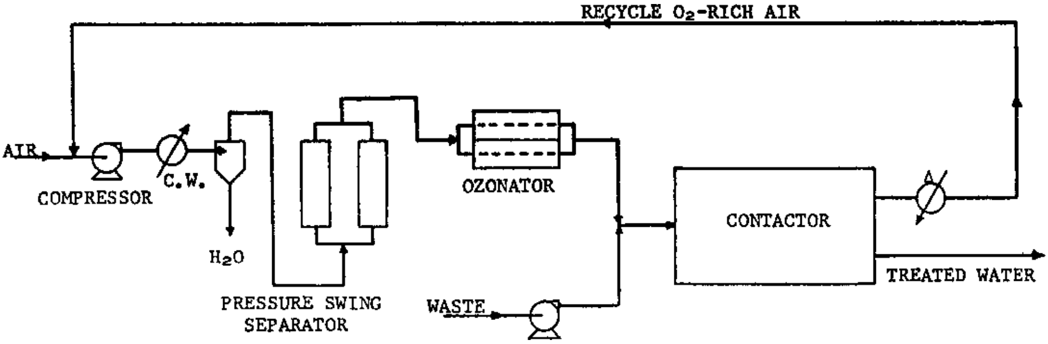


Fig. 8.23. Closed-loop ozonation system using oxygen-rich air (Source: W.R. Grace & Co.).

Table 8.20
Removal of conventional pollutants by ozonation (Source: U.S. EPA)

	Removal data		
Pollutant/parameter	Concentration		Percent removal
	Influent	Effluent	
Classical pollutants (mg/L)			
BOD_5	5,800	5,200	10
COD	77,000	12,000	84
TSS	64	140	NM
Oil and grease	130	4.0	97
Total phenol	47	0.13	>99
Toxic pollutants (μg/L)			
Cyanide	560	1,500	NM
Zinc	2,200	90	96

Sampling: Equal volume grab samples collected throughout an 8-h day; average of 2 days sampling
NM not meaningful.

In the first system, compressed air is cooled to remove moisture and is fed to a dryer. The dry air is fed to the ozone generator and the ozone–air solution (1–3% ozone by weight) is mixed with the incoming water or waste in a contactor. The treated effluent and gases leave the contactor separately. Any excess ozone in the effluent soon decomposes to oxygen while the ozone in the waste gas should be destroyed by heat or by chemical or catalytic decomposition. This system is applicable to very small installations.

The second system is similar to the first but is somewhat more cost efficient for larger installations because air has been replaced by oxygen-enriched feed stream. The use of a PSA technique for producing oxygen-enriched air will reduce the capital and operating costs of the ozone generator.

The third system for ozone treatment is similar to the first but oxygen is fed to the generator and oxygen-rich off-gas is recycled to the front end of the loop. There is an additional deaeration step to remove nitrogen from the wastewater before its treatment so that it does not build up in the gas recycle.

In the fourth system, air is enriched to about 40% oxygen in the startup cycle. In each successive cycle, the recycled gas is cleaned, dried, enriched in oxygen and any excess ozone decomposed by the catalytic effect of the molecular sieves used in the pressure swing

Table 8.21
Removal of toxic pollutants by ozonation (Source: U.S. EPA)

Pollutant	Removal (%)
Heavy metals	
Antimony	76
Arsenic	45
Xylene	97
Cadmium	98
Chromium	52
Copper	75
Lead	98
Mercury	75
Nickel	73
Silver	45
Organic chemicals	
Bis (2-ethylhexyl) phthalate	72
Butyl benzyl phthalate	99
Carbon tetrachloride	75
Chloroform	58
Dichlorobromomethane	99
Diethyl Di-*n*-butyl phthalate	97
Diethyl phthalate	99
Di-*n*-octyl phthalate	78
N-nitrosodiphenylamine	66
2,4-Dimethylphenol	99
Pentachlorophenol	19
Phenol	57
Dichlorobenzene	76
Ethylbenzene	65
Toluene	39
Naphthalene	77
Anthracene/phenanthrene	81

Table 8.22
Removal of cyanide by ozonation (Source: U.S. EPA)

Removal data				
Flow rate (L/min)	Ozone feed rate (g/h)	Cyanide		
		Concentration (μg/L)		Percent removal
		Influent	Effluent	
3,200		900	<20	>97
9.5	3	360	20	94
9.5	3	160	18	89
4.9	6	200	95	51

Sampling: Grab.
Blanks indicate data not available.

separator. The system can be programmed so that the economic point of ozone generation versus oxygen generation (probably around 80% oxygen) is achieved. The other 20% will consist of nitrogen, carbon dioxide, and argon. By mixing adsorbents in the PSA separator, nitrogen, CO_2, and water will be removed in each cycle and oxygen increased. Air of course will be added for makeup. At less than the 10% level, CO_2 and argon have little effect on ozone production efficiency and nitrogen has a positive effect. This system provides the following functions with a single PSA separator in a closed loop with the ozone generator and contact system.

(a) Oxygen enrichment
(b) Removal of nitrogen and CO_2
(c) Drying to −100°F dew point; and
(d) Catalytic decomposition of excess ozone

8.3. *Removal of Pollutants from Sludge by Ozonation*

The removal data compiled by the U.S. Environmental Protection Agency are summarized in Tables 8.20–8.22, The tables clearly show that the ozonation process can efficiently remove not only the classical pollutants, such as BOD, COD, TSS, oil, grease, and phenol (Table 8.20), but also heavy metals and toxic organics (Tables 8.21 and 8.22).

9. NOMENCLATURE

B = Concentration of ozone in liquid/Concentration of ozone in gas, reduced to STP = the Bunsen coefficient of solubility
C = Residual concentration of disinfectant, mg/L

H = Henry's constant, mol/atm (mole fraction of ozone in solution/partial pressure of ozone in gas, in atm)
k_1, k_2, and k_3 = rate constants
L = Lethality coefficient, $(\text{mg/L})^{-1}\ \text{min}^{-1}$
M = a chemical element
$[\text{OH}^-]$ = Hydroxide concentration, g mol/L
T = Temperature, K
t = Time in minutes for 99% microorganism destruction (2-log destruction)

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REFERENCES

1. CEC (2010) Applications and current status of ozone for municipal and industrial wastewater treatment. California Energy Commission (CEC) Website, www.energy.ca.gov
2. U.S. Department of Energy (2003) Pressurized ozone/ultrafiltration membrane system. Office of Industrial Technologies Website, www.oit.doe.gov
3. Park YG (2002) Effect of ozonation for reducing membrane-fouling in the UF membrane. Desalination 147:43–48
4. Wang LK (1983) Pretreatment and ozonation of cooling tower water, Part I. Technical Report # PB84–192053. U.S. Department of Commerce, National Technical Information Service, Springfield, VA, April 1983
5. Wang LK (1983) Pretreatment and ozonation of cooling tower water, Part II. Technical Report # PB84–192046. U.S. Department of Commerce, National Technical Information Service, Springfield, VA, August 1983
6. Wang LK, Wang MHS (1990) New dawn in flotation treatment of industrial water and wastes. Proceedings of the 1990 modern engineering technology seminar, Taipei, Taiwan, ROC, December 1990
7. Chen JN (1987) The functional increment of ozonation process and application for industrial wastewater treatment. Institute of Environmental Engineering, NSC, NSC 87–2211-E-009–027 140.113.2.117/Backup/87-Eng/College_Of_Engineering/Environmental_Engineering.doc
8. Wang LK, Wang MHS, Peery GG, Cheugn RCM (1978) General theories of chemical disinfection and sterilization of sludge, Part 1. Water Sew Works 125(7):30–32
9. Wang LK, Wang MHS, Peery GG, Cheugn RCM (1978) General theories of chemical disinfection and sterilization of sludge, Part 2. Water Sew Works 125(8):58–62

10. Wang LK, Wang MHS, Peery GG, Cheugn RCM (1978) General theories of chemical disinfection and sterilization of sludge, Part 3. Water Sew Works 125(9):99–104
11. Wang LK, Wang MHS, Peery GG, Cheugn RCM (1978) General theories of chemical disinfection and sterilization of sludge, Part 4. Water Sew Works 125(10):33–35
12. Wang LK (1982) Principles and kinetics of oxygenation – ozonation waste treatment system. Technical Report # PB83–127704. U.S. Department of Commerce, National Technical Information Service, Springfield, VA
13. Shammas NK, DeWitt N (1992) Flotation: a viable alternative to sedimentation in wastewater treatment. Water Environment Federation, 65th annual conference, Proceedings of the liquid treatment process symposium, New Orleans, LA, 20–24 September 1992, pp 223–232
14. Shammas NK (1997) Physicochemically-enhanced pollutants separation in wastewater treatment. Proc. international conference: Rehabilitation and development of civil Engineering infrastructure systems – upgrading of water and wastewater treatment facilities, The American University of Beirut and University of Michigan, Beirut, Lebanon, 9–11 June 1997
15. Shammas NK, Krofta M (1994) A compact flotation – filtration tertiary treatment unit for wastewater reuse. Water reuse symposium, AWWA, Dallas, TX, February 27–March 2 1994, pp 97–109
16. Krofta M, Miskovic D, Shammas NK, Burgess D, Lampman L (1994) An innovative multiple stage flotation – filtration low cost municipal wastewater treatment system. IAWQ 17th biennial international conference, Budapest, Hungary, 24–30 July 1994
17. Krofta M, Miskovic D, Shammas NK, Burgess D (1994) Pilot-scale applications of a primary–secondary flotation system on three municipal wastewaters. Specialist conference on flotation processes in water and sludge treatment, Orlando, FL, 26–28 April 1994
18. Wang LK, Shammas NK, Selke WA, Aulenbach DB (2007) Flotation thickening. In: Wang LK, Shammas NK, Hung YT (eds) Biosolids treatment processes. Humana, Totowa, NJ, pp 71–100
19. Wang LK, Fahey EM (2005) Dissolved air flotation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana, Totowa, NJ, pp 431–500
20. Peterson SA (1982) Oxyozosynthesis sludge treatment process – a case study of International Wastewater Reclamation Technologies Inc. New Process. Internal Technical Report, West New York Municipal Utility Authority, West New York, NJ, June 1982
21. U.S. EPA (1994) A plain English guide to the EPA part 503 biosolids rule. Report # EPA 832/R-93/003. U.S. Environmental Protection Agency, Washington, DC, September 1994
22. Wang LK (1984) Waste treatment by innovative flotation-filtration and oxygenation-ozonation process. Technical Report # PB85–174738-A. U.S. Department of Commerce, National Technical Information Service, Springfield, VA
23. Zabady RG, Edwards RN (1980) Oxyozonation process for treatment of municipal and industrial wastewaters and sludges: pilot studies. 52nd annual conference of the Water Pollution Control Association of Pennsylvania, Pennsylvania State University, PA, August 1980
24. Krofta M, Wang LK (1982) Development of innovative sandfloat system for water purification and pollution control. Report # PB83-l0796l. U.S. Department of Commerce, NTIS, Springfield, VA, August 1982
25. Asano T (1981) On-site wastewater reclamation and reuse systems in commercial buildings and apartment complexes. AWWA water reuse symposium II, Washington, DC, August 1981
26. Krofta M, Wang LK (1981) Treatment of Pittsfield raw water for drinking water production by innovative process systems. Report # PB82-l18795. U.S. Department of Commerce, NTIS, Springfield, VA, February 1981

27. Ozonology Inc. (2009) Innovation in ozone generating technologies – air cooled ozone generators. www.ozonology.com
28. O_3 Water Systems (2009) Commercial and industrial ozone equipment. www.o3water.com/Products/prozone.htm
29. Singer SG (2009) POU ozonation disinfection. Semper Pure Systems, Inc., www.pure1.com/P1/NArticles2.htm
30. Editor (2002) 2002 Buyer's guide: ozonators. Environ Prot 13(3):149
31. Harr TE (1975) Residual chlorine in wastewater effluents resulting from disinfection. Technical Paper # 38. NY State Department of Environmental Conservation, March 1975
32. Ouellette RP, King JA, Cheremisinoff PN (1978) Electrotechnology, vol 1, Wastewater treatment and separation methods. Ann Arbor Science Publishers, Ann Arbor, MI
33. Finnegan-Reztek (2009) How does an ozone generator work? www.fin-tek.com/ozone/howdoesanozonegeneratorwork.asp
34. Nathanson R (2003) Ozone: design parameters for using ozone on swimming pools. Water Quality Products 8(4):22, April 2003
35. U.S. EPA (1989) Technologies for upgrading existing or designing new drinking water treatment facilities. EPA/625–4–89/023. U.S. Environmental Protection Agency, Washington, DC
36. U.S. Army (1978) Engineering and design – design of wastewater treatment facilities major systems, Engineering Manual No. 1110–2–501. US Army, Washington, DC
37. GDT (2003) Corporation high efficiency ozone contacting system. GDT Water Process Corporation, Phoenix, AZ, www.gdt-h2o.com
38. Wang LK, Kurylko L, Wang MHS (1991) Gas dissolving system and method. US Patent No. 5049320, U.S. Patent and Trademark Office, Washington, DC, September 1991
39. Manely TC, Niegawski SJ (1967) Ozone. In: Encyclopedia of chemical technology, vol 14. Interscience Publishers, New York, p 410
40. Wang LK, Elmore DC (1981) Computer-aided modeling of water vapor pressure, gas absorption coefficient and oxygen solubility. Technical Report # PB82-l18787. U.S. Department of Commerce, NTIS, Springfield, VA, October 1981
41. Hill AG (1981) Ozone absorption in a pressurized bubble column. Technical paper presented at the AIChE national meeting, Detroit, MI, August 1981
42. Roth JA, Sullivan DE (1981) Solubility of ozone in water. Eng Chem Fundam 20:137–140
43. Smith WW, Bodkin RE (1944) The influence of hydrogen ion concentration on- the bactericidal action of ozone and chlorine. J Bacteriol 47:445
44. Leiguarda RH (1949) Bactericidal action of ozone. An Asoc Quim Argent 37:165 and Water Pollut Abstr 22:268 (1949)
45. Whitson MTB (1950) Symposium on the sterilization of water, (D) other processes with special references to ozone. J Inst Water Engrs 4:600
46. Bernier H (1950) Ozone sterilization of the water supply of nice and coastal communities. Tech Sanit Munic 45:117 and Water Pollut Abstr 24:243 (1951)
47. Bringman G (1954) Determination of the lethal activity of chlorine and ozone on E. coli. Z Hyg Infektionskr 139:130 and Water Pollut Abstr 28:12 (1955)
48. Wuhrmann K, Meyrath J (1955) The bactericidal action of ozone solution. Schweiz Z Allgem Pathol Bakteriol 18:1060 and Water Pollut Abstr 29:223 (1955)
49. Hann VA (1956) Disinfection of drinking water with ozone. J Am Water Works Assoc 48:1316
50. Scott DBM, Lesher EC (1963) Effect of ozone on survival and permeability of E. coli. J Bacteriol 85:567

51. Christensen E, Giese AC (1954) Changes in absorption spectra of nucleic acids and their derivatives following exposure to ozone and ultraviolet radiation. Arch Biochem Biophys 51:208
52. Barron ES (1954) The role of free radicals of oxygen in reactions produced by ionizing radiations. Radiat Res 1:109
53. Murray RGE (1965) Location of mucopeptide of selections of the cell wall of E. coli and other gram-negative bacteria. Can J Microbiol 11:547
54. Smith DK (1969) Disinfection and sterilization of polluted water with ozone. Report AM-6704. Ontario Research Foundation
55. Boucher PL (1967) Microstraining and ozonation of water and wastewater. Proceedings of the 22nd industrial waste conference, Purdue University Engr. Ext. Series 129, p 771
56. Boucher PL (1968) Use of ozone in the reclamation of water from sewage effluent. J Inst Public Health Engrs 67:75
57. Huibers DT, McNabney R, Halfon A (1969) Ozone treatment of secondary effluents from wastewater treatment plants. Robert A. Taft Water Research Center, Report # TWRC-4
58. White GC (1978) Disinfection of wastewater and water for reuse. Van Nostrand Reinhold Co., New York.
59. Ramalho RS (1977) Introduction to wastewater treatment processes. Academic Press, New York
60. Weber WJ (1972) Physicochemical processes for water quality control. Wiley-Interscience, New York
61. Sanks RL (1979) Water treatment plant design. Ann Arbor Science, Ann Arbor, MI
62. Legan RW (1982) Alternative disinfection methods-a comparison of UV and ozone. Ind Water Eng 19(2):12
63. Morris JC (1975) Aspects of the quantitative assessment of germicidal efficiency. In: Johnson JD (ed) Disinfection, water and wastewater. Ann Arbor Science, Ann Arbor, MI, Chap 1
64. APHA AWWA (2005) WPCF standard methods for the examination of water and wastewater. American Public Health Association, Washington, DC, 21st Edition
65. Singer PC, Zilli WB (1975) Ozonation of ammonia in wastewater. Water Res 9:127
66. Teramota M (1981) Kinetics of the self-decomposition of ozone and the ozonation of cyanide ion and dyes in aqueous solutions. J Chem Eng Jpn 14:383
67. Teramota M (1981) Overall rate of ozone oxidation of cyanide in bubble column. J Chem Eng Jpn 14:111
68. Bailey PS (1958) The reaction of ozone with organic compounds. Chem Rev 58:925
69. Pryde EH, Moore DJ, Cowan JC (1968) Hydrolytic, reductive and pyrolytic decomposition of selected ozonolysis products. Water as an ozonization medium. J Am Oil Chem Soc 45:888
70. Criegee R, Lohaus G (1953) Die ozonide ungesattigter cyclischer sulfone. Justus Liebigs Ann Chem 583:1
71. Sturrock MG, Cline EL, Robinson KJ (1963) The Ozonation of phenanthrene with water as participating solvent. J Org Chem 28:2340
72. Keaveney WP, Rush RV, Pappas JJ (1969) Glyoxal from ozonolysis of benzene. Ind Eng Chem Prod Res Dev 8:89
73. Eisenhauer HR (1968) The ozonation of phenolic wastes. J Water Pollut Control Fed 40:1887
74. Bernatek E, Frengen C (1961) Ozonolysis of phenols, I. Ozonolysis of phenol in ethyl acetate. Acta Chem Scand 15:471

75. Eisenhauer HR (1971) Increased rate and efficiency of phenolic waste ozonation. J Water Pollut Control Fed 43:201
76. Ni CH, Chen JN (2001) Degradation of chlorophenols by a new high-pressurized ozonation system. 15th world congress and medical therapy conference, IOA, London
77. Wingard LB Jr, Finn RK (1969) Oxidation of catechol to *cis, cis* - muconic acid with ozone. Ind Eng Chem Prod Res Dev 8:65
78. Bernatek E, Moskeland J, Valen K (1961) Ozonolysis of phenols, II. Catechol, resorcinol and quinol. Acta Chem Scand 15:1454
79. Bernatek E, Frengen C (1962) Ozonolysis of phenols, III. 1-and 2-Naphthol. Acta Chem Scand 15:2421
80. Bailey PS, Batterbee JE, Lane AG (1968) Ozonation of benz (a) anthracene. J Am Chem Soc 90:1027
81. Moriconi EJ, Salce L (1968) Ozonation of polycyclic aromatics. Advances in Chemistry Series, No. 77. American Chemical Society, Washington, DC
82. Mudd JB, Leavitt R, Ongun A, McManus TT (1969) Reaction of ozone with amino acids and proteins. Atmos Environ 3:669
83. White HM, Bailey PS (1965) Ozonation of aromatic aldehydes. J Org Chem 30:3037
84. Erickson RE, Bokalik D, Richards C, Scanlon M, Huddleston G (1966) Mechanism of ozonation reactions II. Aldehydes. J Org Chem 31:461
85. Syrov AA, Tsyskovskii VK (1970) Mechanisms of the action of ozone on aldehydes. J Org Chem USSR 6:1406
86. Price CC, Tumolo AL (1964) The course of ozonation of ethers. J Am Chem Soc 86:4691
87. Erickson RE, Hansen RT, Harkins J (1968) Mechanism of ozonation reactions, III. Ethers. J Am Chem Soc 90:6777
88. Whiting MC, Bolt AJN, Parish JH (1968) The reaction between ozone and saturated compounds. Advances in Chemistry Series, No. 77. American Chemical Society, Washington, DC
89. Schubert CC, Schubert SJ, Pease RN (1956) The oxidation of lower paraffin hydrocarbons, II. Observations on the role of ozone in the slow combustion of isobutane. J Am Chem Soc 78:2044
90. Hamilton GA, Ribner BS, Hellman TM (1968) The mechanism of alkane oxidation by ozone. Advances in Chemistry Series, No. 77. American Chemical Society, Washington, DC
91. Batterbee JE, Bailey PS (1967) Ozonation of carbon-hydrogen bonds. Anthrone. J Org Chem 32:3899
92. Deslongchamps P, Moreau C (1971) Ozonolysis of acetals. (1) Ester syntheses, (2) THP ether cleavage, (3) Selective oxidation of B-glycoside, (4) Oxidative removal of benzylidene and ethylidene protecting groups. Can J Chem 49:2465
93. Mester L (1959) Role of formazan reaction in proving structure of ozone-oxidized carbohydrates. Advances in Chemistry Series, No. 21. American Chemical Society, Washington, DC
94. NTNU (1997) Experimental ozonation in a pressurized reactor. The Pulp and Paper Group, Chemical Engineering Department, NTNU, Norway, www.chemeng.ntnu.no
95. Moe ST, Holen AK (1999) High- and low-pressure ozonation of cellulose model compounds: a comparison of carbohydrate reaction specificity. 10th international symposium on wood and pulping chemistry, vol 2, pp 354–357
96. Schuerck C (1963) Ozonization of cellulose and wood. J Polym Sci C Polym Symp 2:79
97. Dobinson F (1959) Ozonation of malonic acid in aqueous solution. Chem Ind 26:853–854

98. Glaze WH, Rawley R, Lin S (1976) By-products of organic compounds in the presence of ozone and UV light. Technical paper presented at the IOI meeting, Cincinnati, OH, November 1976
99. Guirguis WA, Srivastava P, Moister T, Prober R, Hanna Y (1976) Ozone reactions with organic material in sewage non-sorbuble by activated carbon. Technical paper presented at the IOI meeting, Cincinnati, OH, November 1976
100. Prengle HW Jr, Mauk CE, Payne JE (1976) Ozone-UV oxidation of pesticides in aqueous solution. Technical paper presented at the IOI Meeting, Cincinnati, OH, November 1976
101. Richard Y (1976) Organic materials produced upon ozonation of water. Technical paper presented at the IOI meeting, Cincinnati, OH, November 1976
102. Everard M, Seeley C, Bond C (2002) Biosolids and sustainability**,** 2020 vision seminar. The Natural Step's website: www.naturalstep.org.uk
103. Ergler G (2008) Ozone pilot plant design. O_3 Water Systems, Inc. Website www.o3water.com/Articles/PilotPlantDesign.htm
104. Wang LK (1983) A modified standard method for the determination of ozone residual concentration by spectrophotometer. Technical Report # PB84–204684. U.S. Department of Commerce, National Technical Information Service, Springfield, VA, August 1983
105. Wang LK (1995) The state-of-the-art technologies for water treatment and management, UNIDO Training Manual No. 8–8–95. United Nations Industrial Development Organization (UNIDO), Vienna, Austria
106. IN USA Inc. (2004) Ozone monitoring and control instrumentation. Needham, MA, www.inusacorp.com
107. Wang LK, Wang MHS (2007) Bubble dynamics of adsorptive bubble separation processes. 2007 National engineers week conference, Albany Marriott, Albany, NY, 15–16 February 2007
108. Wang LK, Wang MHS (2007) Emerging induced gas flotation and dissolved gas flotation processes. 2007 National engineers week conference, Albany Marriott, Albany, NY, 15–16 February 2007
109. Wang LK, Wang MHS, Suozzo T, Dixon RA, Wright TL, Sarraino S (2009) Chemical and biochemical technologies for environmental infrastructure sustainability. 2009 National engineers week conference, Albany Marriott, Albany, NY, 5–6 February 2009
110. Kawamura F (1932) J Chem Soc Japan Pure Chem Sect 33:783–787
111. Kirk RE, Othmer DF (1967) Encyclopedia of chemical technology, 2nd edn, vol 14. Wiley, New York, p 412
112. Li KW (1977) Ph.D. Dissertation, Mississippi State University
113. US DOE (2006) Pressurized ozone ultrafiltration membrane system for removing total dissolved solids from paper mill process water. U.S. Dept. of Energy, Washington, DC

9
Wastewater Renovation by Flotation

Nazih K. Shammas

CONTENTS

Abstract The fact that dissolved air flotation (DAF) (with 3–5 min of detention time) can replace sedimentation (with 2–3 h of detention time) for clarification has been overlooked by environmental engineers for many decades. Modern high-rate DAF clarifiers have advanced to such an extent that they could overshadow the conventional settling clarifiers in wastewater treatment. DAF hydraulic loadings increased from 1 to 2.5 L/m^2/s and for a triple stacked unit to 7.5 L/m^2/s; the detention time decreased from 30 to 3 min; air dissolving is improved and now requires only 10-s retention time in an air dissolving tube instead of the previous 60 s. This chapter discusses the field application of the DAF process for primary wastewater clarification, secondary flotation of aeration tank mixed liquor, and the design and operation parameters for a two-stage DAF operation.

Key Words Dissolved air flotation • DAF • primary DAF • secondary DAF • two-stage DAF • wastewater treatment • primary flotation • secondary flotation.

1. INTRODUCTION

The fact that dissolved air flotation (DAF) (with 3–5 min of detention time) can replace sedimentation (with 2–3 h of detention time) for clarification has been overlooked by environmental engineers for many decades. Modern high-rate DAF clarifiers have advanced

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to such an extent that they could overshadow the conventional settling clarifiers in wastewater treatment. DAF hydraulic loadings increased from 1 to 2.5 $L/m^2/s$ and for a triple stacked unit to 7.5 $L/m^2/s$; the detention time decreased from 30 to 3 min; air dissolving is improved and now requires only 10-s retention time in an air dissolving tube (ADT) instead of the previous 60 s (1, 2); the modern DAF unit of smaller size and weight allows for inexpensive construction and flexibility of erection using prefabricated units, and the availability of excellent flocculating chemicals gives a high stability of operation and high clarification degree (3–6).

Flotation has been widely used for industrial waste treatment. Typical industrial wastes treated by flotation are oily wastewaters (7), pulp and paper mill wastes (8, 9), slaughterhouse wastes (10), poultry processing wastewater (11), hazardous wastes (12), tannery effluents (13), and seafood processing wastewater (14). However, although flotation has also been used extensively for waste activated sludge (WAS) thickening (15–17), yet only limited applications are available in wastewater clarification (18–20) or wastewater reuse (21, 22).

Conventional biological treatment (23, 24) is the predominant selection for municipal wastewater treatment plants. Whenever upgrading is deemed to be necessary, the remedial action in most cases is to merely enlarge the size of existing facilities. In both instances the above choices may not be practical or economical. Examples of such cases are as follows:

1. Seasonal operations where huge population swelling occurs during religious festivities, in sea and mountain resorts, and in ski areas (25).
2. Recovery and treatment of wastes generated from agricultural crops, especially those that are seasonal in nature (26, 27).
3. Chemical and toxic wastes that are not amenable to biological treatment (7, 8, 28).
4. Emergency situations that demand immediate action. Such events can not be remediated by biological means.
5. Control and reduction of combined sewer overflows (CSOs), especially where space is at a premium (28, 29).
6. Wastewater renovation and tertiary treatment for water cycling and reuse (25, 30).
7. Retrofitting of treatment plants for upgrading or plant capacity expansions (31–33).

Harleman et al. (29) and Harleman and Murcott (32) consider chemically enhanced primary treatment (CEPT) and chemical secondary treatment (CST) to be significant innovations in wastewater treatment technology. They conclude that CEPT can remove over 80% TSS and 60% BOD compared with 60% TSS and 35% BOD removed by conventional primary treatment. They also indicate that CST can achieve high removals of up to 90% TSS and 80% BOD compared with removal of 85% TSS and 85% BOD by biological secondary treatment (BST). On the other hand, Firmin (34) who reviewed the performance of CEPT plants in North America and Scandinavia has found that their actual removal efficiencies and effluent quality are highly variable and specific to given wastewaters. He concluded that CEPT will remove 65–80% TSS and only 40–50% BOD.

The goal of this chapter is to illustrate and explain how the flotation technology can be employed to further enhance the CEPT concept as a feasible alternative or an upgrade to conventional wastewater treatment processes. An innovative physicochemical treatment system, based on flotation technology developed by the Lenox Institute of Water Technology (35–37), is being used for this purpose. Furthermore, in order to illustrate the universal applicability of this system to various wastewaters, the system was pilot tested at different geographical locations in seven states and on different wastewaters. This multitasked testing program allowed the evaluation of design criteria of flotation cells and the effect of wastewater variability on removal efficiencies and final effluent quality.

The technical feasibility of the DAF process for primary and secondary flotation in wastewater treatment is illustrated by the following applications (31, 38–40):

(a) Applications of one-stage flotation (F-Cell):
    1. Primary clarification of raw wastewater in Indiana
    2. Clarification of primary settled effluent in Maine
    3. Secondary flotation of mixed liquor from an activated sludge aeration tank in Maryland
    4. Full-scale operation of an upgraded conventional activated sludge plant in Texas

(b) Applications of two-stage flotation (F-Cell) and flotation/filtration (FF-Cell):
    1. Wastewater I in Massachusetts
    2. Wastewater II in Arkansas
    3. Wastewater III in Alabama

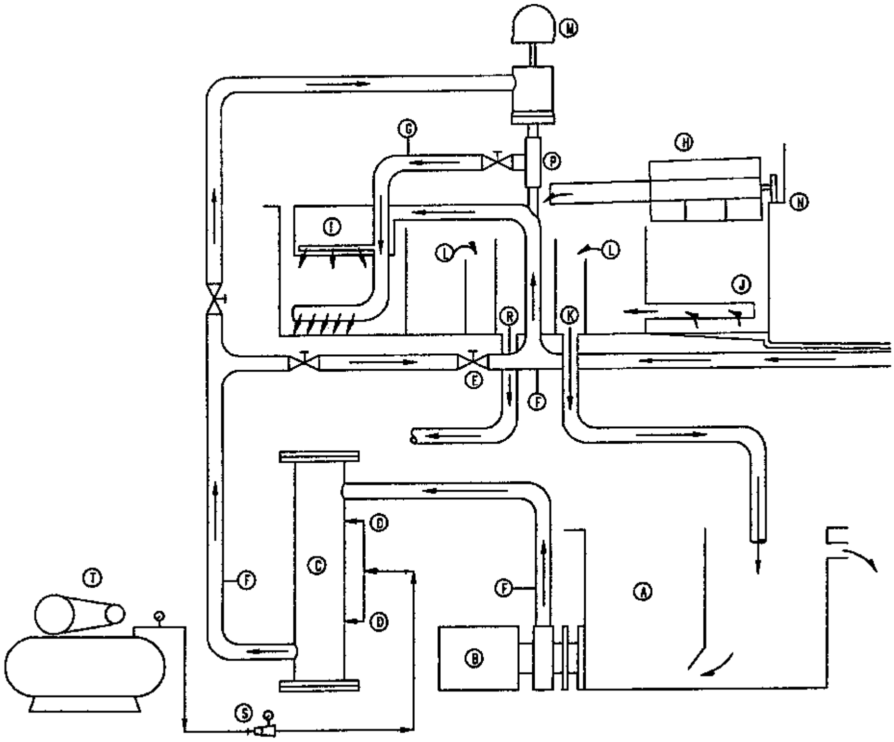
2. DAF PILOT PLANT FOR SINGLE-STAGE OPERATIONS

The DAF pilot plant used in single-stage applications is shown in Fig. 9.1. It is a self-contained, skid-mounted flotation clarifier capable of treating 163 m^3/day (30 gpm) wastewater flow. The flotation tank is 1.2 m (4 ft) in diameter with 0.41–0.46 m (16–18 in.) effective water depth. The system is complete with feed pump, pressure pump, compressor, air dissolving tube, collection tank, and chemical feed equipment. The flotation tank is equipped with a spiral scoop for collection and removal of floated sludge.

The inlet, outlet, and sludge removal mechanisms are contained in the central rotating section. This section and the spiral scoop rotate around the tank at a speed synchronized with the flow. The system is operated in the recycle flow pressurization mode, whereby a portion of clarified effluent (30–40%) is continuously recycled from the collection tank to the air dissolving tube under 400 kPa (60 psi) pressure. After pressure release, the aerated water is mixed with the influent flow just before the inlet to the distribution duct, which moves with the same velocity, but in opposite direction to the incoming flow, thus creating a quiescent state in the flotation chamber. Fine bubbles generated in this manner attach to the suspended particles and float them to the surface.

The spiral scoop takes up the floated biosolids, pouring them into the stationary center section where they are discharged by gravity. Clarified water is removed by extraction pipes that are attached to the moving center section and is discharged into the collection tank.

Wiper blades attached to the moving distribution duct scrape the bottom and the sides of the tank and discharge settled sludge into the built-in sump, for periodic purging. The variable speed gear motor drives the rotating elements and scoop. Electrical current for the gear motor feeds from a rotary contact mounted on the central shaft.



(A)	**Holding Tank (100 Gal.)**	**(J)**	**Clarified Water Extraction Pipes**
(B)	**Pressure Pump (30 GPM @ 60 PSI)**	**(K)**	**Clarified Water Outlet**
(C)	**Air Dissolving Tube**	**(L)**	**Level Control Weir**
(D)	**Air Meters (+/- 1 SCFM)**	**(M)**	**Rotary Electrical Contact**
(E)	**Pressure Release Valve (Globe Valve)**	**(N)**	**Gear Motor**
(F)	**Chemical Feed Fittings**	**(P)**	**Rotary Pipe**
(G)	**Sampling Valve**	**(R)**	**Floated Material Outlet**
(H)	**Spiral Scoop (Float Removal)**	**(S)**	**Air Regulator**
(I)	**Distribution Duct (Raw Water Inlet)**	**(T)**	**Compressor**

Fig. 9.1. The flotation cell (F-cell) flow diagram (31).

3. CLARIFICATION OF RAW WASTEWATER

The results of the pilot applications indicated that the DAF clarifier (F-CELL) achieved good performance in both primary and secondary flotation. Table 9.1 shows that an average removal of 67% in suspended solids from raw wastewater is feasible without any chemical addition. Raw wastewater was pumped to the F-CELL from the Kirklin wastewater plant immediately after the grinder. When the flotation cell was run with polymer addition to the incoming flow, no significant improvement in removal was obtained. One of the collected composite samples was tested for both BOD and ammonia-N. Although the BOD removal

Table 9.1
Clarification of raw wastewater by flotation at Kirklin WWTP, Kirklin, IN (31)

Composite sample	Total suspended solids		
	Influent (mg/L)	Effluent (mg/L)	Removal (%)
1	97	27	72
2	226	129	43
3	298	68	77
4	415	197	53
5	238	54	77
6	300	50	83
Average	262	87	67

was not very high (28% removal from 188 mg/L down to 136 mg/L), the ammonia was almost completely removed. Ammonia-N concentration decreased from 31.4 mg/L in the influent to 0.41 mg/L in the effluent, i.e., 99% removal.

4. CLARIFICATION OF PRIMARY EFFLUENT

The F-CELL was installed at the Bangor, Maine Pollution Abatement Facility to evaluate the DAF performance in the clarification of the plant’s primary effluent. Trials were initially run on the plant effluent without chemical treatment and then with alum treatment only; however, these tests produced poor results. Further tests were made with alum and sodium aluminate and no polymer, but with similar results. Optimum chemical addition was found to consist of 15 mg/L alum, 10 mg/L sodium aluminate, and 1 mg/L anionic polymer (Nalco 2 P0 462). Table 9.2 indicates that suspended solids concentration in the effluent from primary settling can be further reduced to an average value below 20 mg/L by flotation. The average suspended solids concentration was reduced from 73 to 18 mg/L, a reduction of 72%. The averaged biosolids consistency was 2.5% with a range of 1.7–3.8% solids. Approximate biosolids flow was 0.5% of wastewater feed. Six composite samples were analyzed for BOD. The feed BOD ranged between 114 and 164 mg/L with an average value of 128 mg/L, while the effluent BOD ranged between 34 and 67 mg/L with an average value of 45 mg/L. The average BOD removal was 65%.

5. SECONDARY FLOTATION OF AERATION TANK MIXED LIQUOR

The application for secondary flotation of biological mixed liquor from an activated sludge aeration tank was carried out at Patapsco wastewater treatment plant, Baltimore, MD. Data from the application (see Table 9.3) indicated that polymer (Secodyne 1533) addition was not necessary. Biosolids consistency and solids capture did not improve with polymer addition. The biological activated sludge flocs floated easily and quickly, achieving an average biosolids consistency of 4% solids and an average solids capture of 96%. The high solids

Table 9.2
Clarification of primary settling tank effluent by flotation at Bangor WWTP, Bangor, ME (31)

Sample	Total suspended solids			Sludge concentration (%)
	Influent (mg/L)	Effluent (mg/L)	Removal (%)	
1	70	26	63	1.9
2	67	36	46	2.0
3	172	10	94	2.0
4	140	16	89	2.6
5	118	14	88	2.5
6	100	16	84	2.6
7	96	20	79	2.5
8	88	13	85	2.6
9	75	19	75	2.4
10	81	18	78	2.6
11	52	8	85	–
12	55	11	80	–
13	64	12	81	2.9
14	52	16	69	3.2
15	60	29	52	3.8
16	59	18	70	2.3
17	59	25	58	2.4
18	29	14	52	1.7
19	44	19	57	1.9
20	47	16	66	2.3
21	55	16	71	1.9
22	56	18	68	2.8
23	48	23	52	3.1
Average	73	18	72	2.5

content of the DAF float, compared to 0.4–0.7% concentration from a sedimentation tank, reduces the volume of the recycle flow to the aeration basin and consequently increases the hydraulic capacity of the basin and its detention time. This potential of secondary flotation can be utilized for improving the treatment efficiency of an existing overloaded activated sludge plant or for handling additional wastewater flow.

6. FULL-SCALE OPERATION OF AN UPGRADED ACTIVATED SLUDGE PLANT

The activated sludge treatment plant at a paper mill in Lufkin, TX treats 68,200 m^3/day (18 MGD) of wastewater. The plant was designed to produce a final effluent with BOD and TSS that would not exceed 20 mg/L. However, several expansions resulted in poor effluent quality and borderline permit compliance, particularly during the periods of peak BOD loading. The

Table 9.3
Secondary clarification by flotation at Patapsco activated sludge WWTP, Baltimore, MD (31)

Composite sample	Total suspended solids			Sludge concentration (%)	Polymer dosage (mg/L)
	Influent (mg/L)	Effluent (mg/L)	Removal (%)		
1	4,240	220	95	4.0	0
2	3,660	200	95	3.5	3
3	4,550	180	96	4.7	3
4	4,260	140	97	3.6	2
5	5,525	270	95	4.3	2
6	5,610	260	95	4.2	0
7	6,040	160	97	4.1	1
8	6,040	210	97	4.1	0
9	4,050	120	97	3.3	1
Average	4,886	196	96	4.0	1.3

first alternative to solve the plant's problems namely increasing the aeration time by adding another aeration basin of the same size was not a viable option. The company did not have enough land space, and the capital expenditure for this conventional option is high. The alternative decision was the use of a 16.8-m (55-ft) DAF F-CELL (see Fig. 9.2) as a secondary clarifier that would be installed in front of the final sedimentation tanks and has a capacity to handle 30,000 m^3/day (8 MGD) of flow. This was accomplished at only 12% of the cost of the conventional expansion project estimate. A top view of the F-CELL is shown in Fig. 9.3, and the cell details are shown in Fig. 9.4.

The sludge return to the aeration basin from the flotation cell at 2% consistency is five times thicker than the 0.4% sludge return from the final settling tanks (see Fig. 9.2). The resulting reduction in the volume of recycle to the aeration basin by 9,500 m^3/day (2.5 MGD) provides an extra 10% hydraulic capacity for aeration.

The solids removed from the 30,000 m^3/day flow processed by the flotation cell reduced the solids flowing to the final clarifiers by at least 30% such that no violations of the discharge limits have occurred since installation.

The net results were reduced solids loading to the final clarifiers, increased hydraulic capacity and retention time of aeration basin, threefold increase in overall concentration of biosolids, more active recycled sludge, better effluent quality, and no biosolids bulking problems.

7. DAF PILOT PLANT FOR TWO-STAGE OPERATIONS

The DAF pilot plant (flotation/filtration FF-CELL) used in the following applications is shown in Fig. 9.5, and its details are shown in Fig. 9.6. The system, mounted on a mobile trailer, consists of a combination of a primary dissolved oxygen flotation (DAF) process (31) and a secondary dual-media filtration unit (25). The inlet, outlet, and sludge removal

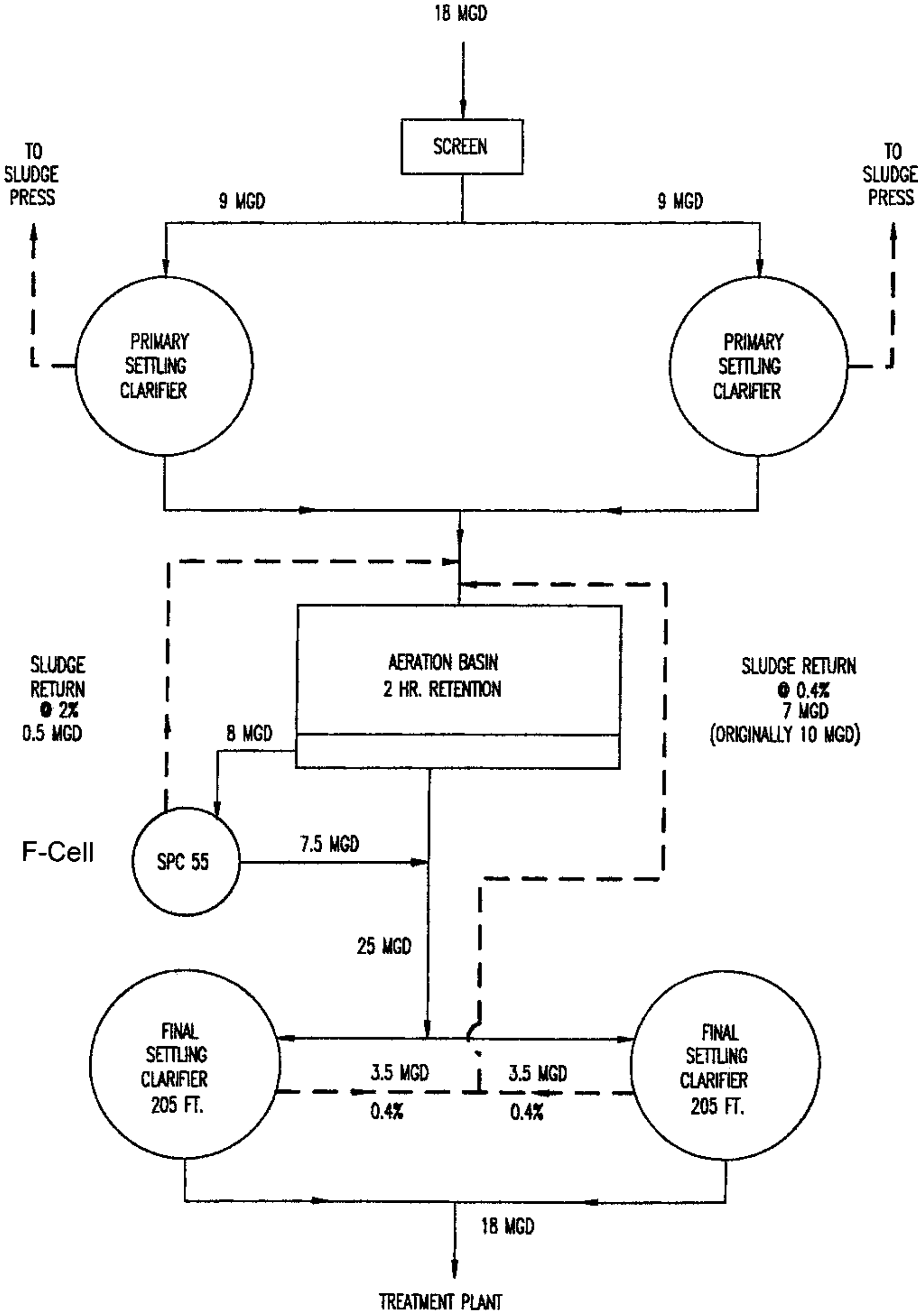


Fig. 9.2. Process flow diagram of upgrade activated sludge plant by using DAF F-cell (31).

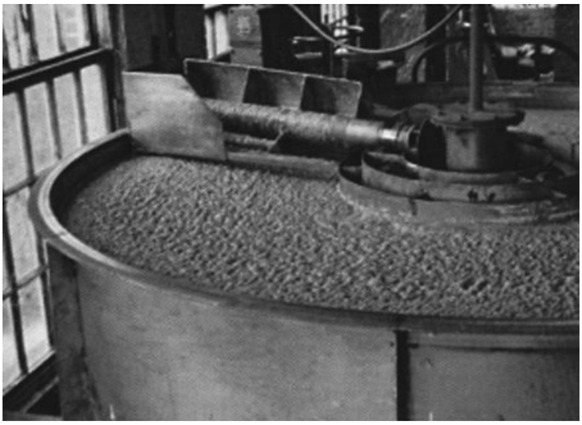


Fig. 9.3. Top view of flotation cell (F-cell) (35).

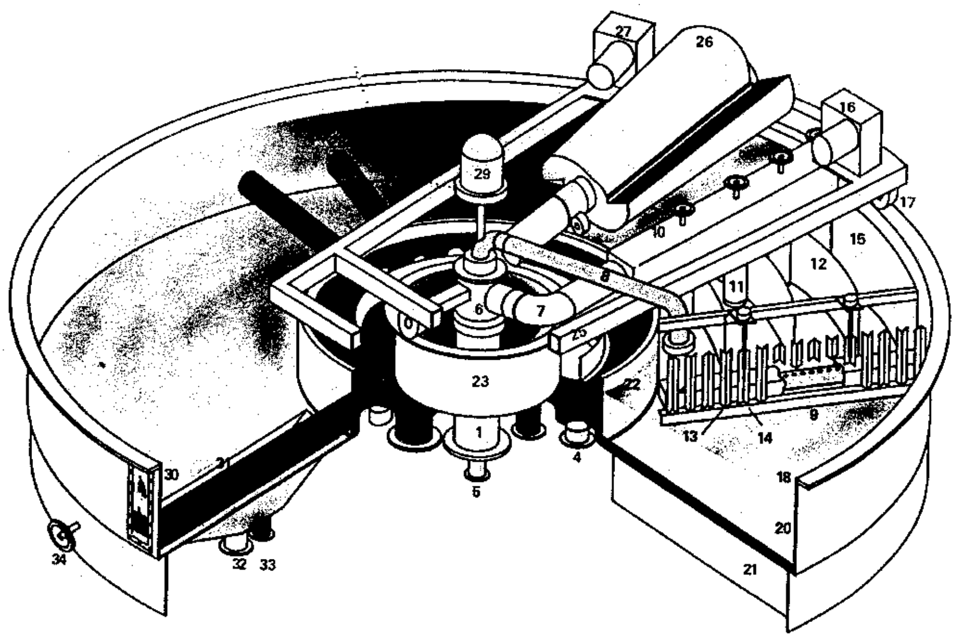
mechanisms of both clarifiers are contained in the central rotating carriage. Raw wastewater mixed with flocculating agents enters the flotation unit through a manifold on the side of the carriage. Because the speed of the carriage is set to match the velocity of the incoming flow, the velocity of the incoming wastewater is effectively zero, enhancing the flotation process.

Flotation is achieved with the introduction of pressurized aerated recycled effluent through the air dissolving tube (ADT). When this water is released, its pressure drops, and the dissolved air comes out as microscopic bubbles, which attach themselves to floc particles, causing them to float to the surface where they are removed by the rotating spiral scoop and discharged into the central sludge or biosolids collector. The clarified water from the flotation process then passes down through the anthracite – sand filtration media located at the bottom of the unit. The filtration compartment is composed of multiple separate sections, which are individually backwashed while the rest of the filter is on line. The backwash water recycled from the filter is mixed with the influent water at the inlet. Thus, backwash discharge is eliminated, and the only discharge is the float, thickened biosolids (2–3% solids concentration) suitable for direct handling, thus also eliminating the need for biosolids thickening.

The pilot plant had a nominal flow rate of 150 L/min (40 gpm). The main characteristics of the units are listed in Table 9.4. Wastewater and air flow rates, ADT pressure, pH, and temperature were monitored continuously. Relevant parameters including TSS, COD, BOD, total phosphorous, and total Kjeldahl nitrogen (TKN) were analyzed according to Standard Methods (41).

8. DESIGN AND OPERATIONAL PARAMETERS FOR THE TWO-STAGE OPERATION

The pilot plant was operated over a broad range of operational parameters, including various flow rates (75–170 L/min) and recycle ratios (5–60%) as well as different coagulant and flocculant combinations and doses (up to 200 and 10 mg/L, respectively). In addition to providing clear-cut evidence about the effectiveness of the multistage flotation system for



1) RAW WATER INLET
2) CLARIFIED WATER OUTLET
3) FLOATED SLUDGE OUTLET
4) CLARIFIED WATER RECYCLE OUTLET
5) PRESSURIZED WATER INLET
6) ROTARY JOINT
7) RUBBER PIPE CONNECTION
8) PRESSURIZED WATER PIPING
9) PRESSURIZED WATER DISTRIBUTION HEADER
10) RAW WATER DISTRIBUTION HEADER
11) DISTRIBUTION HEADER OUTLET PIPES
12) FLOW CONTROL CHANNELS
13) TURBULENCE REDUCTION BAFFLES
14) ADJUSTABLE HEIGHT BAFFLE ATTACHMENT
15) FLOW CONTROL CHANNEL OUTER WALL
16) ROTATING CARRIAGE GEARMOTOR DRIVE
17) CARRIAGE DRIVE WHEEL
18) WHEEL SUPPORT RIM
20) TANK WALL
21) TANK FLOOR SUPPORT STRUCTURE
22) ROTATING CLARIFIED WATER CONTAINMENT WALL
23) SLUDGE WELL
24) LEVEL CONTROL OVERFLOW WEIR
25) ROTATING CARRIAGE STRUCTURE
26) REVOLVING SPIRAL SCOOP
27) SPIRAL SCOOP GEARMOTOR DRIVE
28) CLARIFIED WATER EXTRACTION PIPES
29) ELECTRICAL SLIP RING
30) TANK WINDOW
31) SEDIMENT REMOVAL SUMP
32) FINAL DRAIN
33) SEDIMENT PURGE OUTLET
34) LEVEL CONTROL ADJUSTMENT HANDWHEEL

Fig. 9.4. Details of the flotation cell (F-cell) (35).

treating various municipal wastewaters, the pilot study afforded the opportunity to optimize both coagulant and flocculant dosages as well as relevant operational parameters. However, since the wastewater quality at each location is different, it was expected and actually found that chemical additions did vary. Results of required chemical doses, as well as optimized operational parameters, including hydraulic loading and recycle ratios, are summarized in Table 9.5.

Fig. 9.5. The flotation/filtration cell (FF-cell) (35).

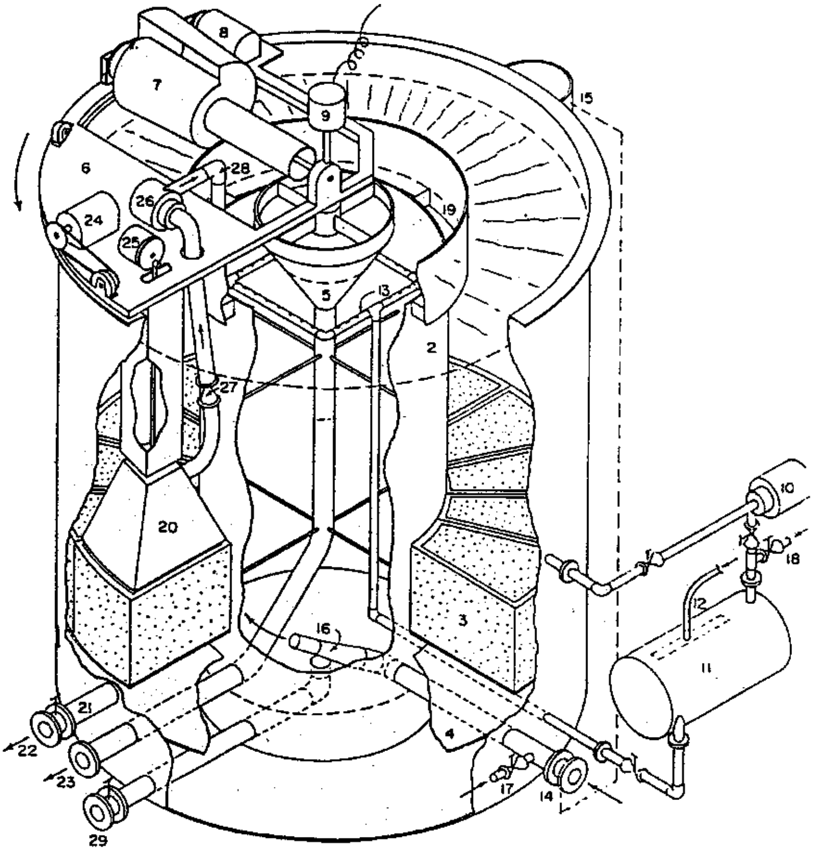
8.1. Hydraulic Loading

The flotation-enhanced treatment system, in addition to improving treatment efficiency, is shown (Table 9.5) to be able to allow hydraulic loading rates (130–200 L/min/m^2) 7–10 times higher than the conventional primary treatment rate of 20 L/min/m^2. The consequence is a corresponding reduction in space requirement from one seventh to one tenth of the space needed by sedimentation clarifiers. This saving in area requirement has a dominant impact on the final cost of the system.

This treatment system based on flotation technology exhibited a similar decided advantage over chemically enhanced primary treatment. According to Harleman and Murcott (32), CEPT allows overflow rates 2–3 times higher than that in conventional clarifiers. Consequently, hydraulic loadings for flotation clarifiers using chemical addition can be tripled or quadrupled over those used for chemically enhanced sedimentation clarifiers.

8.2. Chemical Requirements

Cationic polymers used alone were found to be very effective in the primary stage. The optimum chemical dose was found to be 3–5 mg/L (Table 9.5). In the second stage, a combination of 2.4 mg/L cationic polymer and 83 mg/L ferric sulfate was required for Wastewater I. However, for the other two wastewaters the best combination was using 1 mg/L anionic polymer with 4–8 mg/L alum (Table 9.5). These chemical requirements compare favorably with chemical additions practiced at CEPT plants. Firmin (34) assessed chemically enhanced primary treatment in the USA and reported chemical doses varying



1. Outside tank
2. Inside flocculation tank
3. Sandbed assembly with screen
4. Tank bottom
5. Sludge collection funnel
6. Moveable carriage assembly
7. Spiral scoop
8. Scoop variable speed drive
9. Electrical rotary contact
10. Pressure pump
11. Air dissolving tube
12. Compressed air addition point
13. Aerated water distribution pipes
14. Raw water inlet regulating valve
15. Tank level control sensor
16. Raw water inlet jet nozzle
17. Coagulant addition point
18. Polyelectrolyte addition point
19. Deflector ring into flotation tank
20. Backwash hood assembly
21. Clarified water pipeline
22. Clarified water flow regulating valve
23. Floated sludge discharge pipe
24. Main carriage drive
25. Motor to lift backwash hood assembly
26. Backwash suction pump
27. Check valve (backflow preventor)
28. Dirty backwash water recycle pipe
29. Drain line

Fig. 9.6. Details of flotation/filtration cell (FF-cell) (35).

from 22 mg/L ferric chloride and 0.25 mg/L polymer at Hyperion wastewater treatment plant in Los Angeles to 250 mg/L alum and 6.5 mg/L polymer at Tacoma treatment plant in Washington.

Table 9.4
Characteristics of pilot plant units (38)

Parameter	First stage F-cell	Second stage FF-cell
Nominal capacity, L/min	150	150
Cell diameter, m	1.2	1.5
Cell depth, m	0.6	0.9
Air feed, L/min	2.4	2.4
Air pressure, bar	6	6.5
Sludge scoop speed, Rev./min	2	2
Backwash rate, L/min	Not applicable	38
Backwash time, s	Not applicable	45

Table 9.5
Operational parameters of pilot plant (38)

Parameter	Wastewater I WWTP Massachusetts	Wastewater II WWTP Arkansas	Wastewater III WWTP Alabama
Hydraulic loading, L/min/m^2			
First stage	202	202	202
Second stage	135	130	130
Recycle ratio, %			
First stage	30	24	24
Second stage	30	20	20
Chemical dosage, mg/L			
First stage			
Magnifloc 496 C	4.6	3	4
Second stage			
Magnifloc 496 C	2.4	–	–
Magnifloc 1849 A	–	1	1
Ferric sulfate	83	–	–
Alum	–	8.3	4.1

The estimated cost of chemicals used in the pilot plant applications in terms of 2005 US dollars (42) was \$0.060, \$0.042, and \$0.035 per m^3 of wastewater treated at locations I, II, and III, respectively. The overall average cost was 4.6 cents/m^3.

8.3. Removal Rates

The pilot plant testing results are shown in Tables 9.6–9.8 for Wastewaters I, II, and III, respectively. Average concentrations of TSS, COD, BOD, and total phosphorous and

Table 9.6
Testing results – wastewater I (WWTP, Massachusetts) (38)

Parameter	TSS	COD	BOD_5	Total P	TKN
Concentration, mg/L					
Influent	250	435	252	4.5	32
First stage effluent	43	168	89	3.6	26
Final effluent	1	94	40	1	20
Removal, %					
First stage	83	61	65	20	19
Second stage	95	44	55	72	23
Total	99	78	84	78	38

Table 9.7
Testing results – wastewater II (WWTP, Arkansas) (38)

Parameter	TSS	COD	BOD_5	Total P	TKN
Concentration, mg/L					
Influent	253	197	123	1.8	78
First stage effluent	34	96	68	0.9	30
Final effluent	1	37	20	0.1	18
Removal, %					
First stage	87	51	45	50	62
Second stage	97	62	71	89	40
Total	99	81	84	94	77

Table 9.8
Testing results – wastewater III (WWTP, Alabama) (38)

Parameter	TSS	COD	BOD_5	Total P	TKN
Concentration, mg/L					
Influent	183	133	92	1.6	44
First stage effluent	14	53	10	0.7	22
Final effluent	1	24	8	0.1	19
Removal, %					
First stage	92	60	89	56	50
Second stage	93	55	20	86	14
Total	99	82	91	94	57

Kjeldahl nitrogen (TKN) are cited for plant influent, first-stage effluent after primary flotation in the F-Cell, and final effluent after the secondary flotation–filtration unit FF-Cell. Also shown in same tables are the computed average values of % removals in both primary and secondary cells as well as in the system as a whole.

Significant reductions in all quality parameters were achieved for all wastewaters and at all different locations. TSS concentration in every case was reduced to nondetectable levels (<1 mg/L), resulting in practically complete suspended solids removal (>99%). COD values were reduced by 51–61% in the primary stage and by 44–62% in the secondary unit, with overall reduction of 78–82% (Tables 9.6–9.8). BOD concentrations were also reduced by 45–89% in the F-Cell and by 20–71% in the FF-Cell, with overall reduction of 84–91%. Good nutrients removal was also accomplished. Total phosphorous reduction reached 94% (Tables 9.7 and 9.8), and total Kjeldahl nitrogen was reduced by up to 77% (Table 9.7).

Table 9.9 summarizes the results obtained from the pilot plant study at all various locations. The primary single-stage DAF unit was able to achieve overall average removal efficiencies of 87% total suspended solids, 66% BOD, 57% COD, 42% total phosphorous, and 44% total Kjeldahl nitrogen. The two-stage DAF was able to achieve excellent removal efficiencies of over 99% TSS, 87% BOD, 80% COD, 89% total phosphorous, and 57% TKN.

Table 9.10 presents a summary of the performance of different wastewater treatment processes (1, 32, 34, 43–47) together in comparison with the results of the application of the flotation-enhanced pilot plant system. The data demonstrate the superior effectiveness of flotation-based treatment systems, which are capable of removing 87–99% TSS and 66–87% BOD as opposed to 60–90% and 35–80%, respectively, for other wastewater treatment processes. When this high performance is coupled with the unit's high hydraulic loading rates that are seven to tenfold greater than that in conventional primary systems and three to fourfold greater as opposed to recent experience with chemically enhanced primary treatment, it can be concluded that the innovative flotation-enhanced wastewater treatment system can be used to replace or upgrade conventional physicochemical treatment facilities with a greater flexibility, less land use, and at a saving of 30–50% in cost.

The ramification of this is that combining low installation and operational costs with affordable water user rates would allow municipalities to finance plant construction, through

Table 9.9
Summary of removal rates (38)

Parameter	Removal, % primary first stage	Removal, % total
TSS	87	99
COD	57	80
BOD_5	66	87
Total P	42	89
TKN	44	57

Table 9.10
Comparison of various treatment systems (38)

Parameter	TSS removal (%)	BOD_5 removal (%)	Hydraulic loading (L/min/m^2)	Metal salt dosage (mg/L)	Polymer dosage (mg/L)
Conventional primary	60	35	20	–	–
CEPT	65–80	40–60	40–50	20–250	0.14–6.5
CST	90	80	50	150–160	0.2–2.8
Primary flotation	87	66	200	–	3–4.6
Secondary flotation	99	87	130	4–83	1–2.4

local or international financial institutions, without having to resort to investing its own or asking for grant money. Opting for the extremely compact, modular, and low-cost DAF treatment system allows the building of a plant that is profitable. Financial groups consider municipalities the most stable lenders, which make them attractive to long-term investors. If a municipality proposes to upgrade an existing plant or construct and operate a new wastewater treatment plant with a profit, long-term investors will provide the means. CEPT utilizing DAF in lieu of sedimentation is not only a proven technology; it is also representative of a new way of thinking for wastewater management and a new paradigm for treatment plant design.

APPENDIX

United States Yearly Average Cost Index for Utilities US Army Corps of Engineers (42)

Year	Index	Year	Index
1967	100	1989	383.14
1968	104.83	1990	386.75
1969	112.17	1991	392.35
1970	119.75	1992	399.07
1971	131.73	1993	410.63
1972	141.94	1994	424.91
1973	149.36	1995	439.72
1974	170.45	1996	445.58
1975	190.49	1997	454.99
1976	202.61	1998	459.40
1977	215.84	1999	460.16

(*Continued*)

Year	Index	Year	Index
1978	235.78	2000	468.05
1979	257.20	2001	472.18
1980	277.60	2002	484.41
1981	302.25	2003	495.72
1982	320.13	2004	506.13
1983	330.82	2005	516.75
1984	341.06	2006	528.12
1985	346.12	2007	539.74
1986	347.33	2008	552.16
1987	353.35	2009	570.38
1988	369.45		

REFERENCES

1. Wang LK, Hung YT, Shammas NK (eds) (2005) Physicochemical treatment processes, The Humana Press, Inc., Totowa, NJ. 723 p
2. Wang LK, Hung YT, Shammas NK (eds) (2007) Biosolids treatment processes, The Humana Press, Inc., Totowa, NJ. 820 p
3. Hyde RA, Miller DG, Packham RF, Richards WN (1977) Water clarification by flotation. J Am Water Works Assoc 69:369
4. Zabel T (1985) The advantages of dissolved air flotation for water treatment. J Am Water Works Assoc 77:42
5. Krofta M (1990) Flotation replaces sedimentation in water and effluent clarification, report, Krofta Engineering Corp., Lenox, MA
6. Janssens JG (1992) Developments in coagulation, flocculation and dissolved air flotation. Water/Eng Manag 139:26
7. Eckenfielder WW (1989) Industrial water pollution control, McGraw-Hill, New York, NY
8. Krofta M, Wang LK (1989) Total closing of paper mills with reclamation and deinking installations. Proceedings of the 43rd industrial Waste Conference, Lewis Publishers, Chelsea, MI, p 535
9. Barton CA, Byrd JF, Peterson RC, Walter JH, Woodruff PR (1968) A total systems approach to pollution control at a pulp and paper mill. J Water Pollut Control Fed 40:1471
10. Cooper RN, Denmead CF (1979) Chemical treatment of slaughterhouse wastes with protein recovery. J Water Pollut Control Fed 51:1017
11. Woodard FE, Sproul OJ, Hall MW, Ghosh MM (1972) Abatement of pollution from a poultry processing plant. J Water Pollut Control Fed 44:1909
12. Wang LK, Wang MHS (1980) Control of hazardous wastes in petroleum refining industry, Technical Paper (No. LIR/10–80/2) presented at the 6th Annual Convention of the Chinese-American Academic and Professional Association, New York, NY, 11–13 Oct 1980
13. Wang LK, Dahm DB, Baier RE and Zieglar RE (1975) Treatment of tannery effluents by surface adsorption. J Appl Chem Biotechnol 25:475–490
14. Krofta M, Wang LK, Pollman CD (1989) Treatment of seafood processing wastewater by dissolved air flotation carbon adsorption and free chlorination. Proceedings of the 43rd industrial waste conference, Lewis Publishers, Chelsea, MI, p 535

15. Wang LK, Shammas NK, Selke WA, Aulenbach DB (2007) Flotation thickening. In: Wang LK, Shammas NK, Hung YT (eds) Biosolids treatment processes, The Humana Press, Inc., Totowa, NJ, pp 71–100
16. Metcalf & Eddy, Inc., (2003) Metcalf and Eddy, wastewater engineering treatment and reuse, 4th edn. McGraw Hill, New York
17. Cizinska S, Matejo V, Wase C, Kiasson Y, Krejci J, Daihainmar G (1992) Thickening of waste activated sludge by biological flotation. Water Res 26:139
18. Krofta M, Guss D, Wang LK (1988) Development of low-cost flotation technology and systems for wastewater treatment. Proceedings of the 42nd industrial waste conference, Lewis Publishers, Chelsea, MI, p 185
19. Bratby JR (1982) Treatment of raw wastewater overflows by dissolved air flotation. J Water Pollut Control Fed 54:1558
20. Mennell M, Merrill D, Jorden RM (1974) Treatment of primary effluent by lime precipitation and dissolved air flotation. J Water Pollut Control Fed 46:2471
21. Kiuru HJ (1990) Tertiary wastewater treatment with flotation filters. Wat Sci Tech 22:139
22. Pieterse T, Kfir R (1991) Plant quartet proves potable water reuse. Water Quality Int 4:31
23. Wang LK, Pereira NC, Hung YT, Shammas NK (eds) (2009) Biological treatment processes, The Humana Press, Inc., Totowa, NJ, p 818
24. Wang LK, Shammas NK, Hung YT (eds) (2009) Advanced biological treatment processes, The Humana Press, Inc., Totowa, NJ, p 738
25. Shammas NK, Krofta M (1994) A compact flotation-filtration treatment unit for wastewater reuse. Proceedings of water reuse symposium, AWWA, Dallas, TX, pp 97–109, Feb 27–Mar 2
26. Schneider IAH, Neto VM, Soares A, Rech RL, Rubio J (1995) Primary treatment of soybean protein bearing effluent by dissolved air flotation and by sedimentation. Water Res IAWQ 29(1):69–75
27. Cooper RN, Denmead CF (1979) Chemical treatment of slaughterhouse wastes with protein recovery. J Water Pollut Control Fed 51:1017
28. Wang LK (1991) Water and wastewater treatment using advanced dissolved air flotation, The 1991 annual conference of the Korea society of water pollution research and control, Seoul, Korea, 22–23 Feb 1991
29. Harleman DRF, Wolman LMG, Curll DB III (1992) Boston Harbor cleanup plan can be improved, Paper winner of the 1992 better government competition, Boston, MA
30. Kiuru H (1990) Tertiary wastewater treatment with flotation filters. Water Sci Technol 22(7/8):139–144
31. Shammas NK, DeWitt N (1992) Flotation: a viable alternative to sedimentation in wastewater treatment plants. Water environment federation 65th annual conference, proceedings liquid treatment process symposium, New Orleans, LA, pp 223–232, 20–24 Sept 1992
32. Harleman DRF, Murcott S (1991) Recent experience with chemically-enhanced primary treatment in North America and Scandinavia. J N Engl Water Pollut Control Assoc 25(2):111–125
33. Rad H, Cross JT (1990) Chemically-assisted primary treatment: a viable alternative to upgrading overloaded treatment plants, 63rd annual WPCF conference, Washington, DC
34. Firmin AC (1993) South Essex Sewerage District assessment of chemically-enhanced primary treatment. J N Engl Water Environ Assoc 27(1):61–82
35. Krofta M, Wang LK (2000) Flotation engineering, technical manual no. Lenox/1–06–2000/368, Lenox Institute of Water Technology, Lenox, MA

36. Krofta M, Wang LK (1999) Flotation and related adsorptive bubble separation processes, technical manual no. Lenox 7–25–1999/348, 4th edn. Lenox Institute of Water Technology, Lenox, MA
37. Wang LK, Fahey EM, Wu Z (2005) Dissolved air flotation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes, The Humana Press, Inc., Totowa, NJ, pp 431–500
38. Shammas NK (1997) Physicochemically-enhanced pollutants separation in wastewater treatment, Proceedings of the international conference: rehabilitation and development of civil engineering infrastructure systems – upgrading of water and wastewater treatment facilities, organized by The American University of Beirut and University of Michigan, Beirut, Lebanon, 9–11 June 1997
39. Krofta M, Miskovic D, Shammas NK, Burgess D (1994) Pilot-scale applications of a primary-secondary flotation system on three municipal wastewaters, Specialist Conference on Flotation Processes in Water and Sludge Treatment, Orlando, FL, 26–28 Apr 1994
40. Krofta M, Miskovic D, Shammas NK, Burgess D, Lampman L (1994) An innovative multiple stage flotation-filtration low cost municipal wastewater treatment system, IAWQ 17th Biennial International Conference, Budapest, Hungary, 24–30 July 1994
41. APHA (1992) Standard methods for the examination of water and wastewater, 18th edn. APHA, AWWA, and WEF, Washington, DC
42. U.S. ACE (2009) Civil works construction cost index system manual, 110–2–1304, U.S. Army Corps of Engineers, Tables, Washington, DC, PP 44, PDF file is available on the Internet at http://www.nww.usace.army.mil/cost
43. WPCF (1985) Clarifier design, Manual of Practice FD-8, Water Pollut Control Fed
44. Ekama GA, Barnard GL, Gunthert FW, Krebs P, McCorquodale JA, Parker DS, Wahlberg EJ (eds) (1997) Secondary settling tanks, IWA Publishing, London
45. Wang LK, Hung YT, Shammas NK (eds) (2006) Advanced physicochemical treatment processes, The Humana Press, Inc., Totowa, NJ, p 690
46. Wang LK, Hung YT, Shammas NK (eds) (2007) Advanced physicochemical treatment technologies, The Humana Press, Inc., Totowa, NJ, p 710
47. Wang LK, Shammas NK, Guss DB (2010) Flotation biological systems. In: Wang LK, Ivanov V, Tay JH, Hung YT (eds) Environmental biotechnology, Humana Press, Totowa, NJ, pp 484–506

10
Flotation–Filtration System for Wastewater Reuse

Nazih K. Shammas

CONTENTS

Abstract The strategy for long-term planning and management of water resources is increasingly based on the renovation and utilization of wastewater for use in agricultural and landscape irrigation as well as in industrial production. Conventional wastewater treatment, even when it is economically feasible, is costly because of biosolids handling and tertiary sedimentation tanks. A newly developed flotation/filtration cell is an advanced water clarification package plant, using a combination of chemical flocculation, dissolved air flotation (DAF), and rapid granular filtration in one unit. The average processing time from start to finish is less than 15 min. This innovation replaces a conventional process requiring five separate tanks with a single, compact, and cheaper unit. The aim of this chapter is to discuss six applications that illustrate the versatility and effectiveness of the flotation/filtration cell, to demonstrate the performance of the compact unit in secondary and tertiary treatment of various wastewater effluents, and to illustrate the system's usefulness for wastewater reclamation, recycling, and reuse.

Key Words Flotation–filtration cell • package treatment plant • wastewater renovation • recycling • reuse • activated sludge • rotating biological contactor • trickling filter • lagoon • secondary treatment • tertiary treatment.

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1. INTRODUCTION

In many parts of the world, the limited availability of both ground and fresh surface waters make it imperative to conserve water and to utilize every drop of available wastewater for reuse in beneficial purposes. The strategy for long-term planning and management of water resources is increasingly based on the renovation and utilization of wastewater for use in agricultural and landscape irrigation as well as in industrial production.

Water quality standards or guidelines have been initiated in many states and regions to protect public health, prevent nuisance conditions and preclude damage to crops, soils and groundwater. Risk-based wastewater reclamation criteria often require full tertiary treatment, especially in applications that have high potential exposure such as in using the reclaimed water for unrestricted irrigation (1–5). Conventional full tertiary treatment consists of a train of multiple processes, which include rapid mixing, flocculation, sedimentation and granular filtration in addition to disinfection (2, 3, 6). Such processing, even when it is economically feasible, is costly because of biosolids handling and tertiary sedimentation tanks (6, 7). Thus, research has been directed towards developing an innovative alternative capable of producing a comparatively highly clarified effluent (8–14).

A newly developed flotation/filtration cell (FF-Cell) is an advanced water clarification package plant, using a combination of chemical flocculation (15), dissolved air flotation (DAF), (8) and rapid granular filtration (6) in one unit. The average processing time from start to finish is less than 15 min. The unique compact and efficient design is made possible by the use of the space (water head) above the filter for flotation, a space or water head, which in any case, is necessary for filtration. Two more features were used to reduce space requirements (10, 16, 17):

1. A static hydraulic flocculator was built into the central portion of the tank to combine a third process in the single tank.
2. A segmented continuous backwash filter was used to eliminate requirements for large tanks for clearwell and backwash storage. Therefore, the end result replaces a conventional process requiring five separate tanks with a single, compact, and cheaper unit.

The aim of this chapter is to document six applications to illustrate the versatility and effectiveness of the flotation/filtration cell, to demonstrate the performance of the compact unit in secondary and tertiary treatment of various wastewater effluents, and to illustrate the system's usefulness for wastewater reclamation, recycling, and reuse. The five applications are (18–21):

1. Treatment of primary municipal wastewater effluent at Hoboken, NJ
2. Treatment of raw municipal wastewater at Lee, MA
3. Tertiary treatment of activated sludge effluent at Oak Meadows STP, Licking County, OH
4. Tertiary treatment of RBC Effluent at Jimmy Peak, MA
5. Tertiary treatment of trickling filter effluent at Norwalk, OH
6. Tertiary treatment of lagoons effluent at Arpin, WI

2. FLOTATION/FILTRATION CELL

The flotation/filtration pilot plant used in these applications is shown in Fig. 9.5 and its details are illustrated in Fig. 9.6. The flotation–filtration tank is 1.5 m in diameter and has a designed nominal capacity of 150 L/min of wastewater flow (18).

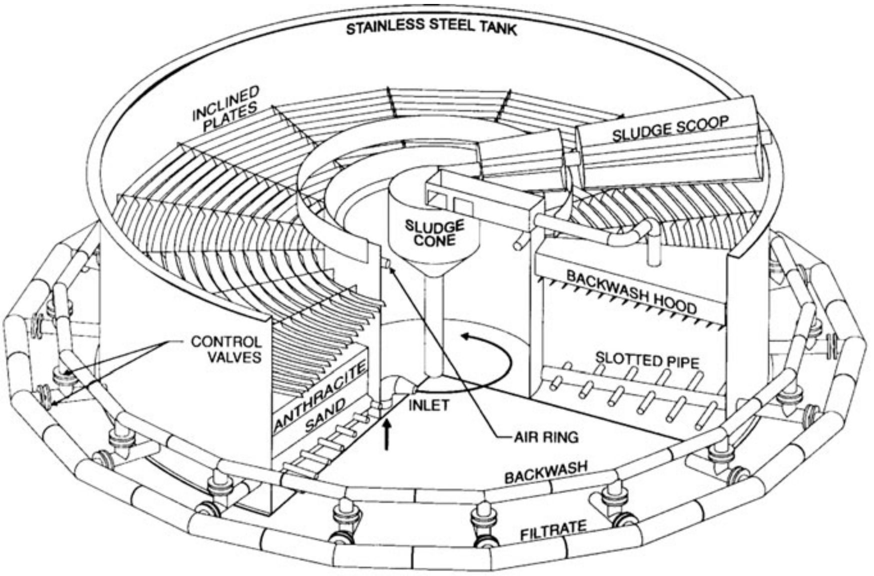
The influent flow is mixed with flocculant and coagulant chemicals, and gently flocculated in the central zone of the tank. The backwash recycled from the filter is mixed with the inflowing water at the flocculator inlet. This eliminates the need for disposal of the backwash separately, and also, in some cases, provides a "seed" of solids for better floc formation. The floc size required for removal of the solids is smaller than that required for settling. This reduces the space requirement for flocculation (10, 22).

When the flocculated solids reach the upper part of the flocculation zone, they are mixed with the recycle flow, which contains millions of microscopic (20–100 μm diameter) air bubbles. The air bubbles are generated by injecting air into recirculated clarified water under pressure (60 psi), followed by rapid decompression under high shear conditions. The amount of recirculated water used varies depending on the amount and type of solids to be removed, but is generally 15–30% of the incoming flow. The air bubbles attach to the flocculated solids, or are entrapped in the floc to produce air-solid agglomerate that rapidly rises to the surface of the tank. The accumulated float (thickened biosolids) at solids content of 2–3% is removed by the spiral scoop and discharged to the biosolids handling system via the central sludge well (8, 16, 17).

As the biosolids rise to the top, the clarified water flows downward through the filter bed. The bottom of the tank is composed of multi-sections of sand filter segments. Each of the 27 segments is individually isolated and backwashed while the remaining parts of the filter are on line. The filter media consist of 0.28-m deep high grade silica sand. The effective size and uniformity coefficient for the sand are 0.35 and 1.55 mm, respectively. The backwashing is uniformly extended over the complete filtering time. This enables the use of a smaller backwash pump, and minimizes or even eliminates any overloading on the unit that may result from the recycling of decanted backwash water (23).

The backwash hood, pump, and motor are mounted on a carriage that rotates on the upper rim of the main tank. The filter segments are set up for backwashing at a predetermined time interval that can be adjusted depending on head loss and the accumulation of solids. The backwash water containing the solids captured by the sand is recirculated back to the flocculator. The clearwell is located immediately below the sand bed. The clear water is utilized directly for backwash as needed.

The filter assures the removal of any solids not removed in the flocculation and flotation stages, the flocculation is enhanced by the recirculated backwash solids, and the filtration is protected by the removal of solids in the flotation stage. The combination of the three operations in a single tank reduces the head loss and turbulence between stages, thus increasing the efficiency of removal of the fragile flocculated solids. No storage is required for the clarified water or the backwash water. Discharge of backwash water is eliminated, and the only discharge is the float, thickened biosolids suitable for handling, thus possibly eliminating the necessity for a biosolids thickener (24–26).



Incoming water or wastewater enters near the bottom of the centrally located flocculator. Chemicals are added for flocculation and coagulation. Pressurized aerated water from the Air Dissolving Tube (ADT) is added at the overflow from the flocculator. The flocculated solids float to the surface and are collected by the *Spiral Scoop* and discharged into the central sludge collector. The clarified water passes through the sandbeds at the bottom of the Sandfloat

Fig. 10.1. Flotation/filtration cell (FF-Cell) (16).

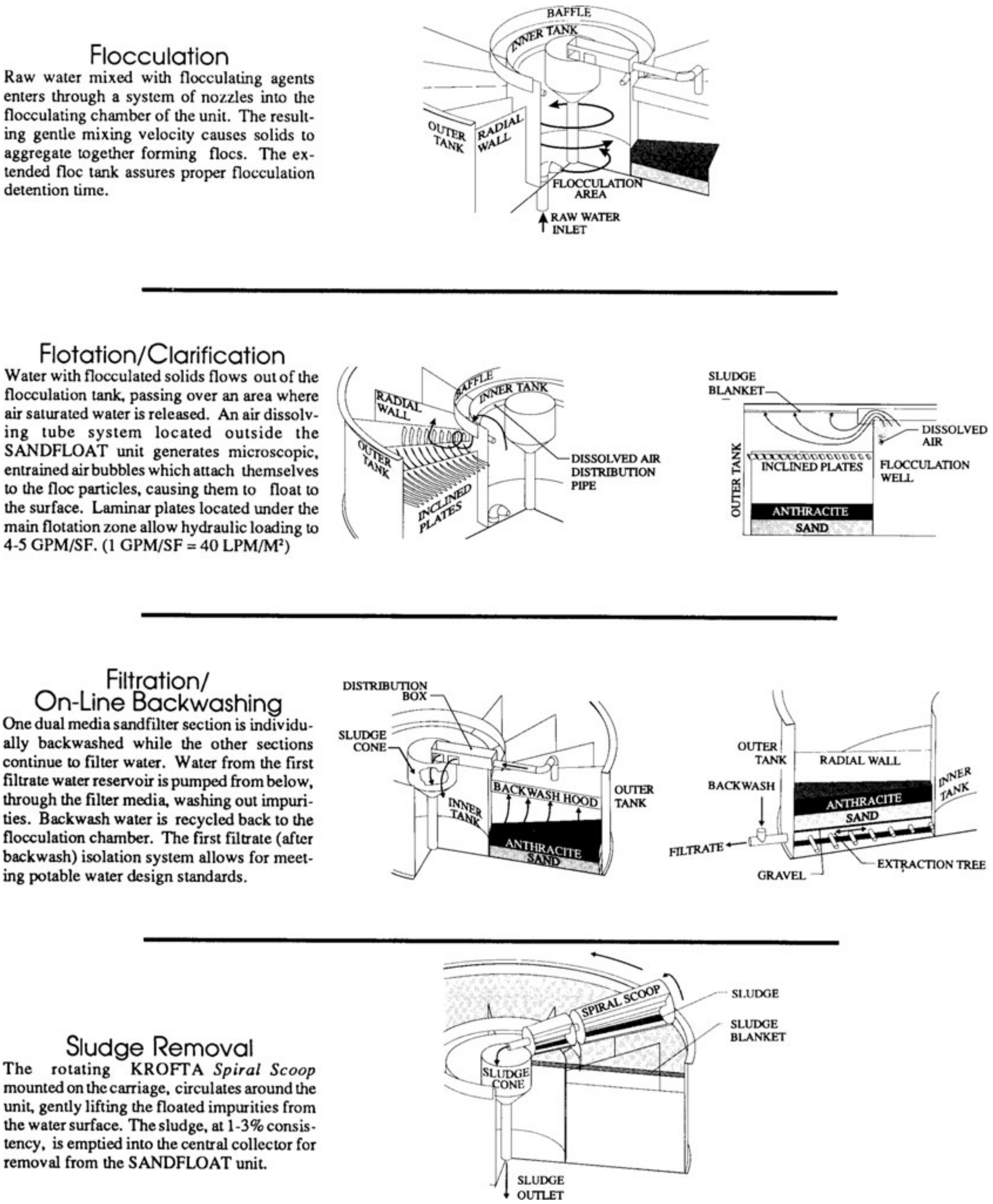
Figures 9.5 and 9.6 illustrate the small flotation-filtration cell (FF-cell) for pilot plant demonstrations. Figure 10.1 illustrates the bird's view a full-scale FF-cell for wastewater treatment applications. Figure 10.2 further illustrates the step-by-step operations of the FF-cell (16).

3. TWO-STAGE FLOTATION SYSTEM

The flow diagram for the two-stage flotation pilot plant is shown in Fig. 10.3. The system, mounted on a mobile trailer, consists of a combination of a primary DAF clarifier, F-Cell (7) and a secondary flotation/filtration clarifier, FF-Cell (18).

The flotation tank is 1.2 m (4 ft) in diameter with 0.41–0.46 m (16–18 in.) effective water depth. The system is complete with feed pump, pressure pump, compressor, air dissolving tube, collection tank, and chemical feed equipment. The flotation tank is equipped with a spiral scoop for collection and removal of floated biosolids (Fig. 10.4).

The inlet, outlet, and biosolids removal mechanisms are contained in the central rotating section. This section and the spiral scoop rotate around the tank at a speed synchronized with the flow. The system is operated in the recycle flow pressurization mode, whereby a portion of clarified effluent (30–40%) is continuously recycled from the collection tank to the air dissolving tube under 400 kPa (60 psi) pressure. After pressure release, the aerated water is



Flocculation

Raw water mixed with flocculating agents enters through a system of nozzles into the flocculating chamber of the unit. The resulting gentle mixing velocity causes solids to aggregate together forming flocs. The extended floc tank assures proper flocculation detention time.

Flotation/Clarification

Water with flocculated solids flows out of the flocculation tank, passing over an area where air saturated water is released. An air dissolving tube system located outside the SANDFLOAT unit generates microscopic, entrained air bubbles which attach themselves to the floc particles, causing them to float to the surface. Laminar plates located under the main flotation zone allow hydraulic loading to 4-5 GPM/SF. (1 GPM/SF = 40 LPM/M²)

Filtration/ On-Line Backwashing

One dual media sandfilter section is individually backwashed while the other sections continue to filter water. Water from the first filtrate water reservoir is pumped from below, through the filter media, washing out impurities. Backwash water is recycled back to the flocculation chamber. The first filtrate (after backwash) isolation system allows for meeting potable water design standards.

Sludge Removal

The rotating KROFTA *Spiral Scoop* mounted on the carriage, circulates around the unit, gently lifting the floated impurities from the water surface. The sludge, at 1-3% consistency, is emptied into the central collector for removal from the SANDFLOAT unit.

Fig. 10.2. Details of the flotation/filtration cell (FF-Cell) (16).

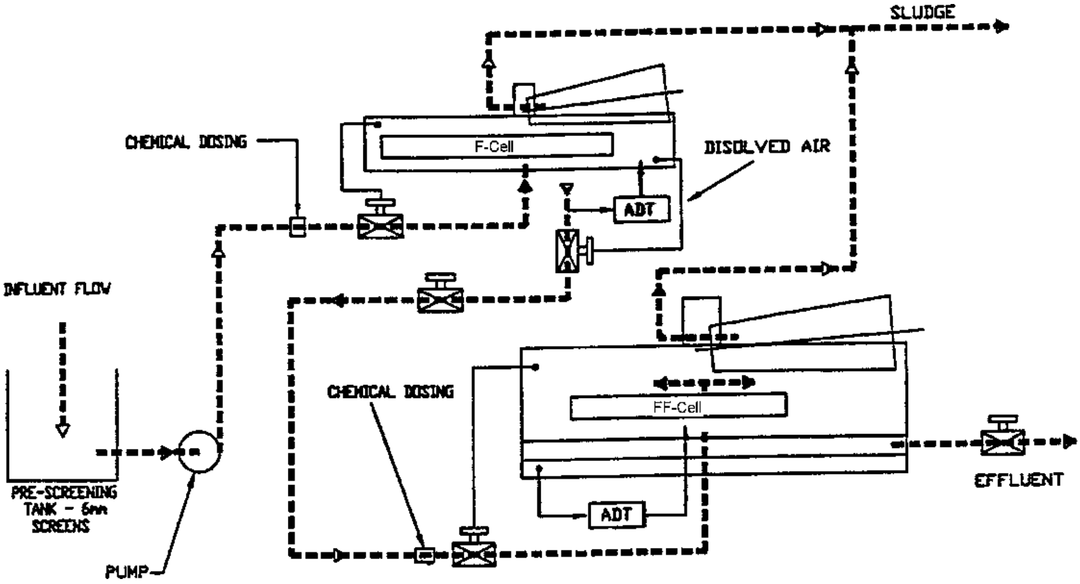


Fig. 10.3. Flow diagram of two-stage flotation system.

mixed with the influent flow just before the inlet to the distribution duct that moves with the same velocity, but in opposite direction to the incoming flow, thus creating a quiescent state in the flotation chamber. Fine bubbles generated in this manner attach to the suspended particles and float them to the surface. The spiral scoop takes up the floated biosolids, pouring them into the stationary center section where they are discharged by gravity. Clarified water is removed by extraction pipes, which are attached to the moving center section and discharged into the collection tank (8, 16, 17).

Wiper blades attached to the moving distribution duct scrape the bottom and the sides of the tank and discharge settled biosolids into the built-in sump, for periodic purging. The variable speed gear motor drives the rotating elements and scoop. Electrical current for the gear motor feeds from a rotary contact mounted on the central shaft.

The second stage FF-Cell is identical to the cell described previously in Sect. 2. The main characteristics of the two cells are listed in Table 10.1.

For further information on the subject of flotation, the reader is referred to the literature (27–32).

4. TREATMENT OF PRIMARY MUNICIPAL EFFLUENT

Hoboken is a city located on the west bank of the Hudson River, between Lincoln Tunnel and Holland Tunnel in New Jersey. It is an old city with an approximate population of 45,000. The primary treatment at the existing 68,000 m^3/day (18 MGD) Hoboken Wastewater Treatment Plant consists of screens and sedimentation clarifiers (18). The effluent was continuously treated by the FF-Cell pilot plant to check its suitability for upgrading the

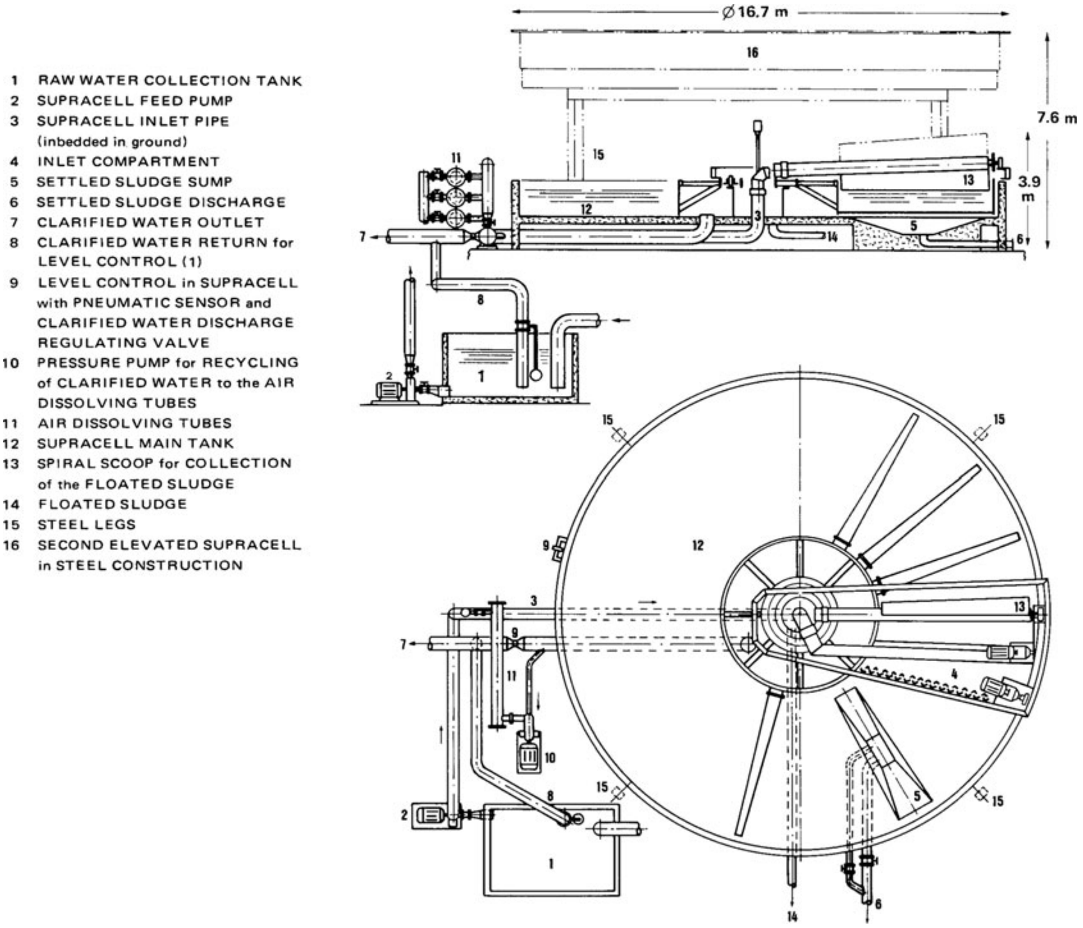


Fig. 10.4. Details of the flotation-cell (F-Cell) (16).

Table 10.1
Characteristics of pilot plant units (20)

Parameter	First stage F-Cell	Second stage FF-Cell
Nominal capacity, L/min	150	150
Cell diameter, m	1.2	1.5
Cell depth, m	0.6	0.9
Air feed, L/min	2.4	2.4
Air pressure, bar	6	6.5
Sludge scoop speed, Rev./min	2	2
Backwash rate, L/min	Not applicable	38
Backwash time, s	Not applicable	45

Table 10.2
Treatment of primary municipal wastewater effluent by FF-Cell at Hoboken, NJ (18)

Parameter	Primary effluent	FF-Cell effluent	Removal[a] (%)
Turbidity, NTU	45	3.3	93
Phosphate-P, mg/L	5.6	0.04	99
BOD_5, mg/L	103	12	88
COD, mg/L	260	80	69
TSS, mg/L	57	2	97
Coliforms, No./100 mL	240,000	5,000	98

FF-Cell flotation/filtration cell.
[a] Chemicals addition: alum (as Al_2O_3) 20 mg/L and polymer 2 mg/L.

quality of the plant effluent. At chemical dosages of 20 mg/L alum and 2 mg/L of nonionic polymer, the primary effluent was successfully treated, as is demonstrated in Table 10.2, by lowering the total suspended solids (TSS) and BOD_5 by 97 and 88%, respectively. The Hoboken primary effluent contents ($BOD_5 = 103$ mg/L and TSS = 57 mg/L) were reduced to 12 and 2 mg/L, respectively. Turbidity and phosphates were also significantly removed; turbidity was lowered from 45 to 3.3 NTU, and phosphate-P was brought down from 5.6 to 0.04 mg/L. It is important to note that the FF-Cell was able to reduce the total coliforms from 240,000/100 to 5,000/100 mL without the use of any disinfectant.

Other applications of flotation for the treatment of primary wastewater effluents have been reported by Schneider et al. (33) and Mennell et al. (34).

5. TREATMENT OF RAW MUNICIPAL WASTEWATER

The pilot plant results of operating the two-stage system for a period of 6 months at the STP in Lee, MA (19) are presented in Table 10.3. All relevant parameters were measured on the raw municipal wastewater effluent water after preliminary flotation in the F-Cell, and final effluent after the secondary flotation–filtration unit (FF-Cell).

Satisfactory results were obtained in a broad range of inlet organic loadings. COD values, which varied from 251 to 1,325 mg/L, were reduced by 75%, and BOD_5 values, which ranged between 108 and 494 mg/L, were also reduced by 75%. The TSS cumulative removal of 99% was very close to the theoretical maximum with an average effluent TSS of 4 mg/L. The overall corresponding turbidity removal was 84%. Also obtained were the following nutrient reductions: phosphorous 82%, total nitrogen 30%, and ammonia–nitrogen 19% (19).

All above-mentioned reductions have been attained over a wide range of flow rates (76–170 L/min) and varying recycle ratios (5–63%). Also using various combinations and concentrations of coagulants and flocculants, it was possible to produce biosolids with a solids content of 3% making it easier and less costly to manage and dispose. The hydraulic loadings were up to 235 L/m^2/min on the primary F-Cell unit and 155 L/m^2/min on the

Table 10.3
Treatment of raw municipal wastewater[a] by two-stage F-Cell and FF-Cell (19)

Parameter	Raw wastewater		F-Cell effluent		FF-Cell effluent		Total removal (%)
	Range	Average	Range	Average	Range	Average	
TSS, mg/L	98–1,191	303	15–240	73	ND-23	4	99
COD, mg/L	251–1,325	571	142–475	290	74–342	145	75
BOD_5, mg/L	108–494	242	68–222	122	30–127	59	75
Turbidity, NTU	44–147	76	20–87	44	0.6–55	12	84
P, mg/L	1.2–12.8	56	1.1–5.8	4.1	0.04–3.3	0.98	82
TKN, mg/L	25–65.2	39	23–61	32	8.4–50	27	30
NH_3-N, mg/L	20–31	23	17–26	21	10–23	19	19
NO_2-N, mg/L	0.7–16.9	2.2	0.1–10.6	1.5	ND-8.6	0.74	66
COD/BOD_5	2.3–2.7	2.4	2.1–2.1	2.4	2.4–2.7	2.4	–

[a] Temperature = 15–20°C, $pH_{Raw} = 6.9–8.1$, $pH_{F\text{-}Cell} = 6.8–7.9$, $pH_{FF\text{-}Cell} = 6.2–7.8$.
F-Cell flotation cell; *FF-Cell* flotation/filtration cell.

secondary FF-Cell unit. These hydraulic loading rates are 7- to 11-fold greater in comparison to the 20 L/m^2/min loading of a conventional sedimentation system.

In addition to proving the effectiveness of the two-stage system in treating raw municipal wastewater, it was possible to optimize the coagulant and flocculant chemicals and doses to the following types and their concentrations (21):

1. *Primary clarification* (F-Cell):
   Ferric sulfate: 75 mg/L
   Magnifloc 496 C: 4.4 mg/L
2. *Secondary clarification* (FF-Cell)
   Magnifloc 496 C: 3.3 mg/L

Enhanced results were obtained for total phosphorous and nitrogen removals as well as for the reduction of various forms of nitrogen. Changing from ferric sulfate to poly aluminum chloride (PAC) in the F-Cell caused a significant reduction in total phosphorous from 7.3 to 0.04 mg/L. This could be explained as an enhanced co- and post-precipitation of phosphorous when PAC was used instead of ferric sulfate. Another application of flotation for treatment of raw wastewater effluents has been reported by Bratby (35).

6. TREATMENT OF ACTIVATED SLUDGE EFFLUENT

An FF-Cell pilot study was performed at the Oak Meadows Sewage Treatment Plant in Licking County, OH (18). The objective of this study was to demonstrate the FF-Cell's performance in the treatment of their secondary clarifier effluent following an aeration basin. The FF-Cell was run at various chemical dosages using up to 5.6 mg/L alum and 0.5 mg/L polymer. All results reported in Table 10.4 were based on daily composite samples. The FF-

Table 10.4
Tertiary treatment of activated sludge effluent by FF-Cell at oak meadows STP, licking county, OH (18)

Period[a]	Chemical addition		Suspended solids (mg/L)		Turbidity (NTU)	
	Chemical	mg/L	In	Out	In	Out
1	Alum (as Al_2O_3)	3.6	23	1.0	2.6	0.95
2	Alum (as Al_2O_3)	4.3	39	2.6	4.3	0.50
	Polymer: 1849A	0.4				
3	Alum (as Al_2O_3)	4.9	5.9	1.0	4.2	0.29
	Polymer: 1849A	0.4				
4	Alum (as Al_2O_3)	5.3	24	2.6	14	0.46
	Polymer: Percol LT-25	0.3				
5	Alum (as Al_2O_3)	5.6	–	–	3.7	0.34
	Polymer: Percol LT-25	0.5				
	Average		23	1.8	5.8	0.50
	Removal, %		92		91	

[a] All tests were done an daily composite samples.

Cell was proven to be effective in the reduction of both suspended solids (92% removal) and turbidity (91% removal). The secondary treatment plant effluent had a TSS content in the range of 6–39 mg/L, which was reduced to an average value of below 2 mg/L. In a similar performance, the treatment plant effluent had turbidities in the range of 2.6–14 NTU, while the FF-Cell was able to attain an average effluent turbidity of 0.5 NTU. The BOD_5 values were consistently at or below 1.0 mg/L. Another application of flotation to tertiary treatment has been reported by Kiuru (36).

7. TREATMENT OF RBC EFFLUENT

An FF-Cell unit was installed at the Jimmy Peak Wastewater Treatment Plant in Hancock, MA (Fig. 10.5). The 400 m^3/day resort area domestic wastewater flows through an aerated equalization tank, two rotating biological contactors (RBC's) (37, 38), one circular secondary sedimentation clarifier (3.6 m diameter), one rectangular tertiary sand filter (3.1 m^2 area), and finally two ultraviolet disinfection units (39) before being discharged to a leaching field. The FF-Cell was fed from the RBC's effluent just before the flow enters the secondary sedimentation clarifier (see Fig. 10.5).

Table 10.5 documents the chemical dosages applied to the FF-Cell influent, as well as the performance data for both the FF-Cell and the conventional combination of secondary clarifier and sand filter as they were run in parallel. The results demonstrate that with optimization of chemical dosages, it is possible to produce effluents that can satisfy the most strict standards or guidelines with BOD_5 and TSS requirements of less than 5 mg/L (18). Another important conclusion can be drawn from the parallel performance of the FF-Cell unit

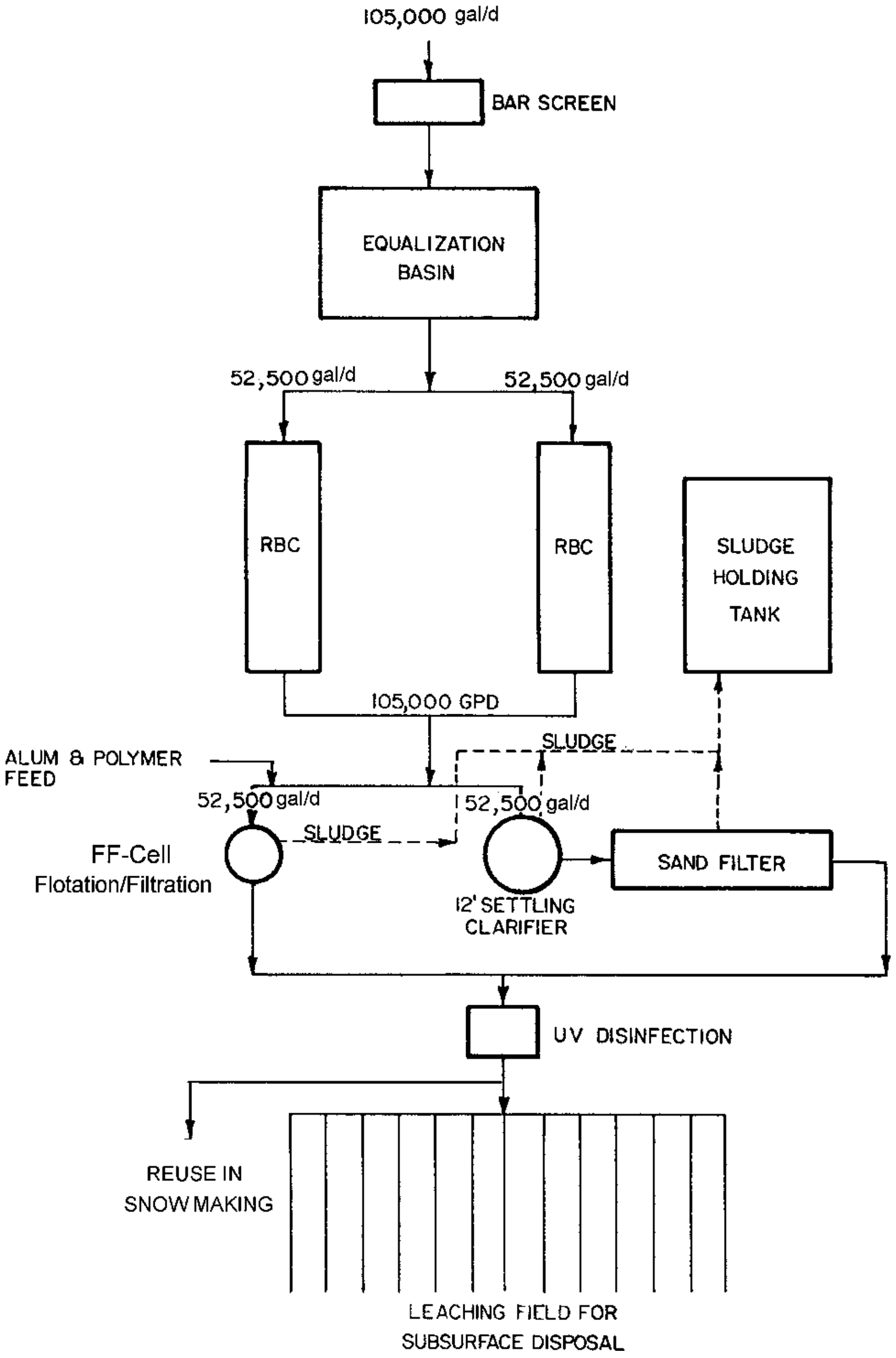


Fig. 10.5. FF-Cell for secondary clarification and tertiary filtration at jiminy peak resort, MA.

Table 10.5
Tertiary treatment of RBC effluent by FF-Cell at Jiminy Peak, MA (18)

Period	Chemical and dosages (mg/L)	BOD_5 (mg/L)			COD (mg/L)			TSS (mg/L)			Total coliforms No./100 mL × 1,000		
		RBC	SC+SF Effluent	FF-Cell	RBC	SC+SF Effluent	FF-Cell	RBC	SC+SF Effluent	FF-Cell	RBC	SC+SF	FF-Cell
1	A = 16, C = 1.5	9.0	4.2	2.1	40	20	25	19	ND	4	21	8	9
2	A = 20.5, D = 1.3	38	24	15	63	39	15	7	1	4	251	146	171
3	A = 60, D = 1.3	70	28	25	216	88	70	116	39	10	TNTC	280	65
4	A = 90.2, C = 0.03	102	27	26	105	75	63	89	18	10	TNTC	430	112
5	A = 43.1, C = 0.004	174	23	11	350	77	81	312	15	30	1,630	1.5	1
6	A = 10.5, D = 1.2	150	8	4.3	150	19	13	131	21	12	600	ND	ND
7	B = 103.8, E = 0.73	118	–	1.6	192	–	5	179	–	15	37.6	–	2.8
Range	Minimum	9.0	4.2	1.6	40	19	5	7	ND	4	21	ND	ND
	Maximum	174	28	26	350	88	81	312	39	30	TNTC	430	171
Average		94	19	12	159	53	39	122	16	12	–	144	52

A: Alum as Al_2O_3; B: Ferric chloride; C: Nalco 2PD-462; D: Nalco 7533; E: Nalco 7766.
RBC rotating biological contactors; *SC* secondary clarifier; *SF* sand filter; *FF-Cell* flotation/filtration; *ND* not detectable; *TNTC* too numerous to count.

and the conventional secondary sedimentation plus filtration: the innovative FF-Cell is superior to conventional tertiary treatment, not only in removal of BOD_5, COD, TSS, and coliforms, but also in land space requirement and consequently in capital cost required to be invested for reusing the treated effluent in snow making machines.

8. TREATMENT OF TRICKLING FILTER EFFLUENT

The effectiveness of the FF-Cell in treating the secondary trickling filter (40) effluent at the Norwalk Wastewater Treatment Plant in Ohio was investigated in this part of the applications. Norwalk is located in northern Ohio, approximately 50 miles southwest of Cleveland and supports a population of 14,500 people. The plant treats combined domestic sewage and food processing waste (18).

Secondary trickling filter effluent was pumped to the FF-Cell with a submersible sump pump at 164 m^3/day. Treatment chemicals were added directly to the feed line using masterflex variable speed peristaltic dosing pumps. Alum was added approximately 12 m ahead of the FF-Cell to allow for thorough mixing. Anionic polymer (Nalco 7769) was added in line just prior to the FF-Cell inlet compartment. TSS, BOD_5, and phosphate-P tests were all

Table 10.6
Tertiary treatment of trickling filter effluent by FF-Cell at Norwalk, OH (18)

Period	TSS (mg/L)		BOD_5 (mg/L)		Phosphates-P (mg/L)	
	In	Out	In	Out	In	Out
1	104	11	54	5	8.8	0.8
2	136	6	51	3	9.2	0.4
3	122	12	–	–	9.6	1.1
4	106	1	45	2	–	0.3
5	72	4	43	3	6.7	0.3
6[a]	28	9	20	4	7.0	0.7
7[a]	132	7	32	4	4.5	0.2
8[a]	103	8	39	4	7.8	0.6
Range						
Minimum	28	1	20	2	4.5	0.2
Maximum	136	12	54	5	9.6	1.1
Average	100	7.2	41	3.6	7.7	0.6
Removal, %	93		91		92	

[a] Optimized chemistry: Alum = 120 mg/L as alum and anionic polymer Nalco 7769 = 0.25 mg/L.
All tests were done on daily composite samples.

performed on daily composite samples collected from the influent and effluent of the FF-Cell. Experimental results are summarized in Table 10.6. It can be seen that on the average the FF-Cell met the tertiary effluent standards (TSS = 10 mg/L, BOD_5 = 10 mg/L, and P = 1 mg/L) with removals above 90%. Considering the final three testing periods (6–8 in Table 10.6) when chemical dosages, 120 mg/L of alum and 0.25 mg/L of polymer, were optimized the FF-Cell effluent met the above mentioned effluent standards all the time. In addition, the average biosolids consistency was 3.2% solids, which negates the need for a biosolids thickener.

9. TREATMENT OF LAGOONS EFFLUENT

Arpin Wastewater Treatment Plant in Arpin, WI, is a system of aerated lagoons (41) treating a combination of dairy processing wastewater and domestic sewage with a high proportion (over 75%) of the flow coming from the dairy. The lagoons effluent contained a lot of colloidal substances and had high color (green) and algae count (18).

A sump pump was used to feed the pilot plant from the third lagoon. Alum and polymer were added to the feed line at dosages of 6–40 mg/L of alum and 0.5–1 mg/L of anionic polymer. The FF-Cell proved itself capable of treating the lagoons effluent and producing a clarified effluent below 20 mg/L in BOD_5 and TSS. The average TSS and BOD_5 values in the effluent were 6 and 12 mg/L, respectively (see Table 10.7). The optimized chemical dosage was 10 mg/L for alum and 1 mg/L for this anionic polymer. At all times during the study, the high consistency green floated biosolids layer was removed by the spiral scoop. Consistencies

Table 10.7
Tertiary treatment of lagoon effluent by FF-Cell at Arpin, WI (18)

Period	TSS (mg/L)		BOD_5 (mg/L)	
	In	Out	In	Out
1	26	14	20	2
2	26	8	26	9
3	28	5	44	21
4	28	2	41	14
5	28	4	30	13
6	28	2	17	14
7	28	5	17	11
8	40	11	20	12
Range	26–40	2–14	17–44	2–21
Average	29	6	27	12
Removal, %	79		56	

Optimized chemical dosage: Alum = 10 mg/L (as Al_2O_3); Anionic polymer Hercofloc 1018 = 1 mg/L.

of over 2% solids were obtained when the FF-Cell's biosolids scoop was operated intermittently allowing a thick biosolids layer to build up. Existing lagoons experiencing operational problems can be improved or upgraded for effluent reuse by the addition of an FF-Cell in series for tertiary treatment.

10. CONCLUSION

The technical feasibility of the innovative FF-Cell system for producing a high quality effluent has been successfully demonstrated by continuous pilot plant operation. An existing secondary biological wastewater treatment plant can be easily upgraded by the addition of an FF-Cell to produce an effluent having a water quality compatible with water reuse requirements. The capital cost of such a system is low because of its short detention time and unique compact design (42).

REFERENCES

1. Shammas NK (1987) Wastewater management and reuse in housing projects. Water reuse symposium IV, implementing water reuse. AWWA Research Foundation, Denver, CO, 2–7 Aug 1987, pp 1363–1378
2. Asano T, Richard D, Crites RW, Tchobanoglous G (1992) Evolution of tertiary treatment requirements in California. Water Environ Technol 4(2):36–41
3. Crook J (1991) Regulatory issues associated with reuse practices throughout the world. AWWA 1991 annual conference proceedings, resources, engineering and operations of the new decade. Philadelphia, PA, 23–27 June 1991, pp 225–239

4. WPCF (1989) Water reuse, manual of practice SM3. Water Pollution Control Federation, Alexandria, VA
5. Shammas NK, El-Rehaili A (1986) Tertiary filtration of wastewater for use in irrigation. Symposium on the effect of water quality on the human health and agriculture in the G.C.C. states. Al-Khobar, Saudi Arabia
6. Wang LK, Hung YT, Shammas NK (eds) (2005) Physicochemical treatment processes. Humana, Totowa, NJ, 723 pp
7. Shammas NK, DeWitt N (1992) Flotation: a viable alternative to sedimentation in wastewater treatment. Water environmental federation 65th annual conference. New Orleans, LA, 20–24 Sept 1992, pp 223–232
8. Wang LK, Fahey EM, Wu Z (2005) Dissolved air flotation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana, Totowa, NJ, pp 431–500
9. Krofta M, Wang LK (1984) Development of innovative flotation-filtration systems for water treatment, Part A: first full-scale Sandfloat Plant in U. S. Proceedings of water reuse symposium III. San Diego, CA, 26–31 Aug 1984, pp 1226–1237
10. Guss D (1991) Improving water quality with flotation/filtration. 1991 Nonwoven conference, TAPPI proceedings. Technology Park/Atlanta, GA, pp 323–326
11. Zabel T (1992) Flotation in water treatment. In: Mavros P, Matis K (eds) Innovations in flotation technology. Kluwer Academic Publishers, Netherlands, pp 431–454
12. Krofta M, Wang LK (1984) Tertiary treatment of secondary effluent by dissolved air flotation and filtration. Civil Eng Pract Des Eng 3:253–272, (NTIS-PB83-171165)
13. Krofta M, Wang LK (1986) Wastewater treatment by a biological-physicochemical two-stage process system. Proceedings of the 41st industrial waste conference, Lewis Publishers, Chelsea, MI, 13–15 May 1986
14. Kiuru H (1990) Tertiary wastewater treatment with flotation filters. Water Sci Technol 22(7/8): 139–144
15. Shammas NK (2005) Coagulation and flocculation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana, Totowa, NJ, pp 103–140
16. Krofta M, Wang LK (2000) Flotation engineering. Technical manual no. Lenox/1-06-2000/368. Lenox Institute of Water Technology, Lenox, MA
17. Krofta M, Wang LK (1999) Flotation and related adsorptive bubble separation processes. Technical manual no. Lenox 7-25-1999/348, 4th edn. Lenox Institute of Water Technology, Lenox, MA
18. Shammas NK, Krofta M (1994) A compact flotation-filtration treatment unit for wastewater reuse. Proceedings water reuse symposium. AWWA, Dallas, TX, 27 Feb–2 Mar 1994, pp 97–109
19. Krofta M, Miskovic D, Shammas NK, Burgess D, Lampman L (1994) An innovative multiple stage flotation-filtration low cost municipal wastewater treatment system. IAWQ 17th biennial international conference. Budapest, Hungary, 24–30 July 1994
20. Shammas NK (1997) Physicochemically-enhanced pollutants separation in wastewater treatment. Proceedings of the international conference: rehabilitation and development of civil engineering infrastructure systems – upgrading of water and wastewater treatment facilities. Organized by The American University of Beirut and University of Michigan, Beirut, Lebanon, 9–11 June 1997
21. Krofta M, Miskovic D, Shammas NK, Burgess D (1994) Pilot-scale applications of a primary-secondary flotation system on three municipal wastewaters. Specialist conference on flotation processes in water and sludge treatment. Orlando, FL, 26–28 Apr 1994

22. Krofta M, Guss D, Wang LK (1988) Development of low- cost flotation technology and systems for wastewater treatment. Proceedings of the 42nd industrial waste conference. Lewis Publishers, Chelsea, MI, p 185
23. Wang LK (1991) Water and wastewater treatment using advanced dissolved air flotation. The 1991 annual conference of the Korea society of water pollution research and control. Seoul, Korea, 22–23 Feb 1991
24. Wang LK, Shammas NK, Hung YT (eds) (2007) Biosolids treatment processes. Humana, Totowa, NJ, 820 pp
25. Wang LK, Shammas NK, Selke WA, Aulenbach DB (2007) Flotation thickening. In: Wang LK, Shammas NK, Hung YT (eds) Biosolids treatment processes. Humana, Totowa, NJ, pp 71–100
26. Cizinska S, Matejo V, Wase C, Kiasson Y, Krejci J, Daihainmar G (1992) Thickening of waste activated sludge by biological flotation. Water Res 26:139
27. Zabel T (1985) The advantages of dissolved air flotation for water treatment. J Am Water Works Assoc 77:42
28. Janssens JG (1992) Developments in coagulation, flocculation and dissolved air flotation. Water/Eng Manag 139:26
29. Metcalf & Eddy, Inc., Metcalf and Eddy (2003) Wastewater engineering treatment and reuse, 4th edn. McGraw Hill, New York, NY
30. Clarke AN, Wilson DJ (1983) Foam flotation-theory and application. Marcel Dekker, New York, NY
31. Lemlich R (1972) Adsorptive bubble separation techniques. Academic Press, New York, NY
32. Sebba F (1962) Ion flotation. Elsevier, New York, pp 137–141
33. Schneider IAH, Neto VM, Soares A, Rech RL, Rubio J (1995) Primary treatment of soybean protein bearing effluent by dissolved air flotation and by sedimentation. Water Res 29(1): 69–75
34. Mennell M, Merrill DT, Jorden RM (1974) Treatment of primary effluent by lime precipitation and dissolved air flotation. J Water Pollut Control Fed 46:2471
35. Bratby JR (1982) Treatment of raw wastewater overflows by dissolved air flotation. J Water Pollut Control Fed 54:1558
36. Kiuru HJ (1990) Tertiary wastewater treatment with flotation filters. Water Sci Technol 22:139
37. Wang LK, Pereira NC, Hung YT, Shammas NK (eds) (2009) Biological treatment processes. Humana, Totowa, NJ, 818 pp
38. Wang LK, Shammas NK, Hung YT (eds) (2009) Advanced biological treatment processes. Humana, Totowa, NJ, 738 pp
39. Wang LK, Hung YT, Shammas NK (eds) (2006) Advanced physicochemical treatment processes. Humana, Totowa, NJ, 690 pp
40. Wang LK, Zucheng W, Shammas NK (2009) Trickling filters. In: Wang LK, Pereira NC, Hung YT, Shammas NK (eds) Biological treatment processes. Humana, Totowa, NJ, pp 371–434
41. Shammas NK, Wang LK, Zucheng W (2009) Waste stabilization ponds and lagoons. In: Wang LK, Pereira NC, Hung YT, Shammas NK (eds) Biological treatment processes. Humana, Totowa, NJ, pp 315–370
42. Wang LK, Shammas NK, Guss DB (2010) Flotation biological systems. In: Wang LK, Ivanov V, Tay JH, Hung YT (eds) Environmental biotechnology. Humana, Totowa, NJ, pp 484–506

11

Algae Removal by Flotation

Donald B. Aulenbach, Nazih K. Shammas, Lawrence K. Wang and Rodney C. Marvin

CONTENTS

Abstract The importance of algae is discussed. Algae are a significant source of oxygen on Earth due to its capability of photosynthesis. Further they are an efficient biological system for converting solar energy into plant life, a source of energy for higher life. However, at high concentrations, called blooms, they can contribute tastes and odors, and even toxins to the surrounding water. They are best removed before they reach a water treatment plant (WTP) where they may rupture and release their taste and odor oils. Algae at both low and high concentrations may be removed by dissolved air flotation (DAF). Even very high concentrations from wastewater treatment lagoons and algae culture ponds are efficiently removed. The recovered algae have many economical uses. When alum or iron salts are added to improve coagulation for algae removal, phosphorus is also removed, thereby lessening productivity in a lake or stream. The development of algae culture ponds heated by waste heat from a nearby power plant, combined with CO_2 and NO_X from fossil fueled power plants' atmospheric discharges, could reduce atmospheric pollution and even global warming. The algae produced and removed can serve as an energy source. A case study is described for the application of a DAF system for upgrading a small drinking WTP. Examples are shown for the separation of algae from wastewater treatment plant lagoons. The use of DAF for separation of algae is an important factor in our lives.

Key Words Algae • nutrients • productivity • biological activity • ponds • lagoons • remediation • removal by DAF • dissolved air flotation.

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1. IMPORTANCE OF ALGAE

All life depends upon water. Water is a unique substance in our universe. More substances dissolve in water more than in any other liquid. Water is most nearly the universal solvent; however, we still have materials that do not dissolve in water or that dissolve very slowly, hence we have containers for carrying the water. The substances dissolved and ionized in water become part of biological life. The unique feature that the solid form of water floats on the liquid form prevents deep lakes and oceans from having permanent ice on their bottoms. Water has a high heat capacity, thereby moderating changes in temperature. It has high heat conductivity, making it ideal for heat transfer. The latent heats of freezing and of vaporization are high, making change of phase difficult, but also providing a means of energy transfer. All these features of water combine to make life possible. "Water is Life."

It is generally agreed that life most likely originated in the ocean, whether by chance or divine decree. The elements probably came up from the magma in the center of the earth through cracks or holes in the crust. Holes include volcanic type activity. The right combination of elements came together, and, more importantly, they managed to copy themselves in a form of reproduction. Energy came from reduction of elements such as sulfur to sulfide and iron to ferrous iron. This is a low energy reaction. There was no oxygen; the system was entirely anaerobic. In some way these substances must have reached the surface of the ocean, where they were exposed to a much greater energy source: the sun. They utilized this energy for further growth and reproduction and found a way to produce oxygen in what we call photosynthesis. This was the first occurrence of aerobic conditions. These organisms, which were most likely single-celled, contained chlorophyll and are the basis of the group of organisms that we now call algae. They are capable of producing oxygen as well as cell material from some essential nutrients with the aid of energy from the sun. This cell material serves as food for higher organisms and is thus considered the basis of our food chain. It has been estimated that 75% of the oxygen on earth is produced by algae in the ocean.

Algae constitute a wide variety of photosynthetic organisms from single-celled to large multicellular sheets of kelp found in the ocean. Large numbers of varieties of species are found in both fresh and ocean salt waters, with fewer numbers that prefer or tolerate brackish waters. Generally, different species prefer fresh or salt waters. They are important in producing organic matter from inorganic materials utilizing the energy from the sun. Thus solar energy is stored as organic material. At the same time they are a principal source of oxygen, maintaining the surface of Earth under aerobic conditions. Thus algae represent the beginning of the transfer of Earth from a primarily anaerobic life to an aerobic one in which oxygen serves as the principal transfer of energy. Not only is this more efficient than anaerobic processes, it also represents converting the energy of the sun to stored energy, thus assuring a longer duration of geological time than depending on only the resources of the Earth.

Certain algae represent a source of human food. Probably the most common is the macroalga used for the wrapper in sushi rolls (1). Spirulina and dulse are also edible. Dulse (*Palmaria palmate*) is red and is eaten raw, dried, or cooked like spinach by people in Ireland and Atlantic Canada. Purple laver (*Porphyra*) is used for making laverbread in the British Isles and for making jelly in Ireland. Irish Moss (*Chondrus crispus*) is used as carrageen for stiffening of milk and dairy products such as ice cream. It is also used to make a clearer beer (2). For centuries, seaweed has been used as a fertilizer. It is high in potassium, used in the production of potash and potassium nitrate. Agar is made from seaweed (3).

Algae have been cultivated for use as food, oil, or pigments. Open ponds are frequently used; however, they are prone to mixed cultures that vary with season and nutrients. Therefore, establishing a constant final end product is difficult. To overcome this, closed chambers are used at constant temperature with known nutrients and at constant, usually artificial, light (4). It has been suggested that CO_2 from fossil-fueled power plants be used as the carbon source, thereby simultaneously reducing discharge of that greenhouse gas. Watersmart Environmental has joined US EPA's CHP (Combined Heat and Power) Partnership with a system to conserve heat and energy (5). The most efficient fossil-fueled power plants can achieve a power efficiency of about 60%. The remaining heat energy is wasted. Using this excess heat to heat adjacent algae ponds will not only increase the total efficiency but also serve as a cooling system for the power plant. In addition, burning fossil fuel produces a mixture of nitrogen oxides, commonly referred to as NO_X, which can be used as a nitrogen source when dissolved in water. With the conservation of heat in the water, nitrogen from the NO_X, and carbon from the CO_2, all that is needed is a source of phosphorus and trace nutrients to provide an optimum growth system for algae. The phosphorus could be supplied by a nearby wastewater treatment plant that would also be the source of the water for the pond. Of course sunlight is also needed. Studies could be made to provide the optimum balance of all these inputs. This would alleviate some problems of fossil-fueled power plants and at the same time produce algae that can be used as fuel or many other uses.

The oils extracted from algae can be used as a form of "biodiesel." It is suggested they would make a substitute for gasoline in that they have a much faster growth rate than terrestrial crops. It is estimated that the yield of oil from algae is between 5,000 and 20,000 gal/ac/year, which is 7–31 times greater than the next best (terrestrial) crop, palm oil, at 635 gal/ac/year (6).

It has been reported (7) that if *Chlamydomonas reinhardtii* is grown in a medium that is deficient in sulfur, it will produce hydrogen instead of oxygen, the normal product of photosynthesis. This could also be used as a substitute for gasoline in transportation vehicles. Algae biomass can be dried and burned similar to wood to produce heat for energy (8). Under anaerobic digestion, algae biomass will produce methane (9). The oil of *Botryococcus braunii* is different than other algal oils in that it can be cracked into gasoline, diesel, and aviation grade kerosene (10).

Spirulina (*Arthrospira platensis*) is a blue-green alga that is high in nutrients and protein. It is often used commercially as a nutrient supplement (11, 12). Extracts and oils are used as additives in various food products (13). They also produce Omega-3 and Omega-6 oils, which have been shown to have medical benefits (14).

2. CHARACTERISTICS OF ALGAE

If algae are so important in our lives, one may ask, "Why are we concerned with means of their removal?" Basically it boils down to one thing: too much of the good thing.

Algae, being living organisms, respire using reduction of oxygen or oxidized materials to gain the energy to sustain life, grow, and reproduce. It is only during daylight that they produce more oxygen than they consume during a 24-h cycle. Respiration is relatively constant, although it varies considerably with the ambient temperature. The problem is that the excess oxygen produced during daylight is released to the surrounding water. Water can contain only a limited amount of dissolved oxygen, which is controlled by the temperature as shown in Table 11.1. Although a limited amount of supersaturation may occur, basically all the oxygen in excess of saturation is released to the atmosphere, particularly when the water is in motion. Thus at night, if large numbers of algae are present, they may consume all of the remaining oxygen, creating anoxic conditions (lack of free oxygen) or anaerobic conditions (lack of free or combined oxygen). This may cause the death of other aquatic organisms, particularly fish that require the presence of some dissolved oxygen. Some less tolerant algae may also die from the lack of oxygen. Thus large numbers of algae tend to create undesirable conditions.

Table 11.1
Solubility of oxygen in fresh water exposed to water saturated air at atmospheric pressure

Temperature (°C)	Oxygen saturation (mg/L)	Temperature (°C)	Oxygen saturation (mg/L)
0.0	14.621	26.0	8.113
1.0	14.216	27.0	7.968
2.0	13.829	28.0	7.827
3.0	13.460	29.0	7.691
4.0	13.107	30.0	7.559
5.0	12.770	31.0	7.430
6.0	12.447	32.0	7.305
7.0	12.139	33.0	7.183
8.0	11.843	34.0	7.065
9.0	11.559	35.0	6.950
10.0	11.288	36.0	6.837
11.0	11.027	37.0	6.727
12.0	10.777	38.0	6.620
13.0	10.537	39.0	6.515
14.0	10.306	40.0	6.412
15.0	10.084	41.0	6.312
16.0	9.870	42.0	6.213
17.0	9.665	43.0	6.116
18.0	9.467	44.0	6.021
19.0	9.276	45.0	5.927
20.0	9.092	46.0	5.835
21.0	8.915	47.0	5.744
22.0	8.743	48.0	5.654
23.0	8.578	49.0	5.565
24.0	8.416	50.0	5.477
25.0	8.263		

Another problem related to large abundances of algae is the release of tastes and odors to the water. Most algae store food as oils. Many of these oils have an undesirable taste and/or odor. Blue-green algae have a reputation for imparting undesirable tastes and odors, but other algae may also impart varying degrees of tastes and odors. When only small numbers of algae are present, these tastes and odors may not be noticeable; however, when large numbers of algae are present, their accumulation results in the noticeable tastes and odors.

Furthermore, certain species of algae are toxic either to other aquatic organisms or to humans. Although not true algae, so-called blue-green algae have a tendency to produce toxins. They may also be classified as cyanobacteria. Pets and farm animals have been known to have died from drinking water containing blue-green algae. Pets may even get sick from licking their wet hair after being in the water. Human reactions to external exposure usually relate to skin irritations such as rashes. Ingestion may cause headaches, nausea, muscular pains, abdominal pain, diarrhea, and vomiting. Death is rare. Again, the toxic level is related to the abundance of the algae; however, toxins have been shown to persist in water several weeks after the bloom has subsided (15).

There are several concerns for water treatment plants (WTPs). The abundance of the algae may prematurely clog any filtration systems. This is particularly true of diatoms, a group of algae that form a shell of silica. These shells are very persistent and tend to clog filters. Actually, diatomaceous earth consists of diatom shells, usually precipitated from ancient oceans, that are commonly used as filtering materials or filtering aids. Another concern is that treatment may rupture the algae, thereby releasing the taste- and odor-producing oils before the whole algae are removed from the treatment system. As with other concerns, large numbers of algae, commonly called a bloom, are what cause the problem.

A survey by Knappe et al. (16) showed that 73% of the WTPs responding experienced algae-related problems in some form or another. This included taste and odor, filter clogging, increased chemical demand, trihalomethane (THM) formation, and algal toxins.

Algae are less likely to cause a problem when there is diversity of species in the water environment. However, even in low nutrient environments, there may be a tendency to develop a monoculture of algae. Typically, algae increase in numbers during the summer season, with maximum numbers in July or August slightly after the summer solstice of maximum sunlight. For years limnologists have observed a dominance of diatoms in spring followed by a dominance of blue-green algae in late summer and fall. It was questioned whether this was attributable to the increase in water temperature, the difference in solar radiation, predation, or some other factors. In a study of Saratoga Lake, NY, Aulenbach (17) showed that diatoms predominated until the silicon level dropped to a level that could no longer support the diatoms. Thereafter, the blue-green algae took over due to lack of competition from the diatoms. Also, the rapid depletion in silicon was attributed to the growth of *Stephanodiscus*, a relatively large diatom. Thus the depletion of the silicon was due, not to the total numbers of diatoms, but to the mass of silicon tied up by the large diatoms. It is this situation that makes evaluation of the trophic state of a body of water based on the diversity of algae alone very difficult.

Rabalais et al. (18) reached a similar conclusion in their studies of the anoxic zone in the Gulf of Mexico. This has been a particular concern since the anoxic zone restricts the production of shrimp, a major economic crop of the Gulf of Mexico. Blue-green algae predominate in the anoxic zone, corresponding with a depleted level of silicon. They attribute the lack of silicon in the Gulf to the dams on the Mississippi River, which trap the sand and silt that normally reach the Gulf.

3. IMPORTANCE OF BIOLOGICAL ACTIVITY

The main direction of this chapter is the removal of algae, the microscopic green plants floating in the water, by dissolved air flotation (DAF). There are larger, macroscopic algae, even up to the large kelp beds of the oceans, but their means of removal is by methods other than DAF. In addition to algae, natural waters contain numerous other organisms of microscopic size. The floating microscopic organisms are called plankton, which may be subdivided into two groups: the phytoplankton or plant life, which includes algae, fungi, and pollens that fall into the lake, and the zooplankton or animal forms. The plankton may also be broken down into the nekton, or free swimming organisms and the benthon, which exist on the bottom. All of these microscopic organisms may be removed with the algae in a DAF system. The algae are of particular interest because they produce oxygen in the presence of sunlight, and convert solar energy into protein, which serves as food for the larger organisms, particularly the zooplankton.

As has been pointed out, the algae present a problem for water supplies when they multiply into massive growths, commonly called blooms. Blooms develop when there is an adequate supply of nutrients to support growth. Most commonly, nitrogen and phosphorus are the controlling nutrients, along with traces of sulfur, iron, and several other trace substances. However, it has been shown that in the case of diatoms, silicon is an essential element, and very frequently is the limiting element in their proliferation. This corresponds with Liebig's Law of the Minimum, which states that the growth of an organism is limited to the element that is present in the lowest concentration in relation to that organism's need. This is very evident in the limit of silicon for diatoms.

Another need for removal of algae is their use in waste treatment processes. The algae present in waters for water supply are relatively low in concentration. However, algae are also used in lagoon treatment of wastewaters, where the algae become the source of the oxygen to maintain aerobic conditions. Here the concentrations are very high. The algae produced must be separated from the treated wastewater prior to discharge to a receiving body of water or to further treatment. Thus the design range for the consideration of the use of DAF for algae removal must include both low concentrations and very high concentrations.

Wastewater treatment lagoons may be designed to provide the equivalent of biological treatment (similar to activated sludge or trickling filters) of a wastewater, or they may be designed to be a polishing treatment that may include additional nutrient (nitrogen and phosphorus) removal plus reaeration. The treatment lagoons may be in the order of 4–5 m deep and are usually aerated by means of an aeration system. The aerators may be either submerged or surface aerators. The aerators provide the major source of oxygen and they also provide mixing, which not only mixes the contents of the lagoon, but also brings the liquid to the surface where additional surface transfer of air takes place. Algae usually grow in this system, but are not relied upon to provide a significant source of oxygen. Polishing lagoons seldom exceed 1 m in depth and have no provisions for mixing. The algae are the major source of oxygen, and surface wind is relied upon to provide mixing. The algae may become very prolific in this type of lagoon, since the nutrient supply is generally adequate. Since there is a diversity of algal species, lack of a specific element, such as silicon for diatoms, has little effect on the total algal biomass. It should be pointed out that this is considered a use for the algae in providing the source of oxygen to maintain an aerobic environment for aerobic treatment. Thus algae removal processes must be designed for both low levels and high levels of algae.

4. CONTROL OF ALGAE IN WATER SUPPLIES

Low levels of algae are desirable in water supplies. They provide oxygen to maintain lakes in an aerobic state. They also are a primary source of organic matter that becomes food for larger (higher) organisms that are subsequently eaten by fish that are a food supply for birds, bears, and humans. The goal is to prevent blooms that may raise the levels of algae that impart tastes and odors, and possibly even toxins, to the water. Blue-green algae are a common source of tastes and odors.

As with any pollution problem, controlling inputs of nutrients to a body of water is more effective than after-the-fact remediation. This means eliminating or reducing the sources of the pollutants. A forested watershed will lessen the amount of nutrients being carried into a body of water. However, lumbering, especially clear-cutting, results in greater carriage of silt and nutrients into the water. Farmed areas contribute large amounts of nutrients and fertilizers. Human development may contribute significantly to the nutrient load in the form of more direct surface runoff to a lake and more, even treated, domestic wastes.

All biological systems require the presence of the proper nutrients to grow and reproduce. For larger organisms, the smaller organisms provide both the nutrients and the energy. Algae obtain their nutrients from dissolved inorganic materials and their energy from the sun. Organisms that rely on inorganic nutrients are called autotrophic, whereas those that rely on organic matter are called heterotrophic. Besides nutrients and energy, growth may depend upon other factors such as temperature, light, etc. However, common to most are carbon, hydrogen, oxygen or another electron acceptor, nitrogen, and phosphorus. Carbon may be obtained from other organic matter (starting with algae) and from the solution of carbon dioxide. Hydrogen may be obtained from electrolysis or from bicarbonates dissolved in the water. Oxygen is most frequently obtained from the dissolved oxygen in the water. Nitrogen is secured from dissolved nitrogenous materials including ammonia, nitrites, and nitrates. Certain blue-green algae can fix gaseous nitrogen from the atmosphere as a nitrogen source. Phosphorus is usually obtained from geological materials and from the breakdown of other organic materials. Some trace substances may also be essential. Sulfur may be present in the soil, and is available from decaying organic matter. Iron is usually available from dissolved mineral deposits. And, of course, silicon is required to form the shell case, called the frustule, of diatoms.

When nutrients cannot be controlled and algae blooms occur, other methods have been used to control algae (and other) growths in a lake. One of the oldest techniques for algae control is the addition of copper sulfate to the lake. To be effective, this must be added at the beginning of the rapid algae growth period in order to restrict the growth. Repeat application during the maximum growing season is common. However, this relieves the symptoms without curing the disease. If the nutrients are not reduced, the growth will recur every spring and copper sulfate must be reapplied. Even though the copper sulfate addition is in the range of 0.1–1 mg/L, repetitive addition can result in a buildup of copper carbonate in the bottom of the lake over a period of years. With time this can result in concentrations harmful to fish and other aquatic life. A big concern is when a lake becomes acidified as the result of acid rain, particularly in the northeast USA. At the low pH of many lakes, the copper carbonate is dissolved, releasing copper (and other precipitated metals) to the water column. This kills not only the algae, but also most other aquatic life including fish. The use of copper sulfate as an interim algal control method until nutrient releases to a lake are reduced and lower algae concentrations can be accepted, but it is not recommended for long-term remediation. Further, the proposed US EPA regulations (EPA-HQ-OPP-2005-0558) for copper risk assessment would greatly lower the acceptable copper concentration in drinking water to a point that would seriously restrict the use of copper sulfate for algae control. A point taken by the American Water Works Association (AWWA) (19) is that the toxins not removed by the copper could be a greater health hazard than the residual copper in the drinking water.

Today there are numerous chemicals available for use as algaecides. Similarly, there are many herbicides available for terrestrial weed control. Many of these herbicides are also effective for algae control. For best control, chemicals should be added before the time of rapid growth in spring. Much literature is available concerning chemicals for algae control. However, there are many different species of algae, and just as many susceptibilities to control by a specific algaecide. The most common algaecides are designed for swimming pools. The algae in a lake may not respond to treatment by swimming pool chemicals. Each situation must be studied independently in order to find the chemical that is most effective and/or economical for a specific situation. In addition, consideration must be made for herbicides from farmland or lawns to gain access to the body of water. These could either add to the effectiveness of a specific algaecide or neutralize its effectiveness. Similar to the use of copper sulfate, chemical addition does not cure the cause of the algal bloom. If provisions are not made to reduce the inputs of nutrients, they may merely cause a problem downstream. Also not controlling the nutrient inputs will mean that the algaecides may have to be added more frequently for effective control.

If a lake or reservoir is to be used as a drinking water supply, caution must be made in the addition of chemicals. Only certain chemicals have been approved for algae control in drinking water supplies. Even these raise questions of safety by the users. Table 11.2 lists the algaecides certified by the National Sanitation Foundation (NSF) for application in drinking water supplies.

Sonar© has been approved for the control of *Eurasian milfoil* in water supply lakes, but the public does not have sufficient assurance that it is safe, so it is not used in Lake George, NY (20). Algaecides are usually designed to break down with time so there is no residual.

Table 11.2
Algaecides certified by National Sanitation Foundation for drinking water applications

Name of algaecide
Sodium chlorite
Calcium hypochlorite
Sodium hypochlorite
Copper sulfate
Algimycin PWF
Sodium percarbonate
HTH® (Chlorine releasing compounds)
Bromochlorodimethylhydantoin
BULAB 6002
Advanced Blue (Copper sulfate)
Chemfloc
Agritec
Earth Tec
Pristine blue (Copper Sulfate)
Lifespan bottled water solution
Lifespan ice solution
PHL 104
Chlorine

They should also be removed by normal water treatment processes. In the case of Lake George, the only treatment is filtration (to remove the algae) and chlorination. Thus there is a stalemate in the use of Sonar© while the milfoil continues to spread.

A rather unique system was studied (21) wherein the algae were coadsorbed with magnetite in the presence of ferric chloride. Greater than 90% chlorophyll removal was achieved using a high-gradient magnetic filter. No information is available as to the development of this system.

A recent device to control algae without the use of chemicals is an ultrasonic transducer called SonicSolutions© (22). An ultrasonic transducer floats just below the water surface and generates a precise frequency that destroys cellular functioning and structure of algae without harming fish, plants, or other aquatic life. Installed after a bloom has been established may significantly reduce the bloom within 2 weeks. Better control is maintained by operating at the start of the spring growth. Present units require between 20 and 45 W of power. Here again, the unit does not reduce the nutrients in the body of water, so they may continue to affect downstream waters and recur in following years in the working pond. Obviously there are no residuals from chemicals from using this system.

5. ALGAE REMOVAL BY DAF

The above-described methods to control algae growths or interfere with their growth do little to alleviate the cause for their productivity: sufficient nutrients to support an undesirable level of their growth. Unless the nutrients are removed from the body of water, these remediation techniques will have to be repeated every year or continuously, depending upon the specific situation. For example, in tropical waters there is less seasonal cycle of growth, and year-round growth can exist so long as the nutrients are available. As soon as the remediation techniques are discontinued, the algae growths will resume. Any actions that kill the algae without their removal will allow the dead algae to sink to the bottom where, if the action has not already ruptured the algae cells and released their organic matter, they will rupture and release its organic matter. This organic matter is then broken down by bacteria, releasing inorganic nutrients. Thus none of these techniques will alleviate the problem by reducing the nutrients available.

Physical removal of the algae may lessen the taste and odor problem and slightly lower the nutrient levels because the inorganic nutrients have been converted to organic algae cell matter. However, additional incoming nutrients may be greater than the amounts removed to the algal cells. Physical removal may include straining through a porous filter or microstrainer. This is effective in removing the algae, but when blooms are present, the filters clog quickly. Similarly, a rapid sand filter as commonly used in water treatment removes most of the algae, but agitation in the sand may rupture the cells, releasing the taste and odor producing oils. Algae from a bloom may also require more frequent backwashing of the sand beds.

Plain sedimentation for algae removal is ineffective, because many of the algae are motile and can swim against their gravity. Therefore, they do not settle out.

DAF has been shown to be an effective means of removal of algae. Dissolved air is introduced as fine bubbles either by means of a diffuser or by release of air from a pressurized tank consisting of either full flow or partial flow as described by Wang et al. (23). The attached air bubbles cause the algae to float to the surface where they can be gently skimmed off without rupturing. The float can be further treated or the oils from the algae can be retrieved for some use. In addition, coagulants are frequently used to augment DAF flotation, and polymers may also increase the removal. Aluminum and iron salts are commonly used as coagulants. Both of these will precipitate phosphates, enabling their removal as described in this book *Flotation Technology* in chapter 13 entitled: Lake Restoration Using DAF (24). Thus DAF with coagulants is effective in both removing the algae and reducing the nutrients available for future algal blooms.

To be most effective, algae should be removed before the treatment plant, particularly before any chlorination. Algae, as with most organics, produce Disinfection Byproducts (DBP) that may be harmful to humans. Further, rupture of the algae cells such as by agitation or rapid sand filtration will release the taste and odor oils, and in some cases toxic substances. Thus removal of algae at the water intake pipe is recommended. In addition, if the algae are removed in the pond using the addition of alum or iron chlorides, there will be some reduction of phosphorus, which may reduce the total algae growth by limiting the essential phosphorus nutrient.

Algae and phosphorus removal have been demonstrated at numerous installations. The City of Pittsfield in western Massachusetts, USA was an early city to install a Krofta Sand-Float system for removal of algae. Since alum was used as a coagulant, it also served to remove phosphate. Results of a pilot study (Table 11.3) (25) using water from Stockbridge

Table 11.3
Results of pilot-scale treatment for removal of algae and phosphorus from Stockbridge Bowl, MA, water using DAF

Time Min	Filter back-wash	Filter effluent quality							
		Turb NTU	Color unit	pH unit	TSS (mg/L)	COD (mg/L)	PO_4–P (mg/L)	Al (mg/L)	Particle Count #/100 mL
0	NA	2.5	20	8.5	104	35	0.19	0.12	4,000
15		0.30							
30	BW	0.30	2	6.7			0		
45		0.28							
60	BW	0.30	2	6.7	0	10	0	0.05	10
75		0.25							
90	BW	0.26	1	6.7			0		
105		0.28							
120	BW	0.29	2	6.7	0	10	0	0.05	0
135		0.26							
150	BW	0.26	2	6.7			0		
165		0.26							
180	BW	0.27	2	6.7	0	18	0	0.05	20
195		0.28							
210	BW	0.26	1	6.7			0		
225		0.25							
240	BW	0.25	1	6.7	0	10	0	0.05	10

Notes: Continuous influent flow rate = 0.36 gpm; effluent flow rate = 0.35 gpm; sludge flow rate = 0.01 gpm; alum dosage = 10 mg/L Al_2O_3; filter backwash time = 37 s/backwash; time including waste discharge = 2.2 min/cycle; volume of filter backwash water = 2.5–2.75 gal/backwash; influent (Stockbridge Bowl Water) conductivity = 131 micromhos/cm; alkalinity 112 mg/L as $CaCO_3$; others, see time at 0 min
*BW*backwash, *NA* not available.
Source: Krofta, Wang Spencer and Weber (25).

Bowl showed significant removal of turbidity (algae) and phosphate within 15 min of the start of the operation. Continuous operation for 4 h showed continuous removal. The size of the treatment system suggested it could be mounted on a barge and floated out into the lake.

Yan (26) described the Jameson Cell that was successfully used in removing algae from oxidation ponds in inland NSW and Victoria, Australia. The system introduces the water to be treated at the top of a vertical tube. An aspirator on this tube draws air into the tube, thus providing the bubbles for flotation. The aerated liquid flows downward through any previously formed float and into the lower portion of the flotation chamber. Clear water is removed from the bottom, and the float is skimmed off the top. Both laboratory cultured and naturally occurring blue-green algae were used in the pilot studies. Jar tests were found to be essential to establishing the optimum flocculent dosage. Results of simultaneous algae and phosphorus removal are shown in Table 11.4.

Table 11.4
Results of pilot-scale removal of algae and phosphorus from Wagga Wagga sewage treatment plant using the Jameson cell

	Feed			Effluent			Removal (%)
	Average	Min	Max	Average	Min	Max	
Turbidity (ntu)	32.9	29	42	7.2	5.5	9	78.1
Suspended solids (mg/L)	71	38	150	5.1	2.3	6.6	92.8
Algal counts (cells/mL)	400,675	158,000	813,400	4821	423	10,921	98.8
Ortho phosphorus (mg/L)	2.58	2.5	2.7	0.07	0.01	0.14	97.3
Total phosphorus (mg/L)	3.58	3.3	4.2	0.21	0.14	0.28	94.2
Total nitrogen (mg/L)	5.66	3.2	11	2	1.9	2.2	64.7

Probably a precursor of the above system was a laboratory scale flotation device developed by Levin, et al. (27). It consisted of a long vertical column with both feed and aeration entering the bottom of the column. The float is removed from a side arm at the top of the column. No flotants are needed, but pH adjustment is important. The length of the column can also be adjusted to obtain optimum flotation. This device was used to evaluate a DAF system for harvesting algae. Their concern was to develop an economical method for harvesting cultivated unicellular algae for food or other purposes. While they did not feel confident to determine accurately the cost of "froth flotation" or induced air flotation (IAF), they did make comparisons with certain key processes. They included an estimated value of dried algae of 80–100 USD/ton (88–110 USD/1,000 kg) reported by Gotaas and Golueke in their 1957 paper (28). They did point out that their froth flotation system produced a froth of 5.9% solids, significantly greater than produced by an industrial centrifuge of that time (1961).

The City of Waco, TX, USA found that algae are the primary source of tastes and odors in Texas waters. Use of a DAF system successfully solved their problem. They found that the odor causing compounds, MIB and geosmin, are released when the algae are killed or damaged. Thus they installed the DAF system at the Lake Brazos River Dam, the source of the drinking water (29).

The South San Joaquin Irrigation District of Manteca, California, USA, used a combination DAF and membrane to successfully remove algae from its water supply reservoir without the need for added polymers (30). The DAF treatment system was Infilco Degremont's AquaDAF© system. The results of pilot studies at two different flow rates are shown in Table 11.5.

A WTP that supplied 15% of the drinking water for the City of Paris, France at the time of the study (1980) successfully removed 95–99% of the algae using preozonation followed by DAF (31).

The recently built DAF system for the City of Tianjin, China treats 500 ML/d (132 MGD) from the Jie Yuan River, making it one of the largest DAF facilities in the world (32). Increasing pollution of the Jie Yuan River caused a severe algae problem in 2000.

Table 11.5
Results of pilot-scale removal of algae from South San Joaquin irrigation district oxidation ponds using AquaDAF

Parameter	Phase 1	Phase 2
Flow rates (gpm)	67–160	118
Rise rates (gpm/ft^2)	7–18	14
Ferric dose (mg/L)	14	10
Effluent pH	6.5	7.0
TOC removal (%)	15–36	28–33
Raw water turbidity (ntu)	2.5–4	2.5–4
Clarified turbidity (ntu)	0.2–0.6	0.4–0.5

The original century old treatment facility was unable to handle the increased strain from the algae. Massive amounts of chemicals were used to control the algae, but these created other problems in the treatment system. The final design of the facility designed by Earth Tech includes DAF and filtration.

Yang et al. showed that zinc can be used as a coagulant for successful removal of algae by DAF (33).

Several studies were conducted at the Department of Chemical Engineering of Imperial College, London, UK, using laboratory cultures of *Scenedesmus quadricauda* to evaluate conditions for removal by DAF. Phoochinda and White (34) reported on the evaluation of two surfactants to increase the aeration rates and reduce bubble size. Cetyltrimethylammonium bromide (CTAB) resulted in 90% algae removal, whereas sodium dodecylsulfate (SDS) gave only 16% removal. Better removals, up to 80%, were achieved for the SDS with optimal pH adjustment. Algae removals decreased at temperatures below 20°C. Further studies by Phoochinda et al. (35) showed that the addition of a commercial cationic polyelectrolyte significantly increased the algal separation, especially for the SDS, and also decreased the amount of water in the float. Phoochinda et al. (36) studied the difference in DAF removal of live and dead (thermally terminated) algae. Variables included two surfactants, aeration rates, pH, and temperature. They also measured zeta potential and surface tension. In most cases, there was better removal of the dead algae than of the live algae.

Liu et al. (37) studied the removal of *Chlorella* sp. also using CTAB and SDS. Similar to the Phoochinda studies, 86% algae removal was achieved using the CTAB, whereas only 20% using the SDS. Addition of 10 mg/L chitosan increased the removal with the SDS to 80%.

Laboratory studies using various river and laboratory cultured algae such as blue-green, green, diatoms, and dinoflagellates showed that at optimum coagulant dosage DAF removed 70–90% of the algae (38). Turbidity removal was over 80% and color removal about 75%.

Kwak et al. (39) found that rainfall contributed significant clay to Korean streams in which algae were being removed. Proper adjustment of zeta potential was essential to removal of the algae.

Studies made by Henderson et al. (40) of the effects of various surfactants on the removal of *Microcystis aeruginosa* by DAF showed that only cationic surfactants improved the removal. The magnitude of the removal differed according to the hydrophobicity of the surfactant. Greater algae removal was achieved as the surfactant was more efficiently absorbed at the bubble interface. At constant dosage, removal efficiency improved with greater recycle, reaching a maximum of 87% removal for *M. aeruginosa.* Studies with other species showed greater removals and at lower surfactant dosages as the algae increased in size.

Zeta potential measurement on the surface of *M. aeruginosa* was used by Taki, et al. (41) to evaluate the possibility of a flotation system combining chemical addition and electrostatic bridge for removal of algae along with ammonia, nitrogen, and phosphate from drinking water. Charge neutralization on the surface of the algae was observed by adhesion of magnesium hydroxide precipitation at elevated pH values. Removal of the algae as measured by chlorophyll-*a* was 84% at pH values greater than 10. Correspondingly, under these conditions phosphate removal was 6.7% and total nitrogen removal was 63.6%.

6. APPLICATION TO DRINKING WATER PURIFICATION

6.1. Background

Located on the Pennsylvania–Maryland border and owned and operated by the City of Cumberland, MD, the Evitts Creek WTP has had continuing problem with algae and soluble manganese that also caused the water to discolor in the distribution system, creating staining problems at the tap.

The Evitts Creek plant provides potable water for Cumberland and surrounding smaller communities in both states and in West Virginia. Both Maryland and Pennsylvania have state regulatory responsibility for the plant. The raw water source is the 2.2 billion gal Lake Koon, which feeds Lake Gordon, a 1.3 billion gal reservoir, where the intake structure is located (42).

When the WTP improvements were being planned in the late 1980s and early 1990s, average flows were below 5 MGD and the City's biggest problem was that its plant had no wastewater treatment for the backwash water used to clean the filters. That put Cumberland in position to be in violation of its discharge permit from the State of Pennsylvania. The fact that Cumberland's Water Plant had no wastewater treatment was not much of a problem as long as Lake Gordon, Cumberland's raw water supply had high quality water. Unfortunately, Lakes Koon and Gordon began to experience excessive algae blooms in 1990 and 1991. The exact cause of the algae is unknown, but years of nutrients washing into the streams that feed the lakes along with the lowering of the lakes for dam repairs and higher than average temperatures in 1990 while dam repairs were underway must have contributed to the problem.

The Cumberland filtration plant was known to have had inadequate pretreatment for particulate removal by settling prior to filtration. The water quality had been so good in Lake Gordon that inadequate settling was not very important to producing high quality water. The large amount of algae, going through the first stage of treatment, had to be captured on the filters, causing them to clog rapidly, and require additional backwashing. At times, as much as 50% of the drinking water produced at the plant had to be used for cleaning the filters. This was a serious problem that caused concern about the plant's ability to produce an adequate quantity of water. The fact that flows were down because of the loss of industrial water users in Cumberland allowed the plant to keep up with demand. The discharge of wastewater became another serious problem. The then new safe drinking water regulations required that Cumberland add alum as a filter aid and because of the algae, powdered activated carbon (PAC) was also added to the water. Both are removed by filtration and then released to the backwash discharge, this was a violation of the permit, which set a limit on aluminum and suspended solids.

6.2. Dissolved Air Flotation to the Rescue

Clearly Cumberland had to add treatment of its backwash water, but if Cumberland wanted to provide more than 4 or 5 MGD of drinking water it had to improve the treatment process prior to filtration, so most of the algae could be removed prior to filtration. The critical need coupled with a somewhat limited budget led the City to select a retrofit of its existing contact basins with a DAF process. In preliminary testing, that process proved to be very exciting and the plant engineers had high hopes that this modification would serve Cumberland for many years. While testing and design were in process the City added a temporary lagoon to capture solids in the wastewater prior to discharge. Unfortunately, that could not be done fast enough to prevent PAC, alum, and chorine from being discharged in the stream of Pennsylvania.

During this same time, Lake Gordon had a bloom of winter algae known as synura. Anyone familiar with this nasty plant knows that it causes a terrible taste and odor problem. It was believed that the planned DAF improvements would be effective in removing this alga; however, it was felt that the plant also needed additional filter renovations. Modernization to meet the new drinking water regulations caused the project to grow, but the original DAF retrofit concept was kept in the project.

6.3. Retrofit vs. New

The City understood that the DAF process installed as retrofit would not be as efficient as a brand new installation; however, it should work well and would make use of the existing circular concrete basins.

During the time the water plant renovations were being designed and constructed, Cumberland began to pick up new water customers. The City signed a contract to supply up to 3.5 MGD to AES, Inc., a cogeneration plant being planned in Allegany County, MD. A federal prison and a state prison also became water customers. For the first time in many years, water demand was increasing in Cumberland.

The retrofitted DAF units were an improvement over the nonfunctioning contact basins, but never performed as expected. The construction contract contained no performance guarantees, and it did not appear that the retrofit process would ever work to the level that was expected from reading published reports form installations in England (42).

6.4. The Plant Situation in the Late 1990s

The 12-MGD plant had a conventional treatment scheme with rapid mix, upflow clarifiers, filters, a clearwell, and a contact tank, along with vacuum drying beds for sludge dewatering. Flow through the plant averaged 9 MGD, with peaks of 13 MGD. The influent turbidity averaged 3 ntu, with influent soluble manganese levels averaging 0.1 mg/L and peaking at 0.172 mg/L.

In the summer of 1998, increased agricultural runoff and a reduction in surrounding forests caused progressively higher algae blooms in southern Pennsylvania's Lake Koon and Lake Gordon, creating severe taste and odor problems and shortened filter run times for the Evitts Creek WTP.

Potassium permanganate ($KMnO_4$) was fed regularly at the intake for taste and odor control and to oxidize the manganese for removal in the clarification stage of the treatment process. Chemical treatment included inorganic flocculent and polymer for clarification, fluoride, caustic for corrosion control, chlorine for disinfection, and ammonia to form chloramines to carry the residual throughout the large distribution system.

6.5. Pilot Study

In the summer of 1999, a state-of-the-art DAF mobile pilot plant was brought in to determine the process effectiveness and to help the engineers develop design criteria. The pilot unit was capable of pumping 36–54 gpm of raw water through the treatment process. Coagulant was fed prior to an in-line mixer, followed by two flocculation tanks, DAF, and finally, filtration, before discharging the effluent to the sewer. The usual plant polyaluminum chloride coagulant doses of 15–20 mg/L were fed during a 6-week pilot study, which achieved an operating loading rate of 7 gpm/ft^2 and an efficient recycle flow of 7.8%.

The pilot DAF indicated that the process could effectively remove algae and manganese, as well as produce a consistent effluent quality for filter loading, thus maximizing the filter run times between backwashes. A belt filter press replaced the sludge drying bed, creating a higher concentration of solids to be hauled away and reducing the sludge volume and cost of further processing.

6.6. Best Alternative for Improvements in 2001

After evaluating the success of the pilot study and visiting several existing DAF installations, Cumberland officials were convinced that a DAF system was the best alternative for the Evitts Creek treatment scheme. A design-build team formed with representatives from the city, the equipment supplier, a local contractor, and the engineering firm, to complete the final design and installation in June 2002.

The project consisted of three 5-MGD DAF systems, each with dual flocculation basins that are 22 ft wide × 32 ft long × 10 ft deep, all the required pumps, a saturation tank, and controls (see Fig. 11.1). The project called for replacing the existing filters with new underdrains, backwash troughs, new media consisting of 12 in. of sand and 18 in. of anthracite per filter, and three dual-filter control consoles to provide automatic control and monitoring of the

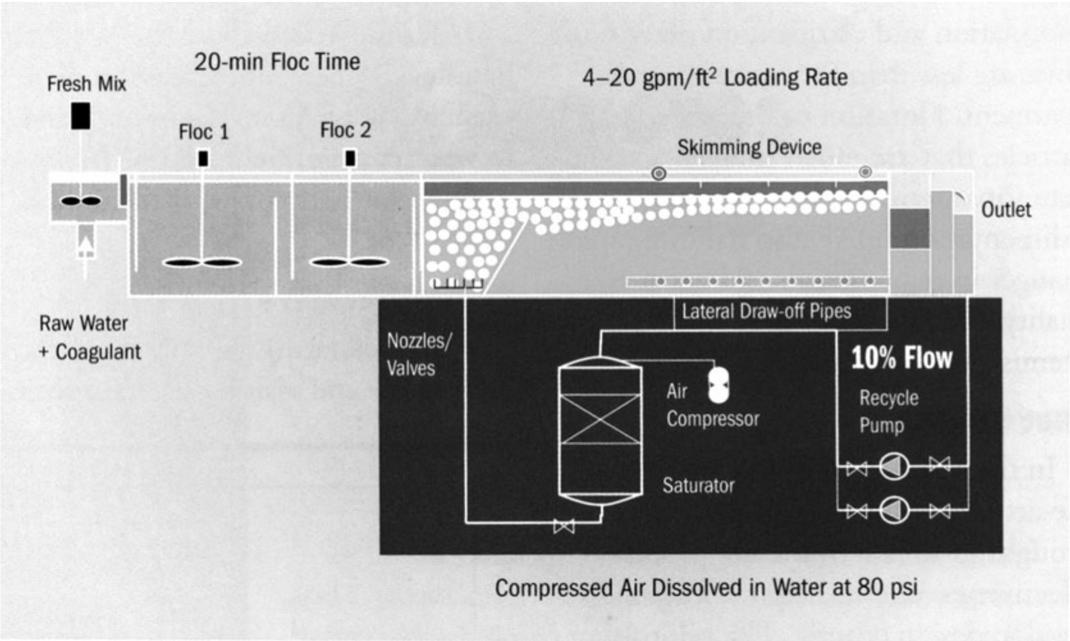

Fig. 11.1. Schematic view of the DAF process.

filter operation and backwash sequence. The new filter system also allowed for the addition of air scour to the backwash procedure (42).

In the DAF process, the recycled water is pressurized and delivered to an air saturation vessel where it is distributed across the entire surface area. Within the vessel is a packing material that breaks down the incoming water into smaller water droplets. The smaller water droplets provide a large surface area to volume ratio. The upper atmosphere of the vessel contains a pressurized volume of air that is readily dissolved into the water particles based on the pressure provided. The pressure must be in the range of 75–90 psig in order to maintain the system efficiency and process operation.

Once the water passes through the plastic packing media, it pools on the bottom of the vessel for a period of time to “off-gas” the excess air entrained. The recycle is then injected back into the basin through a specially engineered recycle injection header equipped with a series of dispersion nozzles. The nozzles in the header provide a dramatic pressure drop from 75 to 90 psig down to the static water pressure in the DAF cell. This sudden pressure drop reverses the physical laws which dissolved the air into the stream and creates a cloud of 30–100 μm bubbles.

The bubbles created by the recycle then attach themselves to the flocculated particles in the water. The bubble attachment decreases the specific gravity of the particles and forces them to rise to the top of the basin where a sludge layer (float) is formed. This sludge layer is supported by the excessive number of bubbles created by the dispersion system. As the sludge layer increases, the sludge is forced to float above the water level allowing it to slightly dewater and thicken. After a few hours of operation, the sludge layer is removed by a mechanical skimmer to the sludge effluent trough.

The entire process is a balance between pressure and flow. The fixed orifice nozzle assembly provided on the dispersion header fixes the pressure in the system. Each nozzle is sized for a specific flow and pressure. The system will therefore only operate at one pressure and one flow. This eliminates any need for adjustment of the recycle flow. Each header may utilize different nozzle diameters. The orifice sizing is typically below 5 mm in diameter. Nozzles do occasionally become blocked, so the operators will need to inspect the nozzles whenever the basin is drained down.

6.7. *Big Benefits and System Success*

The DAF project was completed ahead of schedule in 7 months and under the 4.7 million USD budget. In addition, the smaller footprint of a DAF unit allowed the WTP to handle a 25% increase in plant capacity to 15 MGD, compared to what conventional settling basins or upflow clarifiers could handle in the same space.

The design-build contracting process was very successful for the City on this project. The DAF installation is working great and the project has been expanded to include renovation of five filters and sludge storage in one of the former tanks and sludge drying with a belt filter press.

Aeration has reduced the need to feed $KMnO_4$ at the intake from 9 months per year to only a couple of weeks per year during the summer. The inorganic coagulant chemical feed also has been reduced to between 8 and 15 mg/L, which can be attributed to DAF's efficiency in removing small-diameter particles, as well as to increasing operator experience with the process.

The DAF effluent turbidity is consistently below 0.2 ntu (Table 11.6), and filter runs have increased to the Pennsylvania state-recommended 72-h maximum. Previously, with the upflow clarifier, the filter runs were only 24 h between backwashes. The taste-and-odor

Table 11.6
The performance of the old upflow clarification unit compared to the new DAF process at the Evitts Creek treatment plant

Parameter	Upflow unit	DAF
Raw water turbidity	2.0–5.0 ntu	2.0–5.0 ntu
Raw water manganese	0.1–0.17 mg/L	0.1–0.17 mg/L
Clarified turbidity	1.0 ntu	0.2 ntu
Clarified manganese	0.05 mg/L	0.02 mg/L
Filter run length	24 h	72 h
Filter effluent turbidity	0.1 ntu	0.04 ntu
Filter effluent manganese	0.05 mg/L	0.02 mg/L

Source: Marvin (42).

problems have been resolved, soluble manganese in the finished water is now below 0.02 mg/L, and the process obtains a minimum of 85% removal of the incoming algae. Table 11.6 illustrates the performance of the old upflow clarification unit compared to the new DAF process at the Treatment Plant (42)

The belt press, using cationic polymer as a sludge conditioner, produces sludge cake ranging from 16 to 22% solids. This compares favorably to the drying beds that produced 5% cake solids and required the addition of sawdust filler before the solids were hauled to the landfill. The belt press processes a one-week accumulation of sludge in 10–14 h, compared to the 48–60 h the drying bed required. This has reduced the overall operating costs of the solids handling and disposal operation by greater than 60% (42).

Currently, the DAF system's effluent water quality and subsequent filter run times are exceeding expectations. Also, the maintenance and operations requirements of the DAF units are less than anticipated, allowing plant operators extra time to accomplish more tasks during their shifts.

7. APPLICATION TO WASTEWATER RENOVATION

7.1. Algae Problem in Effluents of Wastewater Treatment Lagoons

Lagoons are one of the most commonly employed secondary waste-treatment systems. US EPA reported that treatment systems in the general category of "stabilization ponds" constituted about one-third of the secondary treatment systems operating in the USA. Stabilization ponds served 7% of people served by secondary treatment plants. These ponds usually serve small communities; 90% were in communities with 10,000 persons or less (43).

Waste-treatment lagoons can be divided into five general classes according to the types of biological transformations taking place in the lagoons. Two of these classes, high-rate aerobic ponds and facultative ponds, are also called oxidation ponds.

1. *High-Rate Aerobic Ponds:* In these ponds, algae production is maximized by allowing maximum light penetration in a shallow pond. These ponds are generally only 12–18 in. in depth.
2. *Facultative Ponds:* Facultative ponds are the most numerous of the pond systems and are deeper than high-rate aerobic ponds, having depths of 3–8 ft. The greater depth allows two zones to develop: an aerobic surface zone and an anaerobic bottom layer.
3. *Anaerobic Ponds*: Organic loads are so high in these ponds that anaerobic conditions prevail throughout.
4. *Maturation or Tertiary Ponds:* The maturation, or tertiary, pond generally is used for polishing effluents from conventional secondary processes, such as trickling filtration or activated sludge.
5. *Aerated Lagoons:* Aerated lagoons derive most of their oxygen for aerobic stabilization by mechanical means, either air diffusion or mechanical aeration. Photosynthetic oxygen generation usually does not play a large role in the process.

The most common algae in oxidation ponds are *Chlorella Sp.* and *Scenedesmus Sp.* (43). These are small (less than 20 μm), nonmotile green algae. Due to their small size and low density they remain in suspension with the slightest current. Thus their removal requires more than plain sedimentation.

With increasingly stringent effluent requirements, waste-treatment lagoons, like any other waste-treatment process, may require modification to meet all objectives. An algal–bacterial symbiosis operates in both aerobic and facultative ponds. Under aerobic conditions, bacteria degrade organic matter according to the following simplified transformation:

$$\mathrm{CH_2O + O_2 \rightarrow CO_2 + H_2O}\ \text{(aerobic bacteria)}.$$

Under anaerobic conditions, the equation is:

$$\mathrm{2CH_2O \rightarrow CH_3COOH \rightarrow CO_2 + CH_4}\ \text{(anaerobic bacteria)}.$$

Algae, in turn, reuse the carbon (as carbon dioxide) to form algal biomass:

$$\mathrm{CO_2 + 2H_2O} + \text{energy} \rightarrow \mathrm{CH_2O + O_2 + H_2O}\ \text{(algae)}.$$

While these equations oversimplify the transformations, they show the recycling of carbon in ponds. Unless the algae are removed, or the carbon is removed through methane fermentation in an anaerobic sludge layer, little organic reduction may occur (44). The fate of algae discharged to receiving waters is an important problem in lagoons. Studies have shown that for two differing aquatic environments the algae did constitute a BOD load on the receiving waters and decreased the dissolved oxygen (DO) levels (45). In these cases, the algae from the pond effluent were in an unfavorable environment for either their maintenance or growth, and they decayed according to the first two equations shown above.

Secondary treatment requirements developed by the US EPA limit treatment-plant effluent BOD and suspended solids (SS) concentrations to less than 30 and 45 mg/L on a monthly and weekly average, respectively. Figure 11.2 presents average effluent qualities for three types of lagoons. None have BOD or SS concentrations of less than 30 mg/L, and the facultative lagoon, the type most commonly used, has an average SS concentration of 70 mg/L. Figure 11.2 clearly indicates that additional treatment will usually be necessary to enable pond systems to meet the secondary treatment requirements.

Lagoons have been providing economical treatment at thousands of locations for decades. Low capital cost, simplicity of operation, and low operation and maintenance costs have favored lagoon treatment. Considering both more stringent water-quality criteria and environmental constraints posed by encroaching suburbanization, however, many lagoons will have to be upgraded in both treatment efficiency and mode of operation.

7.2. *Upgrading Lagoons Through Algae Removal*

The presence of algae in oxidation-pond effluent is undoubtedly the most common problem in upgrading lagoons to meet discharge permit requirements. Algae are manifested principally by high suspended solids and long-term BOD measurements. Figure 11.3 shows effluent BOD from the Stockton, CA, ponds during a summer canning season (details will fellow under Case 2). Physical separation of the algae removed virtually all the long-term BOD. With proper design and operation of the pond treatment system, insertion of an algae-removal step can produce an effluent low in both oxygen demanding substances and nutrients.

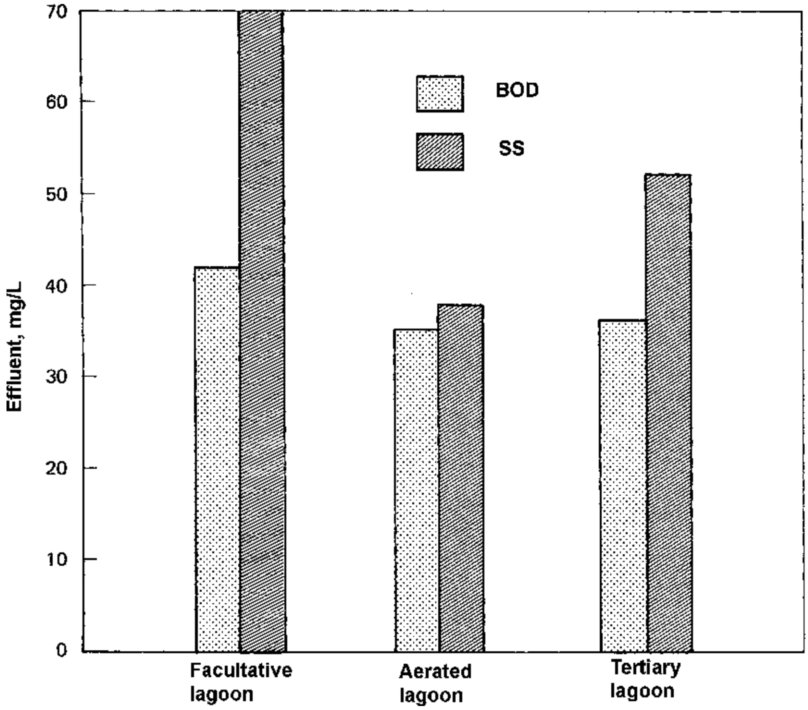

Fig. 11.2. Performance of lagoon systems. Source: US EPA.

Techniques to remove algae from pond effluent have included coagulation–clarification (sedimentation or DAF) processes, filtration, centrifugation, microstraining, chlorination, and land application. In-pond removal systems include aquaculture, series arrangements, intermittent discharge, chlorine addition, or coagulant addition to promote sedimentation within the ponds.

The flotation process involves the formation of fine gas bubbles that are physically attached to the algae solids, causing the solids to float to the tank surface. Chemical coagulation results in the formation of a floc-bubble matrix that allows more efficient separation to take place in the aeration tank.

Two means are available for forming the fine bubbles used in the flotation process: autoflotation and DAF. Autoflotation results from the provision of a region of turbulence near the inlet of the flotation tank (which causes bubbles to be formed from the dissolved gases) and from oxygen supersaturation in the ponds. In DAF, a portion of the influent (or recycled effluent) is pumped to a pressure tank where the liquid is agitated in contact with high pressure air to supersaturate the liquid. The pressurized stream is then mixed with influent, the pressure is released, and fine bubbles are formed. These become attached to the coagulated algae cells. Table 11.7 presents a summary of operating and performance data on coagulation–flotation studies.

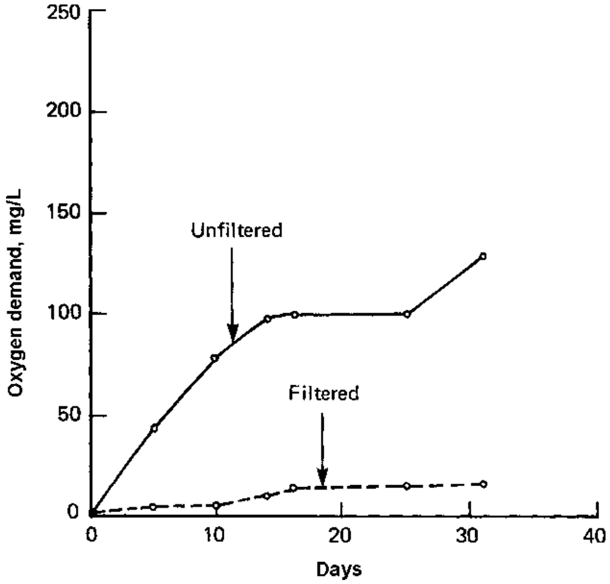

Fig. 11.3. Oxygen demand in filtered and unfiltered oxidation pond effluent.

Information on autoflotation has been developed at Windhoek, South Africa, and Stockton, California (46–48). For autoflotation to be effective, the dissolved oxygen (DO) content of the pond must exceed about 13–15 mg/L. Furthermore, it is advantageous to use carbon dioxide (CO_2), rather than acid, as the pH adjustment chemical with alum. This approach increases the partial pressure of CO_2 and increases the probability of bubble formation, which will improve performance (Table 11.7).

Autoflotation can perform well under the proper circumstances. Its major disadvantage is that it depends on the development of gas supersaturation within the oxidation pond. At Windhoek, the tertiary ponds could be supersaturated around the clock because of their light organic loading and the presence of favorable climatic conditions. At Stockton, the required degree of supersaturation was present only intermittently, and then for less than half the day. The Stockton pond organic loadings (90 lb BOD/acre/d during summer) are closer to normal facultative pond loadings than those at Windhoek. Generally, autoflotation is usable for only a part of the day. The only way to compensate is to increase the number of flotation tanks accordingly and use the process whenever it is operable. The extra cost will favor the selection of DAF in nearly all instances.

The principal advantage of coagulation/DAF over coagulation–flocculation–sedimentation is the smaller tanks required. Flotation can be undertaken in shallow tanks with hydraulic residence times of 7–20 min, rather than 3–4 h required for deep sedimentation tanks. Overflow rates for flotation are higher, about 2.0 gal/min/ft^2 (excluding recycle) compared with 0.8 gal/min/ft^2 or less for conventional sedimentation tanks.

Table 11.7
Summary of typical coagulation–flotation performance

	Coagulant	Dose	Overflow rate (gal/min/ft^2)	Detention time (min)	BOD_5			SS		
					Influent (mg/L)	Effluent (mg/L)	Percent removed	Influent (mg/L)	Effluent (mg/L)	Percent removed
Autoflotation	*Alum*	220 mg/L to	3.5	8	12.1	2.8	77	(a)	(a)	(a)
	CO_2	pH 6.5	1.8	8	12.1	4.4	64	(a)	(a)	(a)
	Alum	200 mg/L to	2.0	22	(a)	(a)	(a)	70	11	85
	CO_2	pH 6.3								
	Alum	200 mg/L to	2.0	22	(a)	(a)	(a)	156	75	44
	acid	pH 6.5								
DAF	*Alum*	225 mg/L to	[b]2.7	[b]17	46	5	89	104	20	81
	acid	pH 6.4								
	Lime	150 mg/L	(a)	[c]12	280–450	0.3	>99	240–360	0–50	>79
	Alum	200 mg/L	[d]4.0	[d]8	93	<3	>97	450	36	92
	Alum	300 mg/L	[e]1.3–2.4	(a)	(a)	(a)	(a)	100	4	96
	Alum	175 mg/L to	[f]2.0	[f]11	(a)	(a)	(a)	150	30	80
	acid	pH 6.0–6.3								
	Alum	125 mg/L	3.3	(a)	65	7.7	88	90	10	89

[a] Not available.
[b] Including 33% pressurized (35–60 psig) recycle.
[c] Including 30% pressurized (50 psig) recycle.
[d] Including 100% pressurized recycle.
[e] Including 25% pressurized (45 psig) recycle.
[f] Including 27% pressurized (55–70 psig) influent.
Source: US EPA (43).

Another advantage of flotation over sedimentation is that a separate flocculation step is not required. In fact, a flocculation step after chemical addition has been found to be detrimental when placed ahead of the introduction of the pressurized flow into the influent (49). The normal purpose of a flocculator is to provide, by gentle agitation, the opportunity for large flocs to form. The downstream introduction of the pressurized stream and the resultant turbulent shearing causes floc breakup to occur, defeating the purpose of the upstream flocculation step. Further, the coagulating power of the chemicals has been lost by this time, and it becomes necessary to add new coagulants to form good float.

7.3. Optimization of Dissolved Air Flotation Operation

Operating parameters used in DAF include surface loading rates, air/solids ratio, pressurization level, coagulant dose, and pH adjustment. Physical design parameters for the flotation tank include the coagulant-addition point, the choice of influent vs. recycle pressurization, and the design details for the flotation tank. The last item is important because most proprietary tank designs were developed for other applications, and some manufacturers have not reevaluated designs for optimal algae removal.

7.3.1. Surface Loading Rates

Studies at Stockton and Sunnyvale, California (46, 47, 50) and at Logan City, UT (51) indicate that maximum surface-loading rates generally vary from 2.0 to 2.7 gal/min/ft^2 (including effluent recycle, where used), depending on tank design. Stone et al. (50) found, in pilot studies at Sunnyvale, that loadings greater than 2.0 gal/min/ft^2 caused deteriorating performance. Stone et al. also concluded that influent pressurization produced better results than recycle pressurization and allowed use of smaller tanks as well. Bare (51) found that 2.35 gal/min/ft^2 was optimum, and Parker et al. (46) used 2.7 gal min/ft^2 at Stockton. Alum was the coagulant used in all cases.

7.3.2. Pressurization and Air/Solids Ratio

The air–solids ratio is defined as the weight of air bubbles added to the process divided by the weight of suspended solids (SS) entering the tank. Values used generally range from 0.05 to 0.10 (46, 51). The air/solids ratio is determined by influent solids concentration, pressure level used, and percentage of influent or recycled effluent pressurized. Pressurization levels used in DAF generally range from 25 to 80 psi. Pressure may be applied to all or a portion of the influent or to a portion of the flotation-tank effluent, which is then recycled to the tank influent. The latter mode has traditionally been used for sludge thickening applications when the influent solids have been flocculated and pressurization of the influent might cause floc breakup.

7.3.3. pH Sensitivity of Metal Ion Flocculation

pH is extremely important in alum and iron coagulation. It is possible to adjust the wastewater pH by adding acid (H_2SO_4, for example), and thus take full advantage of the pH sensitivity of the coagulation reactions. The acid dose required to reach a desired wastewater pH level depends on the coagulant dose and wastewater alkalinity.

Figure 11.4 shows the effect of pH suppression on effluent SS levels during pilot studies at Sunnyvale (50) using alum as the coagulant. It was concluded that not much could be gained by suppressing pH below 6.0, and that the range of 6.0–6.3 could be used for optimum performance. Subsequent neutralization can be accomplished by adding caustic soda.

7.3.4. Alum Dose

Pilot studies at Stockton (46) and Sunnyvale (50) investigated the effect of alum dose on effluent TSS concentrations. The benefit of increasing alum doses is found to be most pronounced up to 150–175 mg/L (Fig. 11.4). Beyond that range, increased alum addition results in only marginal improvement in effluent TSS.

7.3.5. Physical Design

It was noted above that proprietary flotation tank designs do not possess certain features found to be important in pilot and full-scale studies of algae removal. Features incorporated in the flotation tank designs for Sunnyvale and Stockton (see the following cases 1 and 2) are shown in Fig. 11.5 and illustrate important design concepts.

1. A portion of the flotation tank influent rather than recycled effluent is pressurized. Better results were obtained in the Sunnyvale studies using partial influent pressurization and the same overall hydraulic loading rate. Thus, smaller tanks can be used. Usually pressurization of 25% of the flow will provide good results.
2. The location for alum addition is via orifice rings at the point of pressure release where intense turbulence is available for excellent initial mixing of chemicals. This also permits the simultaneous coprecipitation of algae, bubbles, and chemical floc and results in excellent flotation performance. Altering this order of chemical addition invariably leads to performance deterioration.

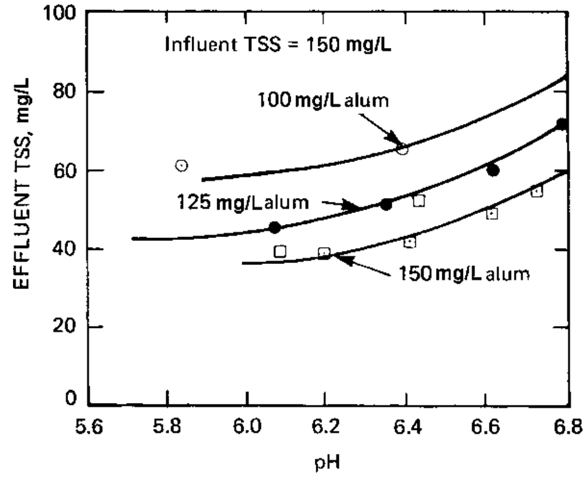

Fig. 11.4. Effect of alum dose and pH on flotation performance.

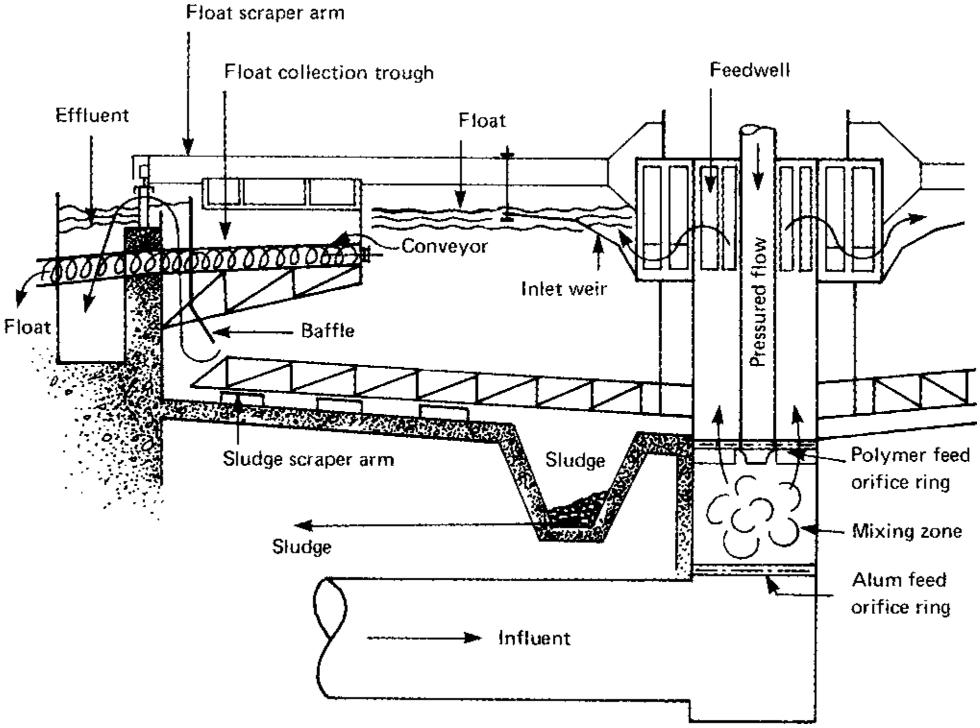

Fig. 11.5. Design of dissolved air flotation (DAF) tank.

3. The point of pressure release is in the feed-well. An orifice, rather than a valve, can be used on the pressurized line because the DAF tanks can operate at constant flow, using the oxidation ponds for flow equalization. In most proprietary designs, a valve is provided on the pressurized line at the outside tank wall, and this permits bubbles to coalesce in the line leading to the feed-well.
4. Care is taken to distribute the wastewater flow evenly into the tank. An inlet weir distributes the flow around the full circumference of the inlet zone and a double ring of gates is used to dissipate turbulence. One full-scale circular tank introduced the influent unevenly, causing nearly all the influent to flow through one-quarter of the tank.
5. Influent is introduced at the surface rather than below the surface as in most proprietary tank designs. The buoyancy of the rising influent introduced below the surface causes density currents that result in short-circuiting of solids into the effluent.
6. Provision of sludge and float scrapers and positive removal of sludge and float will aid performance.
7. Effluent baffles extending down into the tank inhibit short-circuiting of solids.

In addition, the tank surface should be protected from wind currents to prevent movement of the relatively light float across the tank. In rainy climates, the flotation tank should be covered because the float is susceptible to breakdown by rain. Alternatively, the flotation tank could be shut down during rainy periods, which would necessitate larger tanks to accommodate higher flow rates in dry weather.

7.4. Case 1: Sunnyvale Water Pollution Control Plant

Sewage treatment facilities for the city of Sunnyvale, CA, were first placed in operation in September 1956. They included a primary treatment plant with an average capacity of 7.5 MGD of domestic sewage and nonseasonal industrial wastes, and a holding pond with a capacity of 200 MG for seasonal wastes from two large canneries that processed fruit and vegetables. Effluents from the primary plant and the holding pond were discharged directly to Guadalupe Slough, a tributary to South San Francisco Bay (43).

By 1960, the domestic sewage flow had reached the capacity of the primary plant, and conditions in Guadalupe Slough, because more effluents were discharged from the treatment facilities, had deteriorated so much that at times they failed to comply with the minimum requirements established by the Regional Water Quality Control Board. In a study authorized by the city, Brown and Caldwell recommended doubling the capacity of the primary plant and adding an oxidation pond. The facilities were not completed until 1967.

Growth of both domestic and industrial wastes since 1960, and the more stringent requirements of the Regional Water Quality Control Board, required further improvement of the plant. This improvement was completed by the canning season of 1971; three more primary settling basins were added (for a total of nine) and aerators were added to the two ponds.

Originally, the large pond (325 acres) had been used as an oxidation pond for secondary treatment of the domestic wastewaters. The wastewater from the canneries was put directly in the smaller holding pond (100 acres). This pond was designed to operate anaerobically, with odors controlled by calcium or sodium nitrate additives. A considerable quantity of nitrate was required, resulting in high operating costs during the food processing season. Attempted close control of nitrate addition resulted in insufficient amounts being added at times, so that hydrogen sulfide odors did occur.

Design provided for the effluent from the holding pond to be discharged to the oxidation pond at a rate that would maintain aerobic conditions in the oxidation pond. Seasonal wastes increased in quantity and strength beyond expectations, and the holding pond did not have sufficient capacity to contain the waste for the entire canning season. From 1960 onward, it was necessary to discharge some of the holding-pond contents to Guadalupe Slough during the canning season.

Although the 1971 modifications improved the effluent quality of the Sunnyvale plant, the Federal secondary treatment requirement of 30 mg/L BOD and SS could not be met. Moreover, the California Regional Water Quality Control Board, San Francisco Bay Region, has determined from studies carried out over the past decade that, to protect the water quality of South San Francisco Bay, existing facilities must produce an effluent of a quality higher than that defined as secondary treatment quality. Effluent quality requirements for Sunnyvale include those presented in Table 11.8. The requirement for nondissociated ammonia in the receiving water necessitates conversion to nitrate or removal of ammonia in the wastewater because of limited dilution available.

To select the treatment scheme that most fully satisfies the discharge requirements as well as engineering and economic constraints, an analysis was made of all potentially feasible

Table 11.8
Summary of Sunnyvale wastewater discharge requirements

Constituent	Criteria		
	30-day average	Maximum daily	Instantaneous maximum
Effluent limitations			
BOD$_5$			
mg/L	10	20	
lb/d	3,650	7,300	
SS			
mg/L	10	20	
lb/d	3,650	7,300	
Oil and grease			
mg/L	5	10	
lb/d	1,825	3,650	
Chlorine residual (as Cl_2) (mg/L)	0		
Settleable matter (mL/L/h)	0.1		0.2
Turbidity (Jtu)			10
Receiving water limitations			
Nondissociated ammonium hydroxide (as N) (mg/l)			0.025
DO (mg/L)	5.0 minimum; annual median of 80% saturation.		
pH	Effluent pH must not vary from ambient pH by more than 0.2 pH units.		

Source: US EPA (43).

alternatives. Two basic alternatives and five subalternatives were identified. The two basic alternatives were (43, 50):

1. To retain and upgrade existing treatment facilities and processes and provide additional treatment facilities to meet the requirements.
2. To retain existing primary facilities, abandon oxidation ponds (use them as holding basins), provide secondary and tertiary treatment processes, and retain existing sludge-handling and disposal facilities.

The five subalternatives and their cost estimates, expressed in terms of 2007 USD (52), are given in Table 11.9. The group 1 alternatives, involving retention of the ponds and use of tertiary facilities, were less expensive than the group 2 alternatives.

The five feasible plans were evaluated as to their compliance with water-quality goals, flexibility and reliability, cost-effectiveness, reclamation potential, and environmental and social impacts. The apparent best alternative project was subalternative (c), which consisted of adding to the existing facilities DAF and filtration for algae removal, a fixed-growth reactor (trickling filter) for ammonia removal, breakpoint chlorination for supplemental ammonia removal, and dechlorination for toxicity control.

Table 11.9
Costs of Sunnyvale treatment alternatives expressed in 2006 USD

Item	Group 1. Existing primary treatment and oxidation ponds, plus flotation, filtration, and dechlorination			Group 2. Existing primary treatment, plus activated sludge, filtration, and dechlorination	
	Plus breakpoint chlorination, alternative 1(a)	Plus ammonia adsorption on clinoptilolite, alternative 1(b)	Plus nitrification in fixed-growth reactor, alternative 1(c)	Plus nitrification in fixed-growth reactor, alternative 2(a)	Plus breakpoint chlorination, alternative 2(b)
Capital costs[a]	16,170,000	25,700,000	23,970,000	46,870,000	39,060,000
Annual operation and maintenance costs					
Existing treatment	1,600,000	1,600,000	1,600,000	1,280,000	1,280,000
New treatment	3,080,000	1,970,000	1,320,000	1,260,000	3,400,000
Total	4,680,000	3,570,000	2,920,000	2,540,000	4,280,000
Annual cost of capital investment[b]	1,520,000	2,420,000	2,260,000	4,420,000	3,690,000
Total annual cost of treatment	6,200,000	5,990,000	5,180,000	6,960,000	7,970,000

[a] Updated to 2007 USD using US ACE Civil Works Construction Cost Index (52).
[b] Interest at 7% over a 20-year planning period.
Source: US EPA (43).

To optimize the design and operational efficiency of the tertiary treatment unit processes, extensive pilot-plant studies were carried out. The results of these pilot studies formed the basis for plant design. Design data for the DAF facilities are presented in Table 11.10. The tertiary facilities were studied under two operational modes. Under Mode A, pond effluent undergoes DAF ahead of nitrification. Mode B reverses the order of these two unit processes.

The principal advantage of Mode B operation is reduced chemical costs. Nitrification produces acidity, and therefore can be used to offset, or perhaps eliminate, the required acid addition for pH adjustment to optimize DAF when nitrification is first in the flow diagram. Furthermore, under Mode B, less caustic would need to be added to raise the pH before discharge. Receiving water requirements indicate that breakpoint chlorination will be required for interim shallow water discharge requirements, which will apply until an outfall into the bay is constructed. For deepwater discharge through the outfall, an effluent ammonia-nitrogen requirement of 4.0 mg/L is anticipated; for the interim shallow-water discharge, 0.5 mg/L.

Table 11.10
Design data, Sunnyvale tertiary treatment facilities

Parameter	Value
Basic design loadings	
Design population (thousands)	124
Design flow (MGD)	
Canning season	24
Noncanning season	16
Maximum TSS (mg/L)	175
Pond effluent pH, maximum	8
Peak ammonia loading as N (mg/L)	
High-temperature operation[a]	25
Low-temperature operation[b]	22
Dissolved-air flotation system	
Number of units	3
Diameter (ft)	60
Sidewater depth (ft)	7
Area per unit (ft^2)	2,820
Flow rate per unit (MGD)	8
Surfacing loading rate (gal/min/ft^2)	2.0
Solids loading rate (lb/ft^2/d)	4.2
Influent pressurization flow (percent of total)	25
Air-to-solids ratio (lb air per lb influent solids)	0.10
Pressurization level (psig)	80
Influent pH	6.0–6.3
Assumed TSS removal (%)	75
Assumed TSS removal per unit (lb/d)	9,000
Float-removal system	
Assumed float-production rate (gal/min/unit)	114
Assumed solids concentration (%)	2
Assumed float density (lb/ft^3)	31
Float ejectors	
Number	6
Capacity each (gal/min)	75
Design TDH (ft)	8
Float mixers	
Number	2
Horsepower each	15
Float pumps	
Number	3
Capacity each (gal/min)	125
Discharge pressure (psi)	60
Chemical treatment	
Chlorine feed capacity (1,000 lb/d)	24

(*Continued*)

Table 11.10
(Continued)

Parameter	Value
Sulfur dioxide feed capacity (1,000 lb/d)	6
Sulfuric acid	
Feed capacity (1,000 lb/d)	20
Maximum dosage rate (mg/L)	98
Alum, $Al_2(SO_4)_3 \cdot 14.3\ H_2O$	
Feed capacity (lb/day)	30
Maximum dosage rate (mg/L)	150
Polyelectrolyte	
Feed capacity (lb/d)	1,000
Maximum dosage rate (mg/L)	5
Caustic soda	
Feed capacity (1,000 lb/d)	34
Maximum dosage rate (mg/L)	
With breakpoint chlorination	170
Without breakpoint chlorination	80

[a] High temperature range = 13–19°C.
[b] Low temperature range = 7–11°C.
Source: US EPA (43).

The construction of the tertiary facilities was completed in 2 years at 27,820,000 USD (expressed in 2007 Dollars) (52).

7.5. *Case 2: Stockton Regional Wastewater Control Facility*

The City of Stockton, CA, located near the confluence of the San Joaquin and Sacramento rivers, has an unusual water quality problem that requires a unique solution. Historically, the cities of the San Joaquin Valley, particularly Stockton, have been agriculturally oriented. This orientation has resulted in industries that produce unusually heavy loading at the city's Regional Wastewater Control Facility during peak canning periods.

Stockton serves six canners and six other major wet industries, including food processors, in its municipal system. In the summer, these industries caused a peak monthly flow of 40 MGD to the city's treatment plant. BOD loading during that period reached a high of 5,300,000 lb/month. Flows during the remainder of the year are 16 MGD, with 1,300,000 lb/month of BOD. Unfortunately, the peak occurs at the period of critical water quality and low flow in the San Joaquin River, a tidal estuary of San Francisco Bay, into which the plant's effluent is discharged (41).

The Central Valley Regional Water Quality Control Board has established discharge requirements that include the following provisions:

1. The waste discharge shall “not cause the dissolved oxygen of the receiving waters to fall below 5.0 mg/L at any time.”
2. The waste discharge shall “not cause the total nitrogen of the receiving waters to exceed 3.0 mg/L at any time.”

A study of the DO dynamics of the Stockton ship channel, which provides a deepwater link to San Francisco Bay, established the assimilative capacity of the channel for oxygen demanding materials discharged from the Stockton Regional Wastewater Control Facility. The long-term oxygen demand was found to be associated principally with algae; therefore, physical removal of the algae from the pond effluent eliminated most of the long-term BOD. A projection of long-term BOD loads compared with the assimilative capacity of the river indicated that algae removal would permit the DO criterion to be met. At the same time, algal removal would also accomplish nitrogen removal, because most of the nitrogen is in organic form and associated with algae.

To meet the new requirements, Stockton has enlarged and modified its treatment plant. A phased design and construction program was prepared that will enable the city to be in compliance with waste discharge requirements. This program involved improvements to the entire plant, including the following elements (Fig. 11.6):

1. Preliminary treatment
2. Primary sedimentation
3. Secondary treatment (trickling filtration)
4. Tertiary treatment (oxidation ponds and algal removal facilities)
5. Disinfection
6. Solids treatment

Pilot studies were conducted at the Stockton plant during the summer to develop design criteria for the tertiary algae removal facilities (46, 47). At that time pilot-scale and plant-scale tests had established both coagulation–flocculation–sedimentation and coagulation–-flotation as workable, dependable procedures for removal of algae from pond effluents. An economic analysis indicated that flotation would be superior to sedimentation because of higher allowable overflow rates and shorter residence times. It was anticipated that greater sludge concentration could be obtained at approximately the same chemical dose, and smaller tanks could be used.

Because of these anticipated advantages of flotation over sedimentation, it was decided to operate a pilot flotation process to determine if flotation was applicable to Stockton’s wastes and to develop design concepts and criteria for a full-scale unit. Of particular interest was the comparison of pressurized DAF with autoflotation. Results of the studies indicated that while autoflotation exhibited a potential for algae removal, its overall performance was erratic because there was DO supersaturation in the ponds for only a part of the day.

Studies of DAF showed the process to be feasible, and it was chosen subsequently for use in the full-scale facility. In addition to DAF, effluent polishing was provided by dual-media filtration. Breakpoint chlorination was also included for ammonia removal if it is required at those times when the DAF unit is not being operated. Effluent disinfection and dechlorination facilities were also provided. Construction of the tertiary facilities was completed in 2 years

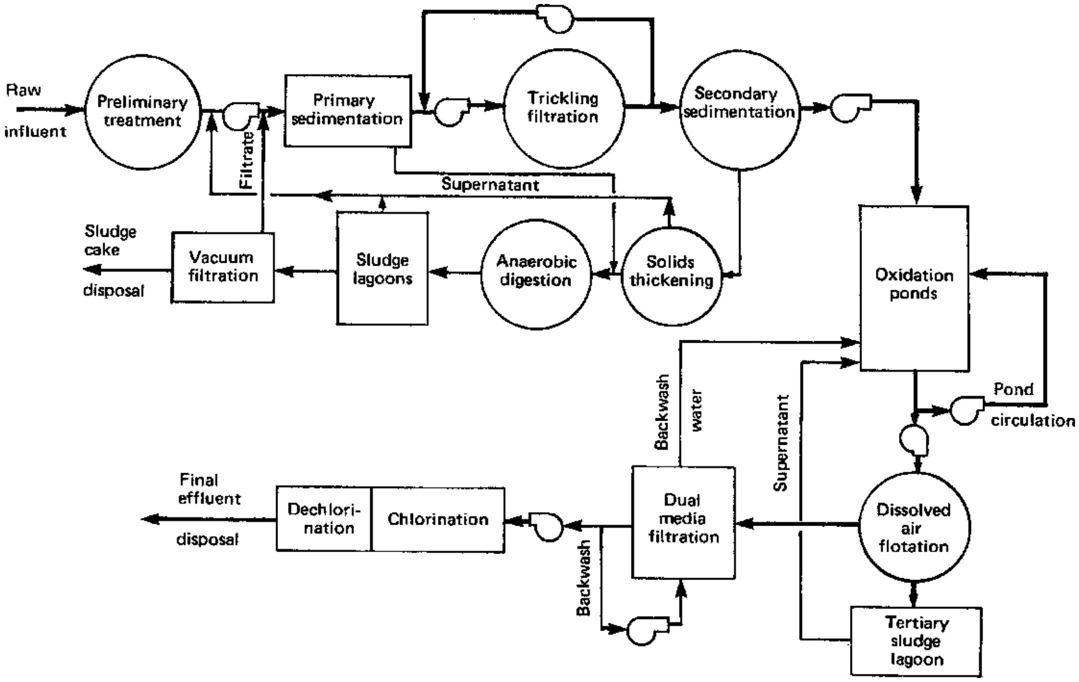

Fig. 11.6. Stockton regional wastewater control facility flow diagram.

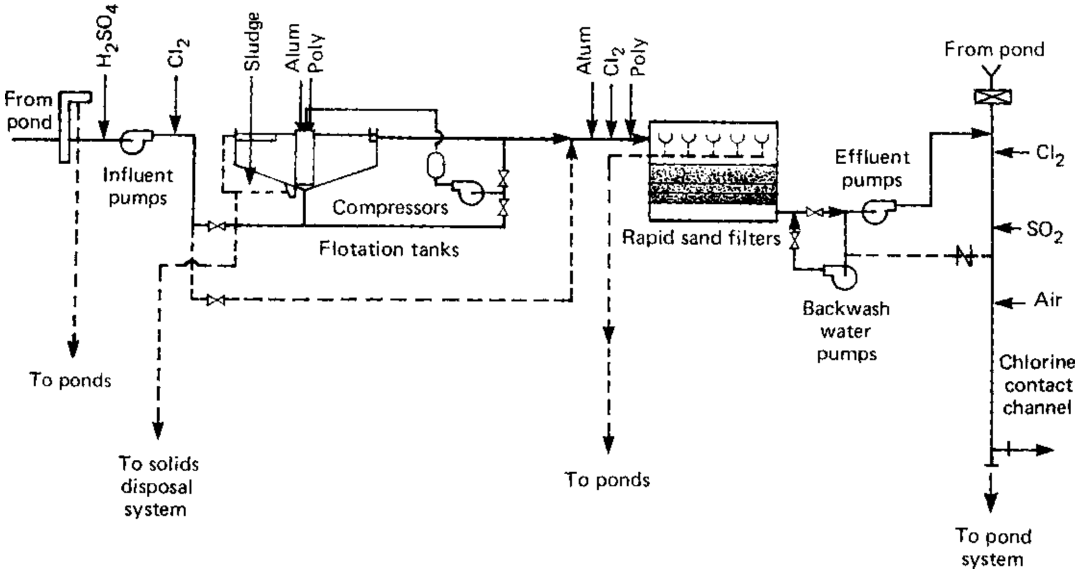

Fig. 11.7. Stockton tertiary facilities flow diagram.

Table 11.11
Design data, Stockton tertiary facilities

Parameter	Value
Tertiary ponds, existing	
Number	4(4)
Area, net water surface (acre)	630
Volume (MG)	1,320
Loading during noncanning season	
BOD total (1,000 lb/d)	3.2
BOD (lb/acre/d)	5
Loading during canning season	
BOD total (1,000 lb/d)	57
BOD (lb/acre/d)	90
Detention (d)	
During noncanning season	57
During canning season	23
Circulation pumping units	
Number	4
Capacity each (MGD)	60
Circulation ratio (at peak)	4.4
Dissolved-air-flotation loadings:	
Flow (MGD)	55
SS concentration (mg/L)	170
pH, peak	9.5
Ammonia, peak concentration (mg/L)	6.5
Chemical treatment	
Alum, peak rates	
Dry dose (mg/L) (17% $Al_2\ O_3$)	250
Volume (1,000 gal/d) (8.3% $Al_2\ O_3$)	21.2
Sulfuric acid, peak rate (93% $H_2\ SO_4$)	
Dose (meq/L)	3.0
Volume (gal/d)	4,700
Polyelectrolyte, peak rate (0.5% solution)	
Flotation tanks:	
Number	4
Diameter each (ft)	85
Side water depth (ft)	7
Solids loading rate (lb/ft^2/d)	5.1
Assumed float concentration (%)	3
Assumed float weight (lb/ft^3)	41
Peak float-discharge rate (gal/min)	600
Surface loading rate, including pressurized flow (gal/min/ft^2)	2.4
Pressurized flow (gal/min)	4,500
Pressure, maximum (psig)	80
Air flow, maximum (scfm)	80
Air/solids ratio, minimum (lb air per lb solids)	0.179

Source: US EPA (43).

from 1976 to 1978 at a cost of 44,200,000 USD (expressed in 2007 Dollars) (52). A flow diagram for the tertiary-treatment facilities is shown in Fig. 11.7 and the design data are given in Table 11.11 (43, 53).

REFERENCES

1. Methuen & Co (2006) Seaweeds and their uses, Methuen & Co. Ltd., London
2. Mumford TF, Miura A (1988) Porphyra as food: cultivation and economics. In: Lembi CA, Waaland JR (eds) Algae and human affairs. Cambridge University Press, Cambridge, pp 87–117
3. Guiry MD, Blunden G (1991) Seaweed resources in Europe: uses and potential. Wiley, New York
4. Spirulina Home Page (2009) Growing premium spirulina, Spirulina Web Site: http://www.spirulina.com
5. Watersmart Environmental (2010) Watersmart environmental joins EPA's CHP [combined heat and power] network, Earthtoys Alternative Energy Library. http://www.watersmart.com
6. DOE (Undated) Biodiesel production from algae. Department of Energy, Aquatic Species Program, National Renewable Energy Laboratory, Golden, CO
7. Wired News (2006) Algae: power plant of the future? Wired News
8. Pamphlet (2006) Energy from algae, access to energy. Cave Junction, OR
9. UNFAO (2006) Livestock's Long Shadow . United Nations Food and Agricultural Organization, Rome, Italy, Nov
10. Hillen LW, Pollard G, Wake LV, White N (1981) Hydrocracking of the oils of *Botryococcus braunii* to transport fuels. Biotechnol Bioeng 24:193–205
11. Aphanizomenon Flos-Aquae (Undated) Blue green algae. Energy for Life Wellness Center, Kelowna, BC
12. US Fisheries Department (2006) Nutritional value of micro-algae. United States Fisheries Department, Washington DC
13. PSU (Undated) Sensory properties of strawberry- and vanilla-flavored ice cream supplemented with an algae oil emulsion. Department of Food Science, Pennsylvania State University, University Park, PA
14. University of Bathe (Undated) Transgenic plants produce Omega-3 and Omega-6 fatty acids. School of Biology and Biochemistry, University of Bathe, Bath
15. Barrow T (2006) Toxic algae-precautions & facts. UNL E-News, University of Nebraska, Lincoln, NE, 1 May 2006
16. Knappe DRU (2004) Algae detection and removal strategies for drinking water treatment. AWWA Research Foundation, Number 90971, Denver, CO
17. Aulenbach DB (2000) Silicon limitation linked to estuarine pollution problems, Presented at 32nd mid-Atlantic industrial and hazardous waste conference, Rensselaer Polytechnic Institute, Troy, New York, June 2000
18. Rabalais NN, Turner RE, Dortch Q, Wiseman WJ Jr, Sen Gupta BK (1996) Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf estuaries. Estuaries 19:386–407
19. AWWA (2006) Coppers risk assessments; notice of availability and risk reduction options. Response to EPA-HQ-OPP-2005-0558, American Water Works Association, Denver, CO, March 27 2006
20. Lake George Association (2006) Ongoing debate between NYS, DEC and the Lake George Assn. about use of Sonar for milfoil control in a drinking water supply. Lake George, New York

21. Yadidia R, Abeliovich A, Belfort G (1977) Algae removal by high gradient magnetic filtration, Environ Sci Tech 11(9):913–916
22. SonicSolutions© LLC (2006) Product pamphlet. West Hatfield, MA
23. Wang LK, Fahey EM, Wu Z (2005) Dissolved air flotation. In: Wang LK, Hung TY, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ, pp 431–500
24. Aulenbach DB, Shammas NK, Wang LK, Derrick R, Kittler I (2010) Lake restoration using dissolved air flotation. In: Wang LK, Shammas NK, Selke WA, Aulenbach DB (eds) Flotation technology. Humana Press, Totowa, NJ
25. Krofta M, Wang LK, Spencer RL, Weber J (1983) Algae separation by dissolved air flotation. In: Proceedings of water quality and public health conference, Worcester Polytechnic Institute, Worcester, MA, p 19
26. Yan YD (2004) Simultaneous algae and phosphorus removal from wastewaters using induced air flotation. Centre for Multiphase Processes, Department of Chemical Engineering, The University of Newcastle, Callaghan, NSW 2308. www.newcastle.edu.au
27. Levin GV, Clendenning JR, Gibor A, Bogar FD (1961) Harvesting of algae by froth flotation. Resources Research, Inc., Washington, DC
28. Gotaas HB, Golueke CG (1957) Recovery of algae from waste stabilization ponds. Algal Research Project, Sanitary Engineering Research Laboratory, 7, I.E.R. Series 44, University of California
29. News Item (2006) Lake Brazos dam. City of Waco, TX
30. Infilco Degremont (2005) AquaDAF© high rate dissolved air flotation system. South San Joaquin Irrigation District, Manteca, CA
31. Montiel A, Welte B, Dolejs P, Edzwald JK, O'Melia CR, Oskam G (1998) Successful removal of algae. Pergamon Press, Oxford
32. News Item (2006) Upgraded Tianjin facility treats water pollution cost-effectively. Earth Tech 21:15–18
33. Yang Z (1991) Flotation of algae in the presence of zinc. Engineering Foundation Conference, Santa Barbara, CA
34. Phoochinda W, White DA (2003) Removal of algae using froth flotation. Environ Technol 24(1):87–96
35. Phoochinda W, White DA, Briscoe BJ (2004) An algal removal using a combination of flocculation and flotation processes. Environ Technol 25(12):1385–1395
36. Phoochinda W, White DA, Briscoe BJ (2005) Comparison between the removal of live and dead algae using froth flotation. J Water Supply: Res Technol 54(2):115–125
37. Liu JC, Chen YM, Yi-Hsu Ju (1999) Separation of algal cells from water by column flotation. Separation Sci Technol 34(11):2259–2272
38. Mulaku WO (2004) Dissolved air flotation process for algae removal. J Civil Eng Res Pract 1(2):27–38
39. Kwak DH, Kim SJ, Jung HJ, Won CH, Kwon SB, Ahn HW, Lee JW (2006) Removal of clay and blue-green algae particles through zeta potential and particle size distribution in the dissolved air flotation process. Water Supply 6(1):95–103
40. Henderson RK, Parsons SA, Jefferson B (2008) Surfactants as bubble surface modifiers in the flotation of algae: dissolved air flotation that utilizes a chemically modified bubble surface. Environ Sci Technol 42(13):4883–4888
41. Taki K, Seki T, Mononobe S, Kato K (2008) Zeta potential measurement on the surface of blue-green algae particles for micro-bubble process. Water Sci Technol WST 57(1):19–25

42. Marvin R (2005) DAF removes algae, eases manganese issues, City Project No. 12–99-WFP, The City of Cumberland, Evitt's Creek water treatment plant dissolved air flotation expansion. Opflow 31(2):10–12
43. US EPA (1973) Upgrading lagoons, EPA-625/4–73–00lb US Environmental Protection Agency, Washington, DC
44. Oswald WJ, Meron A, Zabat MD (1970) Designing waste ponds to meet water quality criteria, In: 2nd international symposium for waste treatment lagoons, Missouri Basin Engineering Health Council and Federal Water Quality Administration, Kansas City, MO, pp 186–194, 23–25 June 1970
45. Bain RC, McCarty PL, Robertson JA, Pierce WH (1970) Effects of an oxidation pond effluent on receiving water in San Joaquin River Estuary, In: 2nd international symposium for waste treatment lagoons, Missouri Basin Engineering Health Council and Federal Water Quality Administration, Kansas City, MO, pp 168–180, 23–25 June 1970
46. Parker DS, Tyler JB, Dosh TJ (1973) Algae removal improves pond effluent. Water Wastes Eng 10(1):26–29
47. Brown and Caldwell (1972) Report on pilot flotation studies at the main water quality control plant, prepared for the city of Stockton, CA, February
48. Middlebrooks EJ (1974) Techniques for algae removal from wastewater stabilization ponds. J Water Pollut Cont Fed 46(12):2676–2695
49. Ramani AR (1974) Factors influencing separation of algal cells from pond effluents by chemical flocculation and dissolved air flotation. Doctoral Dissertation, University of California at Berkeley
50. Stone RW, Parker DS, Cotteral JA (1975) Upgrading lagoon effluent to meet best practicable treatment. J Water Pollut Cont Fed 46(8) August
51. Bare WFR, Jones NB, Middlebrooks EJ (1975) Algae removal using dissolved air flotation. J Water Pollut Cont Fed 47(1):153–169
52. US ACE (2008) Civil works construction cost index system manual, 110–2–1304, US Army Corps of Engineers, Washington, DC, pp 44, PDF file is available on the Internet at http://www.nww.usace.army.mil/cost
53. Wang LK, Wang MHS, Suozzo T, Dixon RA, Wright TL, Sarraino S (2009) Chemical and biochemical technologies for environmental infrastructure sustainability. National Engineers Week Conference, Albany Marriott, Albany, New York, 5–6 February 2009

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Completely Closed Water Systems in Paper Mills

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CONTENTS

Abstract Wastepaper is recycled as pulp for the production of papers or boards. The pulp containing secondary fibers needs to be purified in a deinking installation. A total closed water system is developed for water reclamation in deinking installations. The pulp with inks is first processed with an induced (dispersed) air flotation (IAF) cell and then a washing unit (stock washer). The wastewater is clarified by a dissolved air flotation (DAF) cell for water reclamation. A fractionator (spray filter) is additionally used for the recovery of long fibers from washing water. The sludge is thickened on a thickener (twin wire press). The water reclamation and deinking systems are highly efficient and cost-effective. Special emphasis is placed on the design of individual treatment units and the entire deinking/reclamation system. Several case histories are introduced.

Key Words Dispersed air flotation • dissolved air flotation • closed water system • deinking • recycling • fiber recovery • induced air flotation • paper mill • zero effluent discharge • water reclamation.

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1. INTRODUCTION

The United States is the Saudi Arabia of paper. Nationally, paper makes up nearly 44% of America's discarded consumer waste (1). It is the largest single waste contributor to our ever-filling landfills. Hence, it is imperative upon the nation to recover and recycle more and more of that paper waste. US EPA has recommended content ranges for each component, whenever appropriate, to encourage increased purchasing of paper and paper products containing postconsumer and recovered fiber throughout the US (2).

Wastepaper is recycled as pulp for the production of paper or board. The pulp containing secondary fibers needs to be purified in a deinking installation. Deinking is the process of removing printed inks and finishing materials from the reusable fiber of paper (3). A total closed water system has now been developed for water reclamation in deinking installations. The wastewater with inks is first processed with an induced (dispersed) air flotation (IAF) cell and then a washing unit (stock washer). The wastewater is clarified by a dissolved air flotation cell (DAF) for water reclamation. A fractionator (spray filter) is additionally used for the recovery of long fibers from washing water. The sludge is thickened on a thickener (twin wire press). The water reclamation and deinking systems are highly efficient and cost-effective (4).

Mill water systems can be divided into three main loops (5):

1. Boiler water – used to generate steam mainly for heating drying cylinders. Much is recovered as condensate.
2. Process water – used as a medium for transporting raw materials, i.e., fibers, chemicals etc., as well a seal water showers and washdowns. Statistics show that between 200 and 500 m^3 of water is required to produce 1 ton of paper. However, much of this is reused, and the freshwater requirement averages 35 m^3/ton. Many mills are currently running at much less (see Table 12.1).
3. Cooling waters – this is generally of low quality and is returned to the source with no contamination except perhaps an increase in temperature.

The majority of mills recycle water within separate loops within the paper making process for a number of reasons (5):

1. Recycling retains energy in the form of heat within the mill. Higher temperature has been shown to improve drainage rates, thus allowing machine speed and production to be improved by as much as 4%.
2. Process water loops are chemically rich.

Table 12.1
Water consumption at UK mills – 1990–1991

Paper grade	No. of mills	m^3/tonne
Board	7	13.3±15
Newsprint	3	20.5±5
Tissue	5	49.4±29
Speciality	3	198±175
Printings and writings	5	49.4±15
Printings and writings/speciality	4	55±25

3. Recycling retains raw materials, i.e., fibers and fillers within the system.
4. Retention of materials reduces the effluent pollution load.

High raw material prices combined with high energy costs and progressively stricter effluent pollution control are making wastepaper deinking always more economically feasible and closing of the deinking water systems imperative. To keep the system sweet and prevent build up of dissolved and suspended contaminants, a proportion of the process water is sent for effluent treatment and replaced with freshwater.

Until recently, wastepaper was used without deinking exclusively for the low-grade boards or for multiple layer board as internal gray filler. More and more wastepaper recovered from municipal solid waste collection systems will be used for this purpose. Printed wastepaper will increase in value as a raw material for better grades of paper as the deinking technology is sufficiently developed.

Presently, the bulk of wastepaper deinking is concentrated on newsprint waste deinking. The following two are the reasons: (a) the daily collection of newsprint wastepaper provides for a steady raw material flow and (b) the requirements for degree of brightness for newsprint are not too high.

Another use for wastepaper deinking, although considerably smaller, is for the production of tissue papers. The general trend toward always higher brightness and softness of tissue paper places considerable demand for a continuous improvement of the deinking technology. With considerable distance follows the deinking of printed books with a very high basic value of the original paper fiber.

For decades, two principal deinking systems have been competing:

1. Flotation deinking, extracting ink by foam generated by an IAF cell (mineral filler and paper fines are mainly recovered; therefore, the yield is high, but the physical strength of the deinked stock is poor); and
2. Washing deinking where ink, mineral filler, and fiber fines are washed out at high dilution, and a papermaking fiber of good quality is obtained with the sacrifice of lower yield.

Each system has a preferential use for certain wastepaper grades and final uses of the deinked stock. Many of the newer deinking mills employ a combination of both washing and flotation.

Additional information about the various sources of available fiber may be found on the Kimberly–Clark Website (6) and a simple but informative narration on how paper is recycled on TAPPI Website (7).

2. PROBLEMS ASSOCIATED WITH EFFLUENT RECYCLING

There are four main disadvantages associated with closing of a paper mill (5):

1. Residual Chemical Oxygen Demand (COD) and conductivity resulting in scaling, corrosion, and deposits.
2. A gradual build up of colloidal and suspended solids concentrations causing felt/wire blinding and shower blockages.
3. Increased biological activity and slime buildup.

4. Production problems associated with a build up of anionic trash in the system, i.e., inhibition of rosin sizes and cationic polymers. Research has shown that a build up in both concentration and type of inorganic salts can affect sheet strength.

Even well-managed effluent treatment systems that reduce biological oxygen demand (BOD) significantly may still result in the buildup of a relatively high residual level of COD. This chapter looks at some of the options available to further treat effluent, making it more suitable for recycling, from a practical perspective.

3. REDUCING EFFLUENT AND ZERO EFFLUENT DISCHARGE

The first stage in considering any scheme to recycle effluent is to consider how existing water loops may be improved upon to reduce the volume of effluent to be treated. The majority of existing paper mills could reduce their effluent volumes by the strategic location of filtration and clarification equipment to treat, for example, excess machine whitewater, wire press filtrate, and spray water. One such installation has resulted in a pay back time of less than 6 months due to the use of clarified water to replace fresh water used in high pressure sprays in a tissue mill. With a treatment capacity of 200 m^3/h, the DAF cell also substantially reduced effluent volumes.

Some mills have apparently achieved zero liquid effluent discharge. This was achieved where the build up of dissolved solids in the mill process water loops was of no concern. A survey carried out in 1996 suggested that up to twenty mills worldwide were operating with zero liquid effluent discharge (5). In some cases, the volume of water added to replace that lost through evaporation is sufficient to prevent problems occurring.

One of the earliest examples is the Union Industrial Papelera mill in Spain. In the early eighties, this mill produced 210 tonne/day of fluting and test liner using a 100% wastepaper furnish. Because of increasing concern over both effluent discharge costs and the shortage of adequate supplies of fresh water in this arid region, the mill was forced to stop production for several days at a time. Closing the system and recycling the effluent led to the usual problems as well as those of fiber degradation as a result of the creation of anaerobic conditions. This anaerobic activity also produced gas that caused material to float on the surface of the existing sedimentation clarifier.

Based on pilot studies, the mill installed three DAF cells in a cascade system. The total mill effluent was collected at the lowest point in the mill and pumped to the largest DAF cell first. This *allowed* clarified water quality to be varied according to the application for which it was to be used. The largest cell was run without chemical treatment, and the relatively poor quality clarified water was used as pulper dilution water. A proportion of this water was diverted to a second DAF cell where cleaner clarified water was produced. This was used primarily for wire showers and vacuum pumps. Finally, the smallest clarifier treats a smaller flow with optimized chemical treatment to give a clarified water of a quality suitable for use in higher pressure showers. All the floated fiber was returned to the machine chest. The only water lost was through evaporation and rejects from screens. This was replaced with freshwater. A large tank was used to collect and store excess clarified water from the third cell until

Table 12.2
Performance of DAF cell in treating tertiary effluent

Parameter	Influent	Effluent
TSS (mg/L)	20–200	10–30
COD (mg/L)	100–400	30–150
Color (color unit)	10–100	5–55
Turbidity (NTU)	10–70	5–15

required. To ensure adequate control pH, conductivity, temperature, and turbidity meters were installed at strategic points.

Several UK mills were actively looking at recycling their tertiary effluent. In each case, the mills had an existing three stage effluent treatment system consisting of a primary DAF or sedimentation process, biological treatment, and secondary settling. In each case, the initial bench scale study suggested that DAF was the most suitable technique to reduce suspended solids further by acting as a "catch all" when sludge bulking would result in carry over from the sedimentation unit. The results shown in Table 12.2 are the averages achieved at four different mills (5).

Further work has been carried out in Korea using a coagulation basin followed by a combined flotation–filtration unit to treat tertiary effluent from a newsprint mill with a view to recycling the effluent. Average results indicated that by the addition of 70 mg/L alum and 0.3 mg/L polyelectrolyte, the total suspended solids were reduced from 50 mg/L to less than 5 mg/L (5).

4. DESIGN OF INDIVIDUAL DEINKING AND WATER RECLAMATION FACILITIES

In order to obtain maximum deinking efficiency, the industry has adopted the two-system configuration that operates first with foaming followed by washing to obtain a closed water system, which clarifies the washwater with a dissolved air flotation (DAF) clarifier. A fractionator (spray filter) is additionally used for recovery of longer fibers from washing water. The sludge is thickened on a twin wire press (4).

The combination of both principles of foaming and washing was made possible without raising the installation cost of the deinking plant by using advanced methods for foaming and washing.

4.1. Induced (Dispersed) Air Flotation Deinking Cell

An IAF cell uses the principle that foam extraction is proportional to the surface area and not the volume of the foaming machine. Therefore, a large surface with a low depth (80 cm) is used, and large amounts of foam are easily produced in an inexpensive foaming tank (4).

The IAF cell is specifically designed for deinking of wastepaper. It removes ink from wastepaper by producing foam artificially. This foam collects ink, and when the foam is extracted, the ink is separated from the wastepaper (8, 9). Deinking by flotation has three major efficient processes (10–14):

1. The detachment of the ink particles from the fibers.
2. The effective adhesion of the ink particles onto air bubble surfaces.
3. The removal of froth and ink particles from flotation cells.

Surfactants (15–19) can affect the three processes either positively or negatively. Their role is (20–24):

1. As a dispersant to separate the ink particles from the fiber surface and prevent the redeposition of separated particles on fibers.
2. As a collector to agglomerate small particles to large ones and change the particle surface from hydrophilic to hydrophobic.
3. As a frother to generate a foam layer at the top of the flotation cell for ink removal.

The interfacial activity of frothing agents, surfactants, and polymers in deinking flotation systems has been studied through flotation, atomic force microscopy, zeta potential, contact angle, surface tension, and froth stability measurements (20, 25). These fundamental studies were developed to understand microscopic and molecular effects occurring in flotation of ink particles that may lead to improved designs in deinking flotation processes. In the early years of this decade (2001–2003), an innovative flotation deinking process "Surfactant Spray" was developed by the US Department of Energy (DOE) for improved capital effectiveness and minimized manufacturing impact for the recycling of mixed office waste and newsprint paper.

Normally, the deinking chemicals including dispersant, collector, and frothing agent are added directly to the pulp suspension prior to air flotation. According to the US DOE, this can cause adverse effects, including (25) the following:

1. Contamination of fibers by froth.
2. Decrease in surface hydrophobicity and removal efficiency of the ink particles.
3. Poorer control of froth stability.

Based on laboratory work and scaled-up pilot investigations, the following results have been obtained for the newly developed Surfactant Spray as compared to the normal method of the addition of all the deinking chemicals to the pulp suspension prior to flotation (25):

1. Increased deinking efficiency.
2. Higher recycle fiber quality with brightness gain of 10%.
3. Improved paper machine runability.
4. Reduced air flotation fiber losses by up to 50% compared with conventional technology.
5. Higher capital effectiveness.
6. Minimized environmental impact through reduced water and deinking chemical use.

The construction of an IAF cell should be designed for low power and space requirements as well as for simple operation and low equipment cost. The froth (foam) removes ink preferentially and the subsequent washing can be made in stages that can result in a brighter pulp.

The IAF cell is composed of a shallow tank with a feed well where the wastepaper slurry enters with approximately 4% dry weight consistency. The paper slurry is diluted at the entrance with recycled clarified water to approximately 0.75–1.50% consistency and some foaming chemicals are added at this location. A recycle pump feeds an ejector that discharges tangentially into the tank creating a circular movement of stock in the tank. With a blower, air is added into the ejector at low pressure. This air is dispersed in the ejector and enters into the tank, producing a large amount of foam that travels to the top of the circulating stock. The foam is continuously collected by the foam collector and extracted into the foam suction tank, where a suction blower holds a light vacuum. The foam collapses in the foam suction tank and is extracted continuously by a water lock and discharged into the sludge collection tank. The cleaned stock is discharged in the center of the tank at the bottom opening and overflows the telescopic adjustable weir. From there, it is pumped to the cleaners and to the stock washer (26, 27). Figures 12.1 and 12.2 show an IAF deinking cell and an installation with a 40 ft-diameter IAF cell, respectively.

Production of Air Dry Deinked Stock (assuming 25% shrinkage)

TYPE CAPACITIES

diameter size in ft	metric ton/day	short ton/day (2000lbs/ton)
15	14.5	16.10
18	21.0	23.15
22	31.4	34.62
27	47.0	51.82
30	58.3	64.26
40	104.0	114.66
50	162.0	178.61
60	233.0	256.88
70	318.0	350.60

Water depth in the tank is 1.0 meter (39 inches)

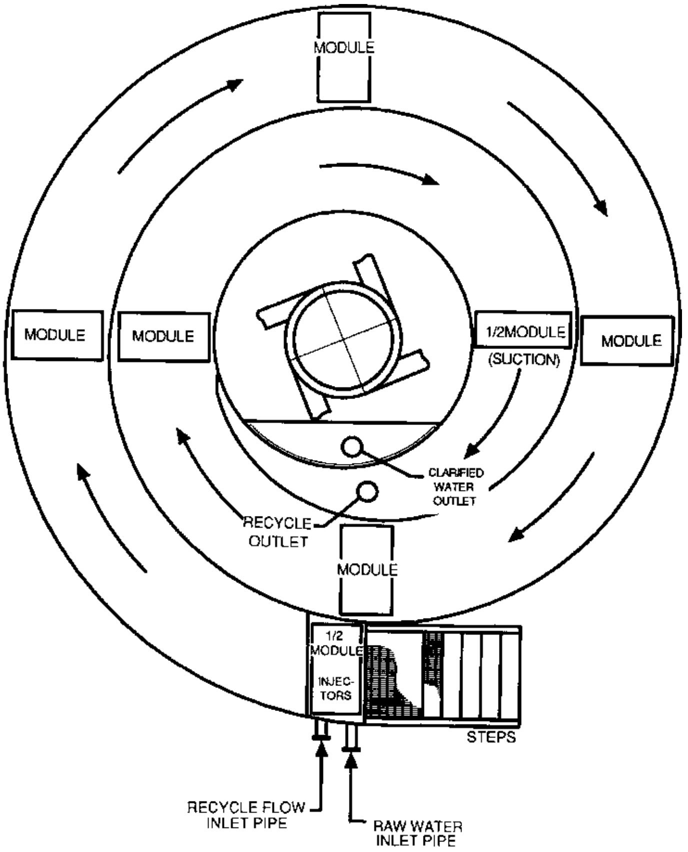

Fig. 12.1. IAF deinking cell.

Fig. 12.2. An installation with a 40 ft-diameter IAF cell.

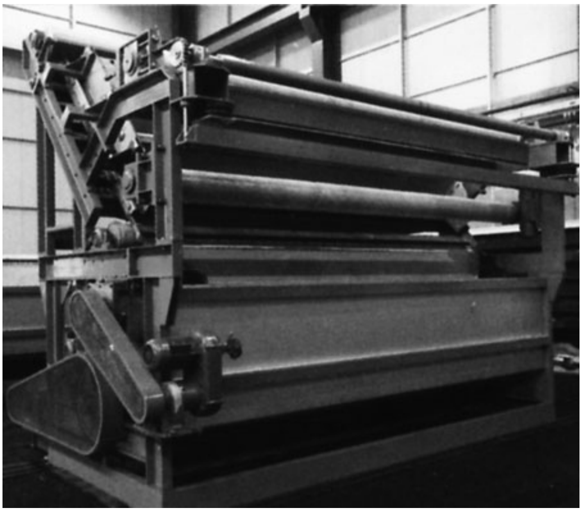

Fig. 12.3. Stock washer.

4.2. Stock Washer

The stock washer (Fig. 12.3) is an improvement of the traditional sidehill washer by having an uphill slowly moving screen and multiple dams for the downflowing stock. A triple washing occurs in the same space as a conventional single sidehill screen. The screen is continuously cleaned, and additional mineral filler from the stock is extracted by a press.

With triple washing using recycled clarified water, a high degree of brightness is obtainable, particularly after the removal of ink in the IAF cell. With multiple washing, it is further possible to control the washing out of the filler and fines from the furnish (4).

The Stock Washer has an inclined upward moving screen that returns back to the bottom thickening drum. The stock to be washed and thickened enters on top with a consistency of 0.6–1.0%. Flowing down over the upper part of the screen, the stock is partially dewatered and accumulates at the first cross barrier. The partially thickened stock is diluted with recycled clarified water and overflows to the second barrier. Partially thickened stock is diluted again, overflows the barrier and flows and rolls down the screen and the stationary inclined board until it enters into the nip between the returning screen and the drum. The stock is pressed by the screen on the drum. The screen wraps around the drum and thickens the stock to high consistency. A press squeezes the deinked stock to higher consistency 9–14%. A transversely mounted rotating screw extracts the thickened stock and discharges it at the side.

The effluent from the three thickening phases is separately collected and discharged into the spray filter for further fiber recovery. The effluent from the spray filter is finally discharged into the DAF cell for further treatment and reclamation.

4.3. *Dissolved Air Flotation Clarifier*

Progressively for large installations, a separate DAF clarifier (28–31) is installed on the alkaline pulper–extractor loop for recovery of chemicals and heat (32, 33).

The DAF clarifier is shown in Fig. 12.4. The inlet, outlet, and sludge removal mechanisms are contained in the central rotating section. This section and the spiral scoop rotate around the tank at a speed synchronized with the flow.

Wastewater, first passing through the air dissolving tube, is released through a rotary joint in the center of the tank. It then passes into the distribution duct that moves forward with the same velocity as the incoming water, thus creating "Zero Velocity." The flotation processes take place in this quiescent state. The spiral scoop takes up the floated sludge, pouring it into the stationary center section where it is discharged by gravity for disposal. Clarified water is removed by extraction pipes that are attached to the moving center section.

Fig. 12.4. 55 ft-diameter DAF clarifier.

The clarified water that normally contains less than 30 mg/L of suspended solids is recycled in the process for reuse.

Wiper blades attached to the moving distribution duct scrape the bottom and the sides of the tank and discharge settled sludge into the built-in sump for periodic purging. The variable speed gear motor drives the rotating elements and scoop. Electrical current for the gear motor feeds from a rotary contact mounted on the central shaft. The use of DAF cell for wastewater treatment and water reclamation has been fully demonstrated (34–43).

4.4. *Spray Filter*

The spray filter, shown in Fig. 12.5, is specifically designed for the fractionation of effluents containing from 20 to 5,000 mg/L of suspended solids. A fine mesh cloth with openings from 74 to 500 μm is used as the filter media, either to separate long fibers from clay and filler or as safety filter for showers using clarified water. The spray filter meets the need for a high throughput unit that can handle wide variations in solids content. It is equipped with a cleaning shower, which greatly reduces the need to remove the cloth for cleaning. All parts in contact with the water are built of 304 stainless steel. The access door has Plexiglas window. All bearing surfaces are made of corrosion-proof plastic materials.

4.5. *Twin Wire Press*

The twin wire press is designed for sludge thickening and dewatering. In operation, the sludge is fed by a pump from the sludge tank to the vertical flocculation compartment on top of the press that is composed of adjustable undulated plates. Flocculating chemicals are fed in along with the sludge. The flocculated sludge leaves the flocculation compartment at the bottom and enters the vertical mixing compartment where multiple horizontal plates gently agitate the sludge (4).

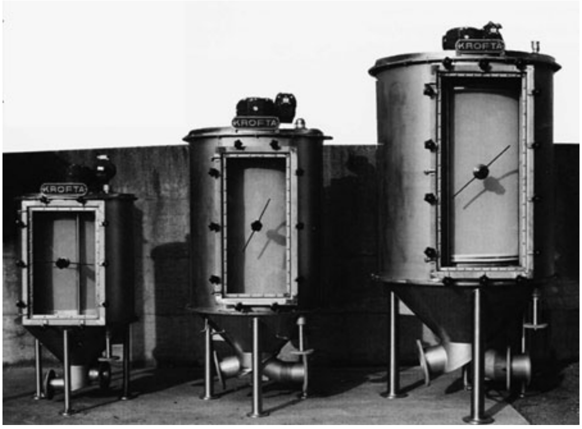

Fig. 12.5. Spray filters.

The wire coming out of the mixing department is inclined upwards where the first dewatering takes place. Then the wire with the sludge turns downward into the wedge-shaped compartment – composed of two wires – which squeeze the sludge in-between. The two wires with the sandwiched sludge run wrapped for half a turn around the large perforated drum that is located at the lower side of the press. After leaving the drum, the double wires move up around several rollers for further dewatering. The rollers have progressively smaller diameter for better dewatering.

At the top of the press, the two wires separate. Each has its own rubber-covered pickup roll with a scraper for sludge discharge into a hopper. The two wires have individual wire guiding devices (pneumatically operated) and manually operated tension rolls. Each wire has a shower with shower water collecting pan.

The twin wire press has a capacity of approximately 10 tonne/day dry weight of sludge per 1.0 m wire width. This refers to primary papermill sludge with adequate chemical conditioner. The inlet consistency is 1.5–4.0% and the discharge has a concentration of 30–35%.

5. CASE HISTORY 1: A COMPLETE SEMI-INDUSTRIAL DEINKING PLANT IN ITALY

Wastepaper deinking is a complex procedure that cannot be demonstrated and tested sufficiently on a laboratory scale (44). An interesting deinking plant with a capacity of 5 tonne/day, which is separate from other papermill operations, is located at the Papermill Cartiera di Vidardo, approximately 35 km (22 miles) from the city of Milan, Italy. The purpose of the plant is to allow those industries that are interested in installing deinking plants the possibility to bring their wastepaper and determine the operating procedure and design factors for the construction of deinking installations to handle the specific needs of their wastepaper.

In such semi-industrial testing, one can determine

1. The quality of the deinked stock (brightness, cleanliness, mineral fillers, and fines content).
2. The yield and fiber and filler loss under different operations.
3. The consumption of chemicals, power, water, and heat.
4. The specific capacity of equipment (pumping time, chemicals acting time, foaming production, cleaning requirements, stock-washing parameters, recycled water clarification requirements, etc.).
5. The overall economic aspect of the deinking process.
6. The specific design of the deinking plant and the individual machine's capacity.

The semi-industrial deinking plant is also useful for chemical companies manufacturing special chemicals for deinking application in order to evaluate the performance of the new chemicals. Also, sufficient amounts of deinked stock can be produced in order to make paper sheets on small paper machines and to evaluate the combination of the stock with other raw materials.

The deinking plant was designed with a maximum versatility, allowing different combinations of the deinking process. It can be operated with foaming and washing together or individually. Each phase can be operated by repeated recycling if desired. Figure 12.6 shows the flow diagram of the semi-industrial deinking plant.

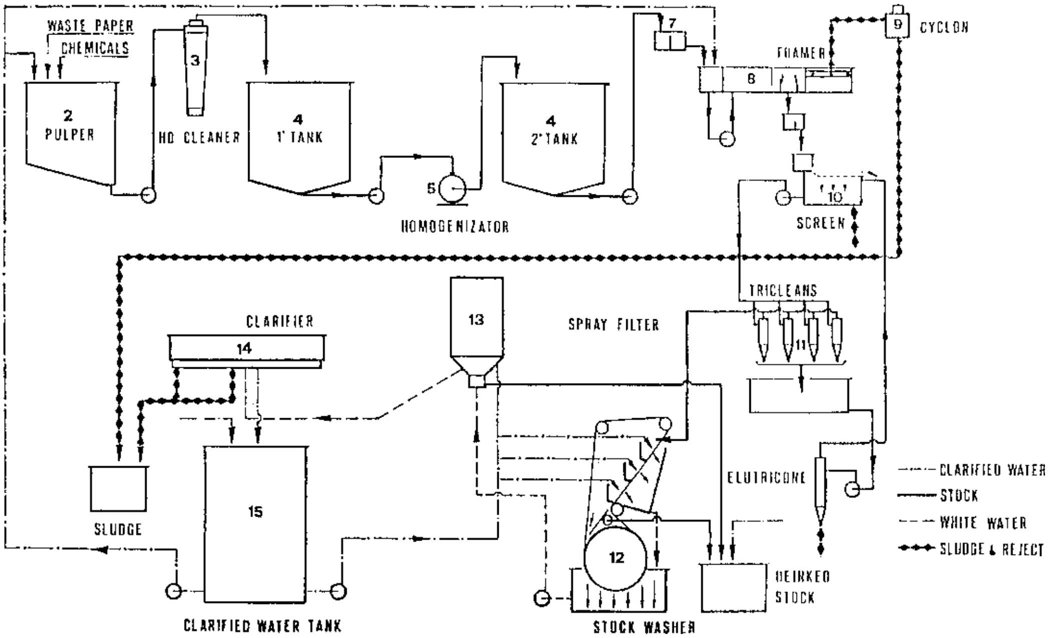

Fig. 12.6. Flow diagram of a semi-industrial deinking plant using total closed water system.

5.1. Loading Platform and Pulper

The loading platform [1] is for accumulation of the wastepaper bales and scales for measuring and feeding into the Pulper [2] with a volume of 3 m^3. The agitator has a horizontal shaft and a perforated plate with 8 mm holes passing the pulped stock. The consistency is kept, depending on the requirements, between 3 and 6% bone dry, having 90–180 kg of dry wastepaper for each batch. The pulping time is 20–30 min and including loading and discharging time, each batch takes approximately 45 min, resulting in a maximum load of 5,760 kg/24 h operation.

Addition of chemicals usually is made following a recipe in the pulper to obtain the required chemical reactions:

1. Saponification of oils combining the printing inks.
2. Dispersion of ink particles into a colloidal state.
3. Surfactant action to collect ink on foam.
4. Detergents for separation of colored pigments in the residuals of saponification.
5. Oxidation for bleaching purpose.
6. Steam for keeping the stock temperature at approximately 60°C.

5.2. High-Density Cleaner

The high-density cleaner [3] is for the separation of coarse impurities. Such impurities should be extracted ahead of defibering action because of their easier elimination.

5.3. *Stock Chest*

The stock Chest [4] is provided a slow running vertical agitator. Required storage of the stock is approximately 1 h. If required, additional steam heating can be provided in the chests.

5.4. *Deflaker*

The deflaker [5] is used after the stock chests or between the two stock chests in order to finely separate all fiber bundles.

5.5. *Headbox*

The headbox [7] over the IAF cell is used for metering the stock to the continuous operation of the successive plant. Clarified water is recycled to dilute the stock to the consistency required for further processing. The consistency can be set between 0.8 and 1.8%. Additional foaming agents may be added continuously at the point of dilution.

5.6. *IAF Cell*

The IAF cell [8] operates with dispersed air producing large amounts of foam. Foam extraction is proportional to the foaming surface and not the depth of the foaming tank. Therefore, the IAF cell operates with only 80 cm water depth.

A very fine dispersion of air is essential, so IAF cells are equipped with multiple injectors in order to create a fine bubble foam. A recycling pump feeds the second inner circle of injector nozzles with the stock already foamed in the outer circle. The stock in this way is subject to multiple foaming with large amounts of foam.

The nozzles–injectors provide a circular movement in the foaming tank that can be adjusted by regulating the flow, air addition, and direction of nozzles. The stock cleaned by foaming is discharged in the center at the bottom of the IAF cell. If desired, the stock can be passed several times through the cell.

The construction of the cell using stainless steel is simple and has a low fabrication cost. The foaming tank is open and allows easy supervision, observation, and cleaning. The foam is sucked by a radial foam aspirator and passed into a cyclone where it is additionally collapsed by spray water. Air aspirated by the foam aspirator keeps the room clean. Because of the large surface and small volume, the retention time in the cell is short, just 5–10 min.

5.7. *Cyclone*

The cyclone [9] is for foam extraction and collapsing. It discharges the collapsed foam directly into the sludge compartment [15].

5.8. *Vibrating Screen*

The vibrating screen [10] is used to additionally screen the foamed stock and eliminate coarser impurities. Alternately, the vibrating screen can also be used ahead of the IAF cell, screening stock before foaming. The rejects are fed into the sludge tank.

5.9. *Triclean and Elutricone*

The Triclean and Elutricone [11] are used for additional elimination of light and heavy contaminants. The cleanliness of the deinked stock is as important as the brightness and removal of the ink and therefore the deinking plant is provided with various stock cleaning devices.

5.10. *Stock Washer*

The stock washer [12] is similar to the one illustrated in Fig. 12.2. Foaming extracts only ink particles over 20 μm in size and the rest of the colloidal ink particles are extracted by washing.

The stock washer operates in a similar fashion to a multiple sidehill screen, combined with a thickener and press. No filtering fiber mat is formed and the stock rolls over the upwards moving plastic wire screen in three sections. At each section, the stock can be diluted and the washing process improved.

This stock washer allows wide variations in the washing process. If colloidal ink is to be removed while the fines and filler are to stay, then washing is done in one section only and the stock washer operates as a thickener without forming a mat. If mineral filler and fines should be removed by deinking of magazine-coated wastepaper with high ash content, then the multiple washing takes effect and the original stock with 20% or more ash can be reduced to some 3–5% ash content. This is particularly important for some tissue manufacturing operation. The outgoing consistency of the deinked stock from the stock washer is 9–14% bone dry. The water used for washing is therefore the water coming with the diluted stock into the stock washer.

5.11. *Spray Filler*

The spray filter [13] is a fractionator to recover longer fibers from the stock washer effluent. Such effluent is sprayed through a fine mesh screen (100–200 μm). Longer fibers are recovered and added to the deinked stock. At larger installations, the fiber recovery is of considerable economical importance.

The stock washer does not form a mat and therefore washes out the colloidal ink particles, mineral filler, and fines far better than any drum thickener or disc filter that always forms a mat and retains colloidal ink in the stock. However, at the same time, some longer fibers escape, which are recovered with the spray filter that is a rather inexpensive machine.

5.12. *DAF Clarifier*

The DAF clarifier is similar to the one shown in Fig. 12.3. It is widely used in many of the largest deinking plants over the world and is an essential part of such deinking installations. In this clarifier, all stock washer effluent is clarified and recycled. There is no excess water leaving this deinking plant. Makeup water is required as the wastepaper enters with only 10% moisture and the deinked stock is discharged with 90% moisture. Some water is also lost with the sludge. It can be calculated that if sludge is thickened to 20% and the sludge water is recycled, the total water consumption for the deinking plant is under 10 L/kg. Because of the high recycling of the clarified water, the heat costs are kept low and the operating temperature can be kept high.

5.13. Clarified Water Tank

The clarified water tank [15] is an essential part of this deinking plant. The valuable high temperature clarified water must be stored to be available to feed the pulper in the batch process. Also, change in the washing and foaming dilution require promptly available clarified warm water.

6. CASE HISTORY 2: IMPROVEMENT OF AN EXISTING DEINKING SYSTEM IN EUROPE

6.1. Existing Deinking System

A European paper mill's deinking system produced 61.3 dry tonne/day of deinked stock using the well-known dispersed or induced air flotation (IAF) process. The mill's water containing ink and fibers was treated by the IAF process using heat and chemicals for the removal of ink along with some long fibers that were lost in the foam.

The original situation of the deinking system is shown in Table 12.3 and Fig. 12.7. The incoming wastepaper stock in the pulper [1] that amounted to 68.6 tonne/day had an ash content of 22.5% and a dryness content of 90%. The wet paper stock was sent to a chest where the recycle water (3,827 L/min on wet basis and 19.7 tonne/day on dry basis) from a surge tank [6] and necessary amounts of makeup water diluted the pulp to about 1.25% dryness. The diluted 1.25% pulp was sent to a dispersed air flotation deinking cell for treatment at 4,437 L/min. The flotation deinking operation is preferentially done at 0.75–1.50% consistency.

Table 12.3
Original deinking system (Case History 2)

Process points	Flow lines	Total stock fiber and ash (tonne/day)	Dryness (% of wet wt)	Ash (% of dry wt)	Ash (tonne/day)	Fiber (tonne/day)	Flow (L/min)
1	Waste paper	68.6	90	22.45	15.4	53.2	–
2	Deinking inlet	88.3	1.25	27.07	23.9	64.4	4,437
3	Discharged foam	7.3	2.66	39.73	2.9	4.4	173
4	Thickener inlet	81.0	1.20	25.67	20.8	60.2	4,264
5	Deinked stock	61.3	8.84	20.06	12.3	49.0	437
6	Thickener effluent	19.7	0.32	43.15	8.5	11.2	3,827
10	Accepted stock	61.3	8.84	20.06	12.3	49.0	437

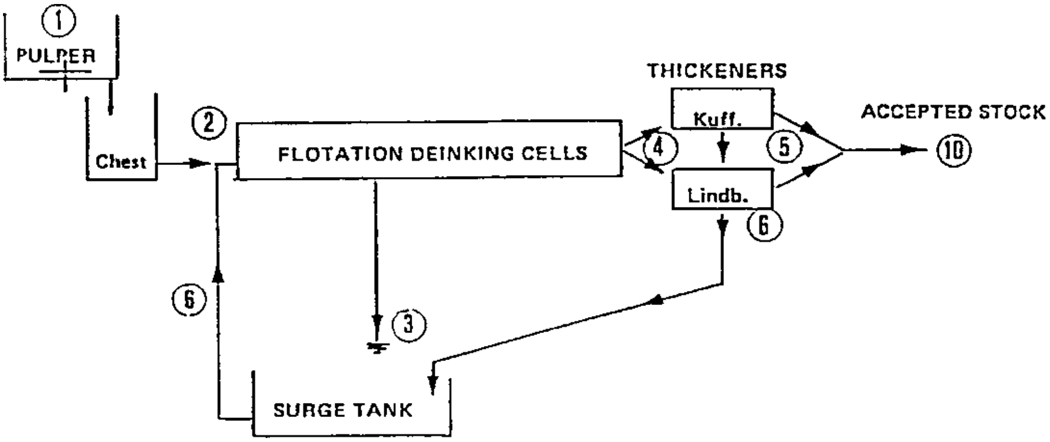

Fig. 12.7. Original deinking system.

The collapsed and condensed foam liquid from the flotation deinking cell amounting to 7.3 tonne/day and 173 L/min was disposed of as waste [3], while the flotation effluent [4] was discharged to two inexpensive thickeners for thickening of pulp in a parallel operation. A Lindblad thickener used a wire covered drum, and a Kufferath thickener used parallel wire covered discs for dewatering without sheet formation. Both thickeners [5] shown in Fig. 12.9 had a rather low stock retaining efficiency of 65–70%. The thickened deinked stock became the accepted stock [10] and the thickener effluent [6] was recycled to a surge tank.

It should be noted that although 88.3 tonne/day passed through the flotation deinking cell, only 61.3 tonne/day of deinked stock was accepted, resulting in a large quantity of stock in the recirculation flow [6]. This was caused by the use of inexpensive thickeners, in turn, the accumulation of substantial amounts of fibers and fillers in the recirculation flow, which was undesirable.

Depending on the used wastepaper type and the required final deinked stock quality, more of the fines or fillers had to be removed from the thickener effluent, if the existing inexpensive thickeners were to be used continuously.

6.2. *Improved Deinking System*

The original deinking system was significantly improved by the addition of four cost-effective units shown in Fig. 12.8:

1. Installation of a spray filter (SPRF 4500) [6a] for recovery of long fibers from the thickener effluent [6] and their reuse [6b] in the accepted stock [10].
2. Installation of a dissolved air flotation clarifier for clarification of the spray filter effluent [6a], and recirculation of a much cleaner effluent [8a] to the surge tank and subsequently to the dispersed air flotation deinking cell [2].

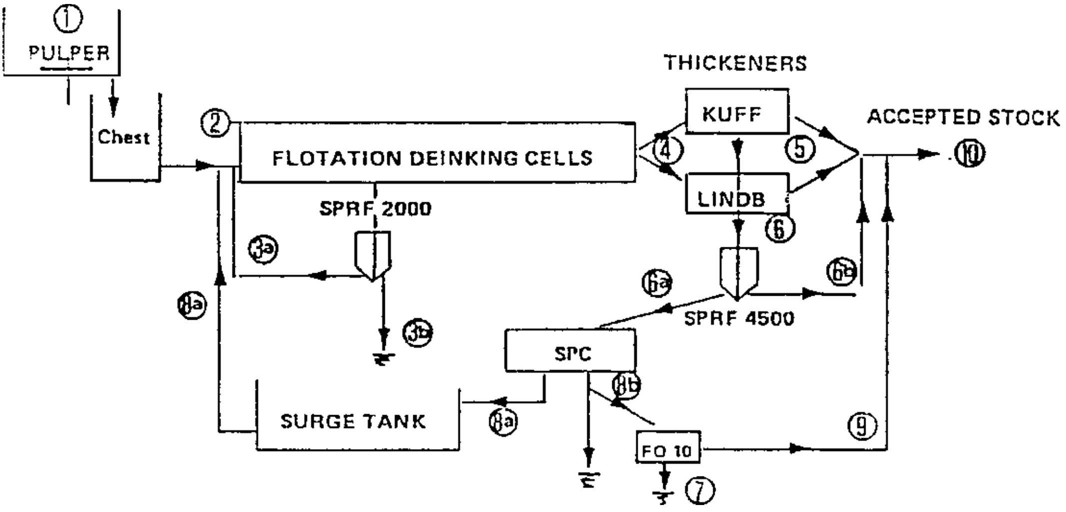

Fig. 12.8. Improved deinking system. *Note:* Flotation deinking cell is the dispersed air flotation cell; SPC is the DAF cell known as Supracell; SPRF is the spray filter.

3. Installation of a spray filter for separating long fibers from the rejected foam stream [3] from the dispersed air flotation deinking cell [2], and recycling the recovered fibers to the deinking cell [3a], before ultimate waste disposal [3b].
4. Installation of an optional small dispersed air flotation cell for increasing the brightness of the reclaimed fines and fillers [9]. Without this cell, the reclaimed fines and fillers can either be discharged directly to the accepted stock [10] through line [9] if the quality of reclaimed fines and fillers permits, or can be discharged directly to the sludge disposal site [11] if the quality of the reclaimed materials is poor.

Table 12.4 and Fig. 12.8 together illustrate how the original deinking system was improved by the four additional installations. It is noted that the incoming raw stock [1] has been increased from 68.6 to 85.0 tonne/day, and the accepted stock [10] has been increased from the original 61.3–75.3 tonne/day.

The improved deinking system has the following special features:

1. The added facilities are extremely compact and very cost-effective.
2. Stock production increased by 14.0 tonne/day, corresponding to an increase of 23%.
3. Low cost thickeners with low recovery efficiency but excellent fractionating/washing effect can still be used.
4. There is a great flexibility in adjusting the final deinked stock quality by separating fines and fillers if and as much as desired.
5. Long fibers from the thickener effluent can now be recovered by a spray filter, for reuse in the accepted stock.
6. Polyelectrolytes or other chemicals can be used in the DAF cell for effective clarification of the recycle flow entering the flotation deinking cell, and for recovery of short fibers.
7. The reclaimed fines and fillers can be selectively added to the accepted stock, depending on the desired quality of the deinked stock. If all fines and fillers are to be recovered, the spray filter can

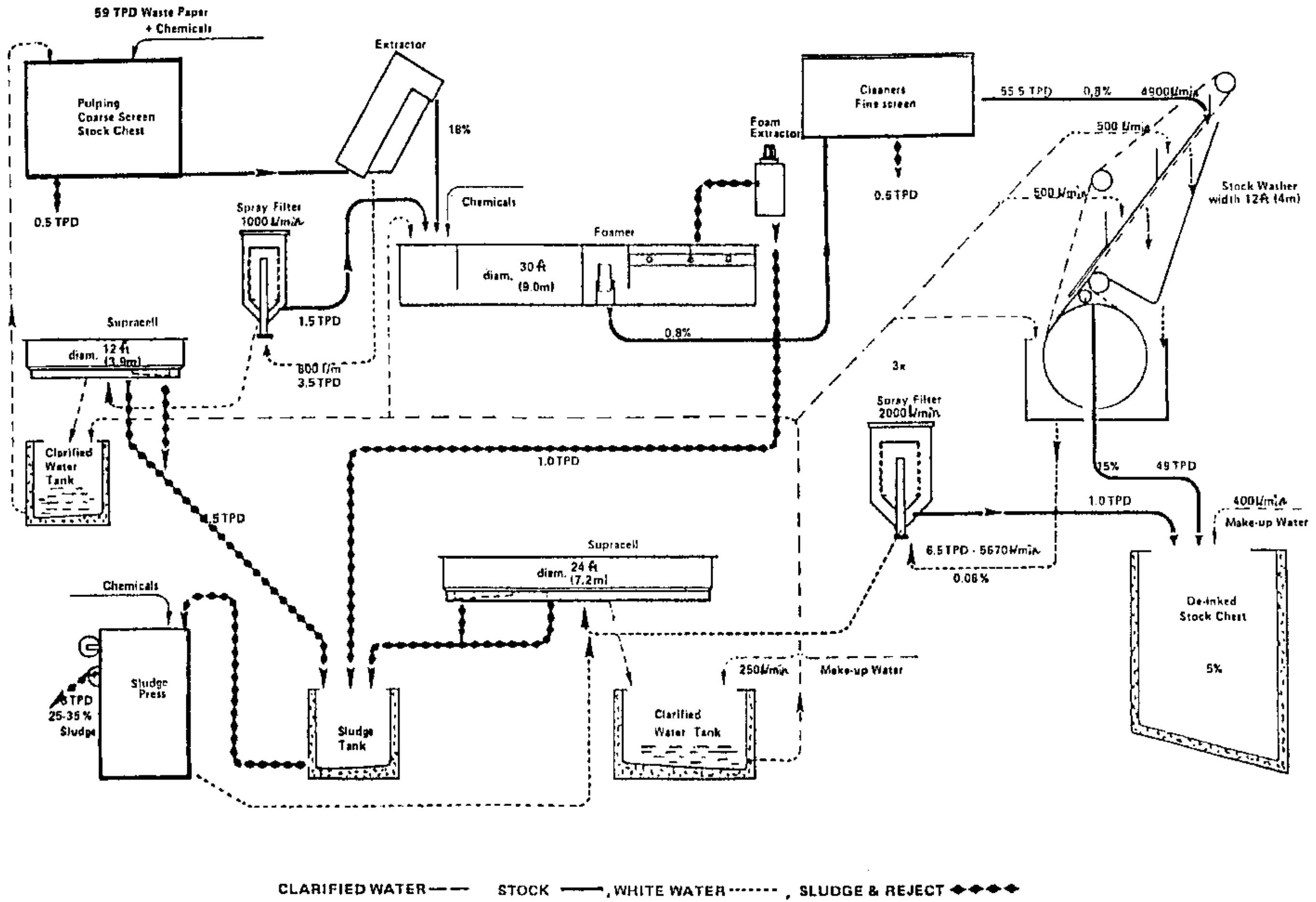

Fig. 12.9. Deinking installation. TPD is the metric dry weight T/day; % is the dry weight in %; LPM is the L/min; *long dash line* is the clarified water; *bold solid line* is the stock stream; *dotted line* is the white water; *diamond shape line* is the sludge rejects.

Table 12.4
Improved deinking system (Case History 2)

Process points	Flow lines	Total stock fiber and ash (tonne/day)	Dryness (% of wet wt)	Ash (% of dry wt)	Ash (tonne/day)	Fiber (tonne/day)	Flow (L/min)
1	Waste paper	85.0	90.00	23.06	19.6	65.4	–
2	Deinking inlet	87.7	1.23	23.72	20.8	66.9	4,500
3a	Recovered fiber	1.5	2.00	40.00	0.6	0.9	47
3b	Filter reject	8.5	3.50	34.12	2.9	5.6	153
4	Thickener inlet	77.7	1.14	22.27	17.3	60.4	4,300
5	Deinked stock	59.5	8.78	16.81	10.0	49.5	427
6	Thickener effluent	18.2	0.30	40.11	7.3	10.9	3,873
6a	Fine fiber	14.8	0.25	43.92	6.5	8.3	3,751
6b	Long fiber	3.4	1.76	23.53	0.8	2.6	122
7	Foamer reject	1.2	1.80	41.67	0.5	0.7	42
8a	Supracell effluent	1.2	0.027	50.00	0.6	0.6	2,772
8b	Floated stock	13.6	0.88	43.38	5.9	7.7	979
9	Foamer stock	12.4	0.83	43.55	5.4	7.0	937
10	Accepted stock	75.3	3.19	21.51	16.2	59.1	1,486

be idled, and all recovered substances from the DAF cell are added to the final accepted stock. If minimum fines and fillers are desired in the deinked stock, then the recovered stock from the DAF cell can be rejected.

8. The short fines and fillers recovered by the DAF cell can be additionally processed through a separate dispersed air flotation cell to increase the brightness of the stock, which is then added to the final accepted stock.
9. The condensed foam from the dispersed air flotation deinking cell can also be processed through a spray filter for recovery of long fibers. Such long fibers can be returned to the inlet of the flotation deinking cell for cost-saving.
10. The capital investment of additional facilities for the deinking process improvement can be recovered within a few years through increased stock production.

7. CASE HISTORY 3: A TOTAL WATER RECYCLE 50-TONNE/DAY DEINKING SYSTEM

Case History 2 clearly indicates how an existing deinking installation was improved by the addition of two spray filters, one DAF cell, and a dispersed air flotation clarifier. Although most of the process water was recycled for reuse, the DAF cell reject, IAF cell reject, and the spray filter reject were discharged as wastewaters.

Under the sponsorship of another paper mill in the US, a new 50-tonne/day deinking installation was designed for total water recycle and reuse in the mill. In other words, the concept of “zero wastewater discharge” now becomes a reality in a paper mill using the secondary fibers. The new deinking installation utilized facilities for pulp preparation, deinking, thickening, long fiber recovery, short fiber recovery, water clarification, etc. Figure 12.9 illustrates the totally closed deinking system for water recycle.

The wastepaper and chemicals are mixed with the recycled clarified water in a pulping stock chest with a coarse screen. Approximately 0.5 tonne/day of undesirable stock is wasted from the chest. The good stock goes from the chest to an extractor where an 18% homogenous stock is produced for feeding to the next dispersed air flotation deinking unit. The white water from the extractor flows to a spray filter for recovery of long fibers.

The 18% stock, chemicals, 1.5 tonne/day long fibers recovered by a spray filter, and the clarified water are all fed to the inlet well of the IAF cell for deinking. The stock's consistency (% wet weight) at the inlet to the deinking cell ranges from 0.75 to 1.50%. After deinking, the consistency of the deinked stock is reduced to 0.8% and is discharged from the center bottom of the cell to a fine screen cleaner where 0.5 tonne/day of sludge (waste stock) is rejected. A foam extractor sucks out 1.0 tonne/day of reject and discharges it to a sludge tank. Approximately 5.5 tonne/day of the deinked stock is discharged to a stock washer at 4,900 L/min for stock washing and thickening to 15%. About 10,000 L/min of clarified water is recycled from the clarified water tank to the stock washer for the washing operation. The white water amounting to 5,670 L/min flows to a spray filter for recovery of long fibers.

Final deinked stock is 50-tonne/day (49 tonne/day from the stock washer and 1 tonne/day long fiber from the spray filter). With the addition of makeup water, the accepted deinked stock has a consistency of 5% in the deinked stock chest.

The heart of this totally closed deinking system is two dissolved air flotation cells used for clarification and recycling of white water streams. It can be seen from 12.9 that two high-rate DAF cells (detention time = 3–5 min) receive the white waters from two spray filters for clarification. The clarified effluents are stored in two clarified tanks for reuse. All rejects flow to a sludge press for dewatering and ultimate disposal. Additional references for the totally or partially closed water systems in mills can be found in the literature (45–51).

8. CASE HISTORY 4: TOTAL CLOSING OF A PAPER MILL WITH DEINKINC AND CLARIFICATION INSTALLATIONS

Total closing of a 98-tonne/day paper mill with deinking and clarification installations has been made possible by the use of two dissolved air flotation (DAF) cells and a flotation–filtration clarifier. The flow diagram with material balance is graphically illustrated in Fig. 12.10.

In this paper mill, the wastepaper with a water content of (0.1 m^3/ton), chemical solution (0.05 m^3/ton), and clarified water (114 m^3/ton) are fed to the dispersed air flotation cell, screens, and stock washer for deinking, washing, and thickening, respectively. Although the capacities of Case Histories 3 and 4 plants are different, the deinking facilities and material balances are similar. The spray filters used in Case History 3 for long fiber recovery are only optional items in Case History 4 for future addition. The clarified water reservoir and sludge thickener of the deinking system in Fig. 12.10 are equivalent to the clarified water tank and sludge press, respectively, in Fig. 12.9.

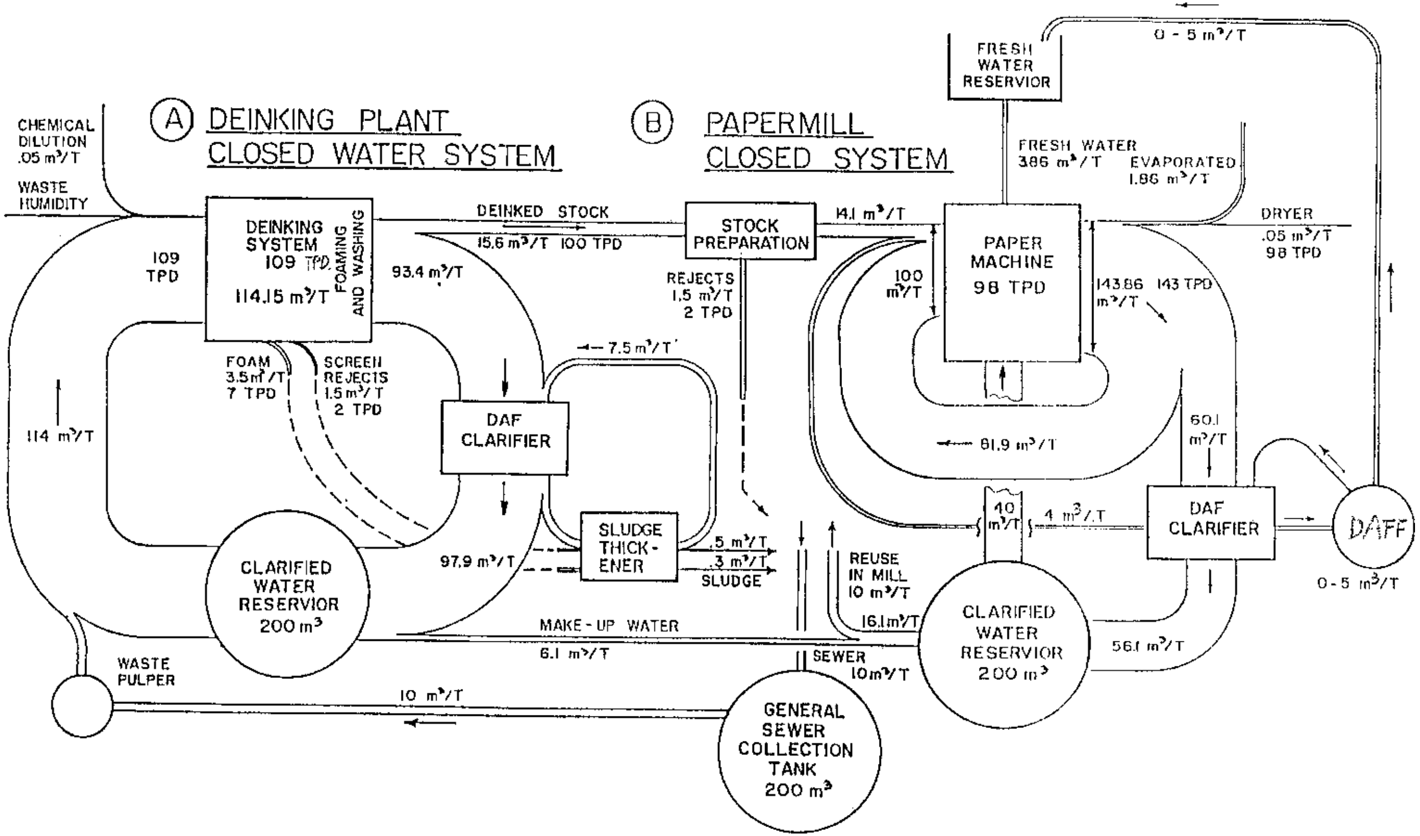

Fig. 12.10. Total closing of a paper mill with deinking and clarification facilities. TPD is the metric dry weight T/day; m^3/T is the cubic meter of water per dry tonne of stock; % is the dry weight in %.

The consistency of the homogenous stock at the IAF cell inlet is 0.88% at 114.2 m^3/ton and 109 tonne/day. The deinked stock (6%; 15.6 m^3/ton; 100 tonne/day) flows to the paper machine, the white water (93.4 m^3/ton) flows to a DAF clarifier, and the two rejects (3.5 m^3/ton from IAF cell and 1.65 m^3/ton from screens) flow to a sludge thickener, for further treatment. The DAF clarifier treats 93.4 m^3/ton of white water from the deinking system and 7.5 m^3/ton of wastewater from the sludge thickener, producing 97.9 m^3/ton of clarified water and 3 m^3/ton of floated scum.

A 200-m^3 clarified water reservoir is sufficient to hold 97.9 m^3/ton of DAF effluent and 16.1 m^3/ton of makeup water from the paper mill for continuous recirculation of 114-m^3/ton clarified water to the deinking system.

The sludge thickener treats 3.0 m^3/ton of DAF clarifier reject, 1.65 m^3/ton of screen reject, and 3.5 m^3/ton of IAF cell reject, and produces 0.65 m^3/ton of waste sludge and 7.5 m^3/ton of wastewater that goes to the DAF clarifier.

In the stock preparation step for Part B of the paper mill operation, 2 tonne/day stock and 1.5 m^3/ton water are lost as rejects, and only 98 tonne/day stock and 14.1 m^3/ton flow are sent to the paper machine. Additional influents to the paper machine are 81.9 m^3/ton from the paper machine's internal circulation, 3.9 m^3/T of makeup fresh water, 40 m^3/ton of clarified water from a reservoir, and 4 m^3/ton of recovered stock from the DAF clarifier. The total input to the paper machine amounts to 143.9 m^3/T of flow and 143 tonne/day of stock.

In the paper manufacturing process, 98 tonne/day of stock at 0.05 m^3/ton of flow go to a dryer for paper making, about 1.8 m^3/ton of water is lost in evaporation, 81.9 m^3/ton of water is internally recycled to the machine's inlet, and about 60.1 m^3/ton of white water flows to a DAF clarifier for clarification.

As shown in Part B of Fig. 12.12, the DAF clarifier treats the white water from the paper machine and discharges its effluent to a 200-m^3 clarified water reservoir for subsequent in-plant reuse.

A portion of the DAF clarifier effluent, up to 5 m^3/ton, can be further treated by a flotation–filtration clarifier (52–55) if the highest clarification is required. The high quality effluent is suitable for paper manufacturing.

9. CASE HISTORY 5: A COMPLETELY CLOSED WATER SYSTEM IN A SPAIN PAPER MILL

A Spain Paper Mill produces 210 T/day of fluting and test liner. The plant water capacity is 1,562 m^3/h (7,290 gpm), and the raw material is 100% waste paper. In this paper mill's completely closed water system (Fig. 12.11), recovered effluent fibers are reused in the fabrication and the clarified water is used for various purposes in the mill. The plant units are built using 316 stainless steel to avoid corrosion due to the high salinity of the recycled water.

As shown in the water system flow diagram (Fig. 12.12), the total mill effluent is collected in tank [2] and pumped to the first flotation cell [4]. Part of the clarified water from flotation

Fig. 12.11. Closed water system in the Spain paper mill.

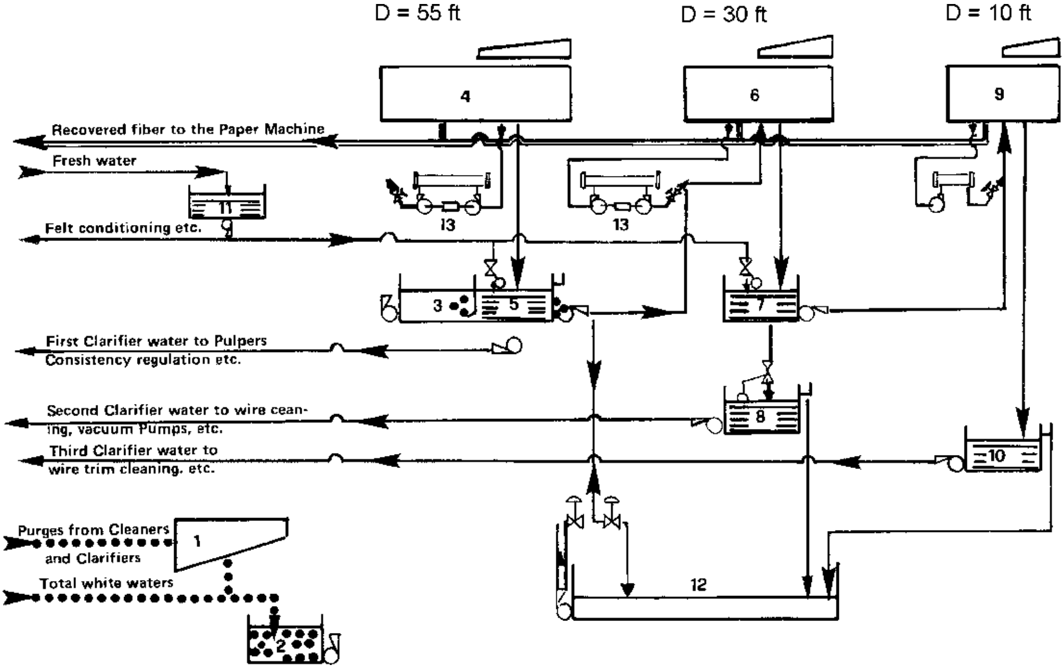

Fig. 12.12. Flow diagram of the closed water system in the Spain paper mill.

cell [4] is pumped from tank [5] to the second flotation cell [6]. Floated solids are recycled into the production of the clarified water and reused for suitable applications.

Part of flotation cell [6] clarified water is pumped from tank [7] to the third flotation cell [9]. Floated solids are returned to the paper machine and screened, clarified water is used where

Table 12.5
Performance of closed water system in the Spain paper mill

Flotation cell diameter (ft)	Inlet suspended solids (mg/L)	Outlet suspended solids (mg/L)	Chemical usage (mg/L)
55	5,000	1,500	0
30	1,500	300	0
10	300	50	0

clean water is required. Water containing sand (purge water from cleaners and settled sludge from the flotation cells) is treated in the rejects thickener [1] that acts as a sand-separator. Fresh water is provided to compensate for evaporation and other losses.

The whole plant works automatically with the help of control equipment for turbidity, pH, and flow. A system of storage tanks and pumps balance the variations in normal production of process water. A pond is used for water storage at the time of complete shutdown. The pump turbine installations in pressurization loops of flotation cells [4] and [6] are energy saving. The performance of the flotation units in terms of solids removal and water quality is shown in Table 12.5.

10. CONCLUSIONS

Closing up of a water system involves a custom-made approach for each paper mill, due to the many individualities of each mill installation. For practical application, the term “totally closed system” is applied to mean a system to be closed 100% with no wastewater discharge and the rejected waste sludge. A small amount of fresh makeup water must always be added, in the order of 250–500 gal/dry ton of stock (56).

The dispersed air flotation cell and the dissolved air flotation cell are the major components of the total water recycle deinking system. Both types of air flotation cells can prevent anaerobic buildup in the system because of their extremely short detention time and high oxygen content. Conventional sedimentation clarifiers (or settling cones) are generally not acceptable in a totally closed system because of their large volume, thin settled sludge, long detention time, and possible anaerobic problems. Dispersed air flotation is the most effective means for separating ink from fiber and clay, with very small water and material loss.

Technically, disc filters can also be used for replacement of DAF cells in water clarification. Disc filters also produce small volumes of sludge with high consistencies, but their cost is very high. DAF cell is, therefore, the most efficient and cost-effective means for water clarification.

The use of organic polymers in DAF cells is preferred due to the small amount of material added, the fact that they can be removed by DAF clarification, and the fact that polymers do not change the system pH.

The spray filter is a fractionation process unit for separation of long fibers from low-consistency stock by its microscreens (50–300 μm opening size). The spray filter is an optional facility that is highly recommended for long fiber recovery.

Corrosion may be high in the closed system because of the buildup of inorganic dissolved solids. Stainless steel piping is advisable for new deinking systems. PVC pipe is more cost-effective and is frequently used in the mills with partial or total closed water systems.

The benefits of a closed deinking paper mill in increased process efficiency and "zero waste-water discharge" are considerable. In most cases, the closed system pays for itself without even considering the pollution control benefits. For instance, tissue machines changing from cold fresh water to recycled warm water for felt cleaning have experienced paybacks of one year or less on equipment investment in screens and flotation cells. In addition to heat savings, savings in recovered fiber, clay, chemicals, and of course water are all significant.

REFERENCES

1. Partners in Design (2010) Eco strategies: facts and fiction, http://www.pidseattle.com/ECO/factfict.html
2. U.S. EPA, Paper Products Recovered Materials Advisory Notice, US Environmental Protection Agency, Federal Register Environment Documents, Washington, DC, August (2005)
3. Conserveatree (2010) The state of the recycled paper world, San Francisco, CA, Web location at: http://www.conservatree.com/paper/PaperTypes/StateRecyWorld.shtml
4. Krofta M, Wang LK (1989) Total closing of paper mills with reclamation and deinking installations. In: Proc. 43rd Purdue industrial waste conf., Lewis Publishers, Chelsea, MI
5. Woollen PS (1997) Recycling of tertiary effluent back into the paper mill, Krofta Engineering Paper, UK
6. Johnston R (2009) An environmental report on sources of fiber for tissue making, Kimberly-Clark, Web location at: http://www.kca.com.au
7. TAPPI (2010) How is paper recycled? The Technical Association for the Worldwide Pulp, Paper and Converting Industry, http://www.tappi.org/paperu/all_about_paper/earth_answers/EarthAnswers_Recycle.pdf
8. Somasundaran P, Zhang L, Krishnakumar S, Slepetys R (1999) Flotation deinking: a review of the principles and techniques. Prog Pap Recycl 8(3):22–36
9. Wood and Paper Sci. (2002) Introduction to the science involved in flotation deinking, http://www.cfr.ncsu.edu/wps/k12activities/ppts/flotation
10. Zhao Y, Deng Y, Zhu JY (2004) Roles of surfactants in flotation deinking, recycling 101. Prog Pap Recycl 14(1):41
11. Drelich J, Nalaskowski J, Gosiewska A, Beach E, Miller JD (2000) Long-range attractive forces and energy barriers in de-inking flotation: AFM studies of interactions between polyethylene and toner. J Adhes Sci Technol 14:1829–1843
12. Drelich J, Pletka J, Boyd P, Raber E, Herron D, Luhta E, Walqui H, Tervo N, Boston S, Wieland J, Morgan J, Sabo N, (2001) Interfacial chemistry aspects of de-inking flotation of mixed office paper. In: SME annual meeting, Denver, Colorado, February 2001
13. Mc Kinney RWJ (1988) Evaluation of deinking performance. TAPPI J 71(1):129–131
14. Pirttinen E, Stenius P (2000) The effects of chemical conditions on newsprint ink detachment and fragmentation. TAPPI J 83(11):1–14
15. Borchardt JK (1992) Chemical structure, property relationships of deinking surfactants. Prog Pap Recycl 1(2):45–60
16. Borchardt JK (1997) The use of surfactants in de-inking paper for paper recycling. Curr Opin Colloid Interface Sci 2:402–408

17. Drelich J, Zahn R, Miller JD, Borchardt JK (2001) Contact angle relaxation for ethoxylated alcohol solutions on hydrophobic surfaces. In: Mittal KL (ed) Contact angles, wettability and adhesion. VSP, the Netherlands
18. Lion Corporation (2010) Paper-pulp chemicals. Lion Corporation, Chemical Division, Web location at: http://www.lion.co.jp/chem/en/cata_en/f42–43.htm
19. Tomah Products, Inc. (2002) Nonatell1353 Flotation Deinking Agent, Product Bulletin, Web location at: www.tomah3.com
20. IPST (2003) Froth flotation deinking technology. Transfer Fact Sheet, Institute of Paper Science and Technology, Atlanta, GA. US Patent 5,876,558, January 2003
21. Beneventi D, Carre B (2000) The mechanisms of flotation deinking and the role of fillers. Prog Pap Recycl 9(2):77–85
22. Borchardt JK (1994) Possible deinking mechanisms and potential analogies to laundering. Prog Pap Recycl 2(2):47–53
23. Borchardt JK (1994) Mechanistic insights into de-inking. Colloids Surf 88:13–25
24. Rao RN, Stenius P (1998) Mechanisms of ink release from model surfaces and fiber. J Pulp Pap Sci 24(6):183–187
25. US DOE (2001) Surfactant spray: a novel technology to improve flotation deinking performance. Office of Industrial Technologies, Energy Efficiency and Renewable Energy, US Department of Energy (DOE), Washington, DC, Web location at: http://www.oit.doe.gov, February 2001
26. Wang LK (2006) Adsorptive bubble separation and dispersed air flotation. In: Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical treatment processes. Humana, Totowa, NJ, pp 81–122
27. Krofta M, Wang LK (1999) Flotation and related adsorptive bubble separation processes, Technical Manual No. Lenox 7-25-1999/348, 4th edn. Lenox Institute of Water Technology, Lenox, MA
28. Wang LK, Fahey EM, Wu Z (2005) Dissolved air flotation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana, Totowa, NJ, pp 431–500
29. Krofta M, Wang LK (2000) Flotation engineering, First edn, Technical Manual No. Lenox/1-06-2000/368. Lenox Institute of Water Technology, Lenox, MA
30. Shammas NK, DeWitt N (1992) Flotation: a viable alternative to sedimentation in wastewater treatment. In: Water Environment Federation, 65th annual conference, proc. liquid treatment process symposium, New Orleans, LA, pp 223–232, Sept. 20–24
31. Shammas NK, Wang LK, Hahn HH (2010) Fundamentals of wastewater flotation. In: Wang LK, Shammas NK, Selke WA, Aulenbach DB (eds) Flotation technology. Humana, Totowa, NJ
32. Azevedo MAD, Drelich J, Miller JD (1999) The effect of pH on pulping and flotation of mixed office wastepaper. J Pulp Pap Sci 25(9):317–320
33. Deng Y, Abazeri M (1998) True flotation and physical entrapment: the mechanisms of fiber loss in flotation deinking. Nord Pulp Pap Res J 13(1):4
34. Krofta M, Guss MD, Wang LK (1983) Improved biological treatment with a secondary flotation clarifier. Civ Eng Pract Des Eng 2:307–324
35. Krofta M, Wang LK (1984) Development of innovative Sandfloat systems for water purification and pollution control. ASPE J Eng Plumbing 0(1):1–16
36. Krofta M, Wang LK (1984) Tertiary treatment of secondary effluent by dissolved air flotation and filtration. Civ Eng Pract Des Eng 3:253–272
37. Krofta M, Wang LK, Kurylko L, Thayer AE (1983) Pretreatment and ozonation of cooling tower water, part I. U.S. Dept. of Commerce, National Technical Information Service, Springfield, VA, Report PB84-192053, April 1983

38. Krofta M, Wang LK, Kurylko L, Thayer AF (1983) Pretreatment and ozonation of cooling tower water, part II. U.S. Dept. of Commerce, National Technical Information Service, Springfield, VA, Report PB84-192046, August 1983
39. Krofta M, Wang LK (1987) Flotation technology and secondary clarification. TAPPI J 70 (4):92–96
40. Ackel C (1988) Controlling wastewater color via coagulation and flotation separation. TAPPJ J 71 (2):37–39
41. Krofta M, Miskovic D, Shammas NK, Burgess D (1994) Pilot-scale applications of a primary-secondary flotation system on three municipal wastewaters. In: Specialist conference on flotation processes in water and sludge treatment, Orlando, FL, 26–28 April 1994
42. Shammas NK (1997) Physicochemically-enhanced pollutants separation in wastewater treatment. In: Proc. international conference: rehabilitation and development of civil engineering infrastructure systems – upgrading of water and wastewater treatment facilities, organized by The American University of Beirut and University of Michigan, Beirut, Lebanon, June 9–11 1997
43. Shammas NK (2010) Wastewater renovation by flotation. In: Wang LK, Shammas NK, Selke WA, Aulenbach DB (eds) Flotation technology. Humana, Totowa, NJ
44. Venditti R (2006) Lab manual: flotation deinking experiment: flotation deinking of copy paper. Department of Wood and Paper Science, Raleigh, NC
45. Brecht W (1973) Investigation of closed water systems in another waste paper processing plant. WochenBlatt für Papierfabrikation 101:113–119
46. Dalpke HL (1975) Special difficulties with entirely closed water circuits. Das Papier 236–240; Streebin LF (1976) Water reuse in a paper reprocessing plant, EPA-600/2 76 232, US Environmental Protection Agency, October 1976
47. Springer AM (1975) The relation between process water quality characteristics and its reuse potential in combination board mills. NCASI Bull 282. Oct. National Council for Air and Stream Improvement, Inc. Corvallis, OR, USA
48. Guss DB (1977) Closed water systems in mills using secondary fiber. The TAPPI alkaline pulping and secondary fibers con., November 1977. TAPPI. www.tappi.org
49. Krofta M (1971) Closed water circuits in board mills. WochenBlatt für Papierfabrikation 99:781–784
50. Guss DB (1995) Water system closure strategies using flotation and filtration. In: Proc. of CPPA, environmental conf., Halifax, October 1995
51. Wiseman N, Ogden G (1996) Zero liquid effluent technologies for the paper industry. Pap Technol 37:31–38
52. Krofta M, Miskovic D, Shammas NK, Burgess D, Lampman L (1994) An innovative multiple stage flotation-filtration low cost municipal wastewater treatment system. In: IWA 17th biennial international conference, Budapest, Hungary, 24–30 July 1994
53. Shammas NK, Krofta M (1994) A compact flotation-filtration tertiary treatment unit for wastewater reuse. In: Water reuse symposium, AWWA, Dallas, TX, pp 97–109, February 27–March 2 1994
54. Wang LK (2006) Emerging flotation technology. In: Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical treatment technologies. Humana, Totowa, NJ, pp 449–484
55. Shammas NK (2010) Flotation-filtration system for wastewater reuse. In: Wang LK, Shammas NK, Selke WA and Aulenbach DB (eds) Flotation technology. Humana, Totowa, NJ
56. Shammas NK (2010) Waste management in the pulp and paper industry. In: Wang LK, Hung YT, Shammas NK (eds) Handbook of advanced industrial and hazardous wastes treatment. CRC, Boca Raton, FL, pp 857–912

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Lake Restoration Using Dissolved Air Flotation

Donald B. Aulenbach, Nazih K. Shammas, Lawrence K. Wang and R. Derrick I. Kittler

CONTENTS

Abstract The steps leading to the demise of a lake are discussed. One of the primary causes of the death of a lake is excessive biological growth, called eutrophication. Biological growth is limited primarily by the availability of the nutrients necessary for growth. It has been shown that phosphorus is most frequently the limiting nutrient to control biological growth in a lake, but nitrogen is also commonly limiting. Phosphorus may be permanently removed from a lake by various processes, whereas nitrogen is difficult to remove permanently due to the fact that certain blue-green algae can fix atmospheric nitrogen as a nitrogen source. Thus, emphasis has been placed on the removal of phosphorus. There are various methods for the treatment of wastewaters to remove the nutrients before being discharged to a body of water. Once in a lake, phosphorus removal is most frequently achieved by producing an insoluble aluminum salt of the phosphorus, but iron salts are effective under aerobic conditions. Calcium salts are effective in removing phosphorus, but they generally adversely increase the pH of the lake. Precipitated aluminum phosphate salts may be allowed to settle to the bottom of the lake, or they may be removed from the water column. A study showed that removing the phosphate-rich hypolimnetic waters from a summer stratified temperate climate lake, precipitating the phosphorus as either aluminum or iron salts, separating the precipitate

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by DAF, and returning the phosphate reduced water to the lake were very effective in controlling the phosphorus nutrient content in Devils Lake, WI.

Key Words Nutrients • productivity • biological activity • stratification; eutrophication • remediation • phosphorus precipitation • DAF • flotation.

1. IMPORTANCE OF LAKES

All lakes and reservoirs have a finite life. That life may be measured in geological time or in human lifetimes. The general pattern of aging of a lake is for the lake to fill in with either allochthonous materials (carried into the lake from inlet streams or direct runoff) or autochthonous materials (generated by biological growth within the lake). As a lake ages, the water becomes more shallow. The decreased volume of water concentrates the same nutrient input. This encourages more biological growth, which further fills in the lake with dead biomass. When the depth decreases to about 2 m, rooted aquatic plants proliferate because of their access to direct sunlight. This further increases the filling in of the lake. Most frequently (but not always), when a lake reaches this point, it becomes a wetland or a bog. At this point, emergent plants and eventually trees appear. These tend to take up the moisture, drying out the system. The wet organic material may progress to peat, a useful source of fuel. In geologic time, with the aid of pressure, this progressed to coal, a very valuable source of energy.

However useful peat and coal may be as a source of energy and raw materials, lakes are considered more important for their water. All life depends upon water and its unusual characteristics. In addition to water for drinking, water is essential for irrigating crops. Irrigation is the largest consumer of water on Earth today. As the population of earth grows, there will be a greater demand for food, much of it needing irrigation. Other industries require water, including process water and cooling water. Thus, water is essential for life as well as for modern day living.

In addition, water in its place, such as a lake, is important to our livelihood. Besides its use in transportation, many recreational activities, such as swimming and boating, depend upon lakes and streams. Further, lakes have an aesthetic quality. Many poems and stories have been written about lakes. The beauty and tranquility of lakes adds to our consolation. Storms on a lake inspire awe. Thus, it may be seen that lakes are essential to our way of life.

In this chapter, reservoirs are considered in the same manner as lakes. By definition, reservoirs are artificial lakes, generally constructed to serve a specific purpose. The purpose may include drinking water supply, flood control, low flow augmentation, travel enhancement, storage for periods of low precipitation, recreation, and any combination of these. The life of a reservoir mimics that of a lake, although the factors that influence the life of a reservoir may be somewhat different, or in different magnitude, from those that impact the life of a lake. In both cases, these factors are so variable that to predict the life of a lake, each lake must be studied as its own entity. No two lakes or reservoirs are exactly the same, nor have the same needs.

It may be concluded that the preservation of lakes and the extension of their lives is important to the continuation of human life on Earth.

2. CHARACTERISTICS OF LAKES

Even though each lake has its own characteristics, we can make generalities on the factors that influence the life of a lake or reservoir. By understanding these characteristics, we can devise the means of slowing the aging process and, in some cases, even reversing that process. By studying ancient lakes and terminal lakes, we can describe the factors that have either preserved the lake or hastened its demise.

There are numerous factors that control the life of a lake. Not in any preferred order, the morphology of a lake is an initial factor. Deep lakes with steep sides seem to have greater longevity. Large shallow areas tend to encourage rooted plant growth, which leads to the more rapid filling in of the lake. Steep sides may even limit human habitation as experienced in Crater Lake, Oregon, formed in the caldera of a former volcano. The smaller the ratio of the watershed to the lake surface area, the longer its life; again Crater Lake is a prime example. Larger Lakes such as the Great Lakes of North America have a long life. The underlying geological formations in the lake may contribute essential nutrients that may allow biological growth. A forested watershed will lessen the amount of nutrients being carried into the lake. Conversely, farmed areas contribute large amounts of nutrients from fertilizers. Human development may contribute significantly to the demise of a lake. While everyone enjoys the beauty and the recreation attractions of a lake, more inhabitants result in more direct surface runoff to the lake and more domestic wastes containing nutrients to ultimately reach the lake. A significant impact is lakeside homeowners who pride themselves with their green lawns, right down to the water's edge, kept green with fertilizers, which readily reach the lake. Again, no two lakes are identical, and the combination of factors affecting a lake's life is infinite.

Deep lakes in temperate climates exhibit an interesting circulation pattern. Under ordinary conditions, there is a period of stratification during ice cover in the winter and another period of stratification during the summer. There are also two periods during which the water is completely mixed from top to bottom by the impact of wind at the surface. This occurs when the water temperature is uniform with depth, and usually occurs just before ice formation (fall turnover) and just after ice out (spring turnover). Such a lake is called dimictic. This pattern is the result of the temperature-density relationship and the anomalous condition of water being most dense at 4°C. Thus, in winter, the bottom temperature is 4°C, while the ice on the surface is at zero. During summer, the surface is warmed by the sun, while the bottom may remain at or near 4°C. Thermal stratification usually occurs as a result of a combination of solar heating of the surface, the impact of wind, and the temperature-viscosity relationship of the water. This summer stratification prevents surface reaerated water from being carried to greater depths, a factor that also contributes to the long-term demise of the lake.

The temperature succession in a lake may be shown starting with ice cover in winter. The surface ice is at or below 0°C, while the bottom is at 4°C. There is no mixing of this water because the ice cover prevents any wind effects. Biological activity is also at a minimum.

As spring comes, the sun melts the ice and then begins to warm the surface of the lake. As all of the water approaches 4°C, even a gentle wind will mix this isothermal water from top to bottom, called the spring overturn. As the sun warms the surface of the lake, the warmer water will tend to float on the surface due to its lower density. If this heating occurs during a period of strong wind, there may still be complete mixing and the entire lake will be heated to the temperature of the surface. However, if warming occurs during a period of light or no wind, a point is reached at which the wind does not have sufficient energy to mix the upper warmer water with the cooler lower layer of water with greater density and viscosity. This forms a period of summer stratification where there is circulation near the surface, but none below a certain depth. Frequently, in large deep temperate lakes, the level of stratification occurs at about 10 m depth. Further, the shape and orientation of the lake to the wind have an influence on the depth of the upper mixed zone. During summer, in a typical temperate lake, there is a warm upper layer that is equally mixed by the wind, then a zone in which there is a rapid decrease in temperature with depth, and finally a layer of relatively cold uncirculating water near the bottom. Thus, the lake is divided into three layers in which the upper layer is called the epilimnion, the middle layer the metalimnion or the thermocline, and the bottom layer the hypolimnion, as shown in Fig. 13.1.

The summer stratification may last up to 5 months, during which time there is little to no mixing in the hypolimnion and no opportunity for oxygen from surface aeration to reach this area. So long as only a little decomposable organic matter is present at the onset of

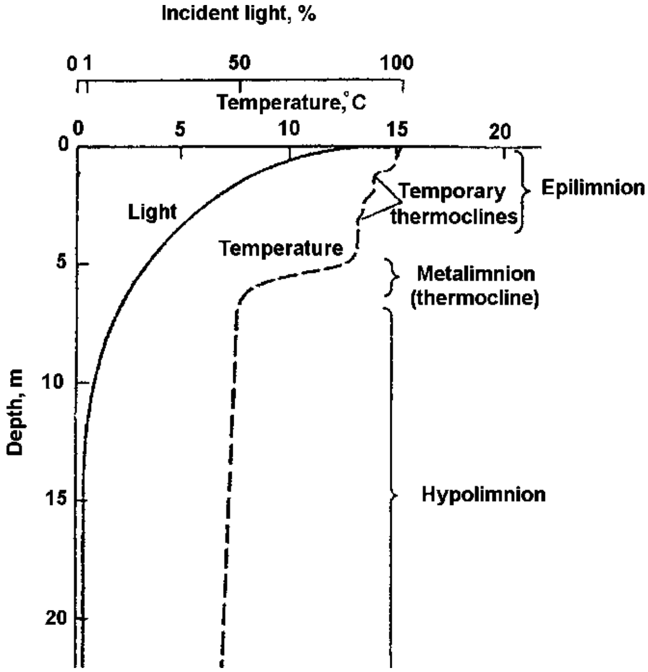

Fig. 13.1. Temperature and light profiles in a temperate climate lake during summer stratification.

stratification, the available oxygen present may not be entirely consumed. The colder bottom water temperature also contributes to a slower biological activity, thereby conserving the oxygen supply. This condition is conducive to supporting a cold-water fish habitat. However, if large amounts of decomposable organic matter settle into the hypolimnion, the limited amount of oxygen available may be consumed and the hypolimnion will become anaerobic. Not only will this interfere with fish life, but it will also result in the release of certain nutrients, specifically phosphorus, that are insoluble in aerobic conditions, but soluble under anaerobic conditions. The presence of more nutrients may increase oxygen-consuming biological activity that will further create anaerobic conditions.

As fall approaches, the surface of the lake is cooled and the cooler water circulates to a depth of equal temperature and/or density. This tends to lower the thermocline until the lake becomes uniform in temperature. Now, even a light wind can circulate the water from top to bottom and the period of fall overturn occurs. During this time, complete oxygen saturation of the water usually occurs and aerobic reactions persist.

As the air temperature reaches 4°C and becomes colder, the surface of the lake will approach 0°C, but the denser 4°C water will remain on the bottom. When ice covers the surface, the period of winter stagnation begins. The duration of this depends upon latitude, altitude, weather conditions, and numerous specific lake conditions. Lakes with significant warm underground springs have been found to have less ice cover and in some instances have holes in the ice above the location of the spring. Very deep lakes such as Lake Baikal, Crater Lake, and Lake Tahoe contain so much heat energy in the water that they do not freeze. Figure 13.2 summarizes the circulation/depth patterns during the seasons in a deep temperate climate lake.

3. IMPORTANCE OF BIOLOGICAL ACTIVITY

It may be noted in this discussion that the inter-relationship between nutrients and biological activity represents a continuing thread in the study of the life of a lake. Thus, an understanding of the relationship between biological activity in a lake and its aging process is essential (1).

A lake contains many biological communities. Within the water column are numerous organisms of microscopic size. The floating microscopic organisms are called plankton, which may be subdivided into two groups: the phytoplankton or plant life, which includes algae, fungi, and pollens that fall into the lake, and the zooplankton or animal forms. The plankton may also be broken down into the nekton, or free swimming organisms and the benthon, which exist on the bottom.

A prime concern is the algae, the microscopic green plants floating in the water column. These organisms represent the base of the food chain in that they can convert simple inorganic matter into organic matter with the aid of sunlight in the process called photosynthesis. In this process of cell growth, oxygen is also produced. It has been estimated that three-fourth of the Earth's supply of oxygen is generated by algae in the ocean. In terms of the food chain, the algae may be consumed by the zooplankton, which in turn are consumed by larger animal forms, which may be consumed by small fish, which may be consumed by

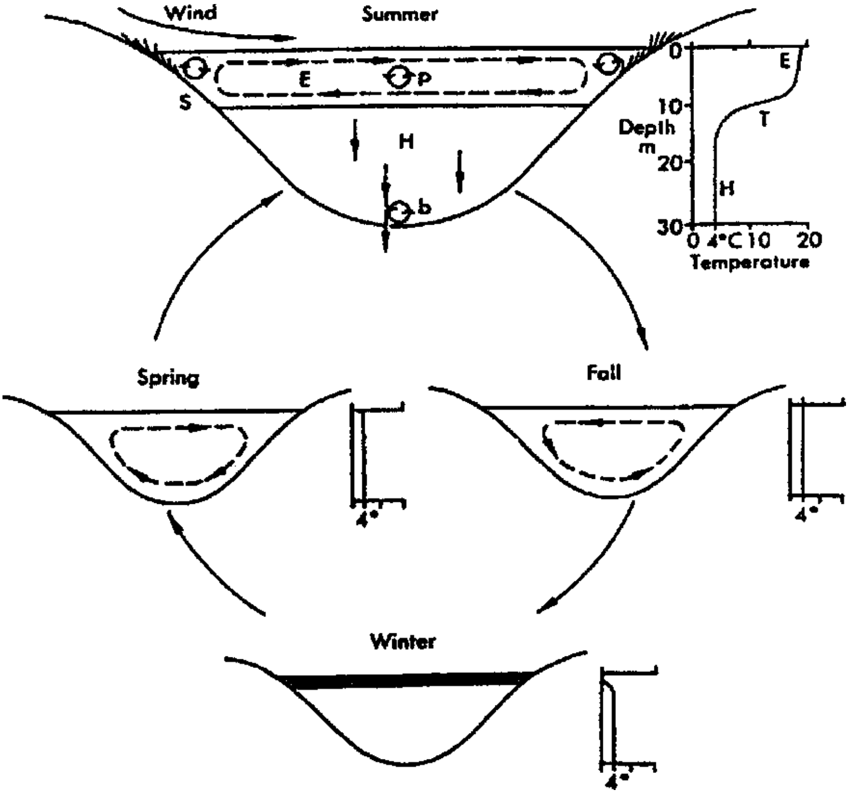

Fig. 13.2. Seasonal circulation patterns in a deep temperate climate lake.

larger fish, which may be consumed by larger vertebrates, including humans. The microscopic algae are the start of this food chain.

All biological systems require the presence of the proper nutrients and energy to grow and reproduce. For larger organisms, the smaller organisms provide both the nutrients and the energy. However, algae obtain their nutrients from dissolved inorganic materials and their energy from the sun. Organisms that rely on inorganic nutrients are called autotrophic, whereas those that rely on organic matter are called heterotrophic. Besides nutrients and energy, growth may depend upon other factors such as temperature, light, etc. Nutrients in a lake may vary with location, including depth, and time. Specific organisms may have individual nutrient and environmental requirements. However, common to most are carbon, hydrogen, oxygen or another electron acceptor, nitrogen, and phosphorus. Carbon may be obtained from the solution of carbon dioxide. Hydrogen may be obtained from electrolysis or from bicarbonates dissolved in the water. Oxygen is most frequently obtained from the dissolved oxygen in the water. Nitrogen is secured from dissolved nitrogenous materials, including ammonia, nitrites, and nitrates. Certain blue-green algae can obtain gaseous nitrogen from the atmosphere. Phosphorus is usually obtained from geological materials and from the breakdown of other organic materials. A general rule for the ratio of nutrients to support the growth of organisms is 60 parts of carbon to 15 parts of nitrogen to 1 part of phosphorus. Some trace substances may also be essential. One of these is sulfur, which may be present in the soil, and is available in decaying organic matter. Another is silicon, which is required to form the shell case, called the frustule, of diatoms.

Every species of organism has a specific requirement for nutrients. Other factors being satisfactory, organisms will continue to grow until one of the essential nutrients has been completely utilized. Then growth may be retarded or completely stopped. Conversely, providing the limited nutrient will encourage additional growth. Frequently, limiting nutrients such as nitrogen and phosphorus are contained in wastes, including human wastes. Conventional wastewater treatment does not remove nitrogen and phosphorus. Thus, additional treatment to remove these nutrients is frequently required before discharge into a lake.

Productivity in a lake is commonly expressed as the amount of fishable fish in a lake. Since the number of fish is directly related to the fish food and the food ultimately is a function of algae in the food chain, which in turn is a function of the available nutrients, we can use the measurement of the nutrients to estimate the potential productivity of a lake. Whether or not productivity is desirable is up to individual taste. A lake that is low in productivity will be clear and have a low fish population. A lake that is high in fish population tends to be turbid and frequently accompanied by extensive shoreline weed growths. Moreover, the fish population will vary in each case with game fish, such as trout and salmon, predominant in less productive lakes and pan fish, such as bass, pickerel, and catfish, predominant in highly productive lakes.

The term oligotrophic has been used to describe lakes low in nutrients and consequently low in productivity. Lakes high in productivity are termed eutrophic. As a general rule, lakes proceed from oligotrophic to eutrophic as the lake ages. Some researchers add the word mesotrophic to designate lakes on the verge of becoming eutrophic. These terms are not intended to imply that all eutrophic lakes are undesirable or that all oligotrophic lakes are desirable. The desirability of a specific level of productivity is a function of the specific use of the lake. Probably what is desirable is a mixture of lakes of the different types. The long-range problem is that as lakes age the nutrients accumulate within the lake. New nutrients are brought into the lake from allochthonous inputs. Siltation may decrease the volume of water within the lake, thus concentrating the nutrients. Anthropogenic inputs such as wastewaters and fertilizers add significantly to the nutrient level. Deforestation results in more rapid runoff, which carries both silt and nutrients into the lake. All these combine to increase eutrophication in a lake.

4. CONSIDERATIONS IN REMEDIATION

In order to prolong the life of a lake, actions must be taken to reduce the rate of eutrophication. Very little can be done to overcome the natural process of eutrophication. However, much can be done to overcome the anthropogenic impacts. It is easy to say just stop any human activities that contribute to the eutrophication, but that is difficult to achieve. The best that can be done is to determine what activity will provide the best return for the effort and/or expenditure.

Sakamoto (2) showed a direct correlation between the phosphorus concentration in a lake at the time of spring turnover and the amount of productivity as measured by the amount of chlorophyll-α present during summer Fig. (13.3). Correspondingly, the greater the chlorophyll-α content, which indicates the presence of algae, the greater the turbidity of the water, and therefore, the lower the clarity of the water as measured by the Secchi disk depth. While there was good coordination between the phosphorus content and the chlorophyll-α, there was poor correlation between chlorophyll-α and the clarity of the water. Substances other than chlorophyll-α can impact the turbidity of the water. These include the presence of zooplankton that feed on the phytoplankton, and particulate matter, such as fine clay or silt that is carried into the lake in the runoff.

Numerous models have been derived to correlate certain specific parameters with the trophic state of a lake. Two stand out as being quite reliable and simple. Both relate total phosphorus loading to the trophic state of the lake as a function of the body of water. In the original work by Vollenweider (3), he showed a correlation between the total phosphorus loading and the mean depth of the lake. Many lakes were studied, and there was a good correlation between these two parameters. Later, Vollenweider and Dillon (4) improved the

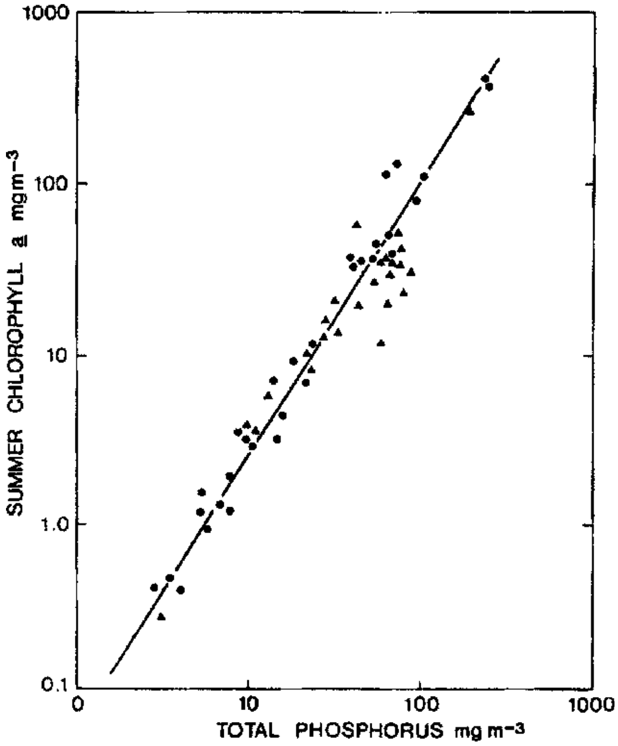

Fig. 13.3. Total phosphorus concentrations at spring turnover *vs.* average summer. Chlorophyll α concentrations. *Dots* represent data from Sakamoto, 1966 (2); *Triangles* are for other lakes in the literature; *Line* is the regression line for Sakamoto points; Correlation coefficient (*r*) is 0.97.

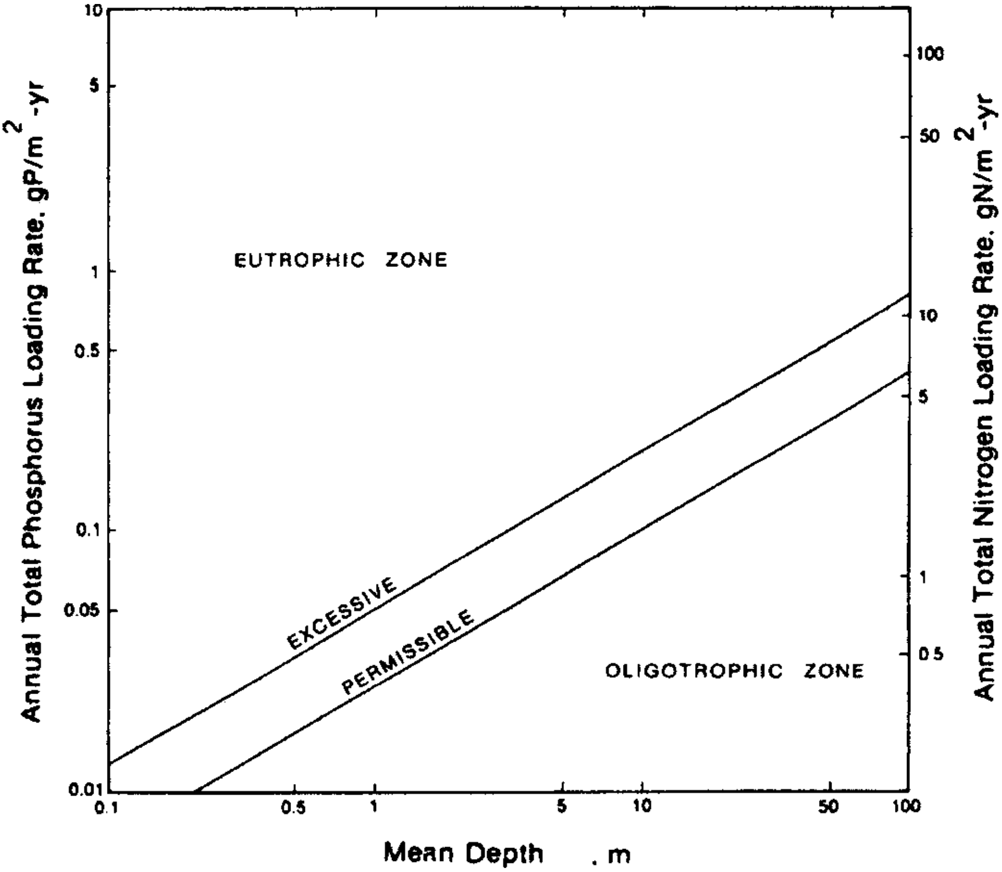

Fig. 13.4. Trophic state of a lake based on its mean depth and nutrient loading.

model by comparing phosphorus loadings with the mean depth and the retention time of the lake Fig. (13.4). The correlation was poor with lakes that were not phosphorus limited.

5. TREATMENT TO PREVENT NUTRIENT DISCHARGES

It is apparent that the most effective measure to control eutrophication would be to control the nutrient inputs. However, this is neither always possible, nor practical. It is nearly impossible to lower the total carbon inputs to a lake because there is always some dissolved carbon dioxide present in the atmosphere that can become available as a carbon source. It is not desirable to limit the oxygen, as that would encourage anaerobic decomposition with its odors and other undesirable conditions. Nitrogenous materials can be removed from a wastewater treatment plant effluent, but certain blue-green algae can utilize nitrogen from the atmosphere. Phosphorus can also be removed from wastewater effluents. Unless there is a large phosphate deposit in the watershed or the lake bed, this can result in a permanent removal of the phosphate so long as the lake maintains aerobic conditions. Thus, phosphorus removal has received much attention in the effort to limit primary productivity. Furthermore, in his study of lakes around the world, Vollenweider (3) observed that the nutrient most frequently limiting productivity in lakes was phosphorus.

Since phosphorus is most frequently the limiting nutrient in a lake, more efforts have been directed toward finding the means of reducing phosphorus inputs to a lake. Means that have been applied include diversion of all stormwater runoff from the lake, installation of stormwater infiltration basins, removal of phosphorus from treatment plant effluents, the use of land application of wastewaters, and passing treatment plant effluents through wetlands before they enter the lake.

Another reason why phosphorus has been chosen as the nutrient to be removed is the ease of precipitating phosphorus with iron, aluminum, or calcium salts, with the subsequent removal of the solids. Phelps (5) showed that limiting the phosphorus concentration in a lake at the time of spring turnover to less than 10 μg/L would limit excess productivity in most lakes.

The removal of phosphorus from wastewaters in the treatment processes is important in limiting phosphorus discharges to streams and lakes. These include both biological and chemical treatment systems.

Most biological treatment systems rely on a peculiar trait of many organisms, specifically those present in typical biological wastewater treatment systems, especially activated sludge systems. When these organisms are starved for phosphorus, such as under anoxic conditions, and then subjected to normal aerobic activated sludge aeration, they take up more phosphorus than immediately needed, a term called luxury uptake. Thus, treatment involves alternating anoxic and aerobic treatment in separate tanks, or alternating conditions in a single tank, with the removal of excess phosphorus in the waste sludge.

Wilson (6) summarized some of these processes, sometimes known as the Ludzack–Ettinger and Johannesburg or Bardenpho processes, which are patented. Variations include the number and order of anoxic and aerobic tanks, the location of both return activated sludge and mixed liquor suspended solids to help create anoxic conditions, and the use of an added carbon source, such as methanol, to create the anoxic conditions. If effluent requirements require phosphorus levels less than 0.3 mg/L, additional chemical treatment is usually needed. Wilson compared biological and chemical phosphorus removal and concluded that multiple aeration tanks consume energy; return activated sludge and mixed liquor suspended solids require more energy; the cost of a carbon source (methanol) may be great; multiple tanks require more space; and for low phosphorus effluent demands, chemical treatment is needed anyway. He also pointed out that the additional volume of sludge created by the addition of chemicals is small compared to the volume of waste sludge already created.

In order to achieve total phosphorus levels in wastewater discharges of less than 0.1 mg/L, chemical precipitation is very useful. Phosphorus forms insoluble salts with aluminum, iron, and calcium. Aluminum is most commonly used. The iron phosphate sediment must be kept aerobic to prevent the release of the phosphorus when less soluble iron sulfide is created. Calcium is usually applied as lime, which has a high pH. This may be detrimental under certain circumstances. Availability and cost of the chemicals has a large role in the choice of chemical. Eberhardt (7) has published a report on calculating the optimum aluminum dose.

Tabor (8) evaluated two patented treatment systems for phosphorus removal. The Actiflo process consists of coagulant addition with rapid mix, polymer and sand addition, slow mix for particle agglomeration and floc formation, plate settlers for solids/liquid separation, separation of the sand from the solids in a hydroclone, and return of the sand to the system. The DensaDeg process consists of coagulant with rapid mix, polymer and thickened return activated sludge addition, a plug flow zone for particle agglomeration and floc formation, tube settlers for solids/liquid separation, and thickening of solids for recycle and disposal. Both systems are capable of removing total phosphorus to less than 0.2 mg/L.

Patoczka (9) described upgrading an existing conventional activated sludge treatment plant utilizing a backwashable sand filter to achieve an effluent total phosphorus content of less than 0.1 mg/L. Chemical addition was shown to be effective. Both alum and iron salts were studied, and the optimum dosages and pH for each were determined for the particular waste. The effects of chemical addition at the primary settling tank, the aeration tank, and the final clarifier were studied. The most effective location for adding the chemicals and the most effective chemical for phosphate removal was by the addition of alum at the final clarifier, however, some savings in chemical may be achieved by adding it in the aeration unit since some chemical would be added from the return activated sludge. Alum addition increased the sludge generation in the range of 0.5–0.7 lb of dry sludge per lb of alum used. Chemical addition aided sludge settling in the final clarifier and also increased BOD and TSS removal.

The Federal Highway Authority has issued a report for the best management practices for stormwater management (10). A simple method is an alum injection system that adds alum directly to a stormwater channel at a flow-controlled rate. The precipitated chemicals are merely discharged to the receiving stream or lake where they settle to the bottom (under appropriate flow conditions). The added solids in lake sediment are considered insignificant. Total phosphorus in Lake Ella, Florida was reduced by 89%, and total nitrogen by 78% (11). Pitt (12) described a multi-chambered treatment train that consists of a series of treatment units that mimic a conventional wastewater treatment plant. In the first tank, mild aeration separates the heavy solids from the lighter ones. In the bottom of the second tank, most of the solids are settled out by an inclined tray settler, and above this, a dissolved air flotation (DAF) system lifts floatables and oil to the surface. The final tank uses a sand/peat filter for final treatment. Total phosphorus removal was determined to be 88%. Allard et al. (13) patented the StormTreat System for treating stormwater. It consists of a circular holding tank 1.2 m deep with discharge to the subsurface of a surrounding wetland. Overall the system removed total phosphorus by 89%. Claytor and Schueler (14) have described a constructed vegetated rock filter for biological treatment of stormwater, with application to the subsurface of the filter. This achieved 82% removal of total phosphorus.

Farming is a major source of nutrient discharges to streams and ultimately to lakes. Runoff from fertilized fields carries the excess fertilizer off the field. This can be controlled by establishing an unfertilized buffer zone between an active field and the waterbody. Also, the trend toward large feedlots has exacerbated runoff problems. A large combined animal and plant farm in the UK has installed an environmentally sound water and wastewater system (15). The collected liquid wastes are treated in a DAF system before entering a reedbed treatment system. The effluent flows into a lake whose overflow passes into a willow plantation. Water from the lake is used for irrigation and pig wallowing. Seepage under the lake is pumped out a sufficient distance away to allow for reuse. The lake also serves as a fish and wildlife habitat.

In studies at the Lake George Village, NY sewage treatment plant using trickling filters and alum addition before the secondary clarifiers, with the final effluent being dosed onto deep natural sand beds, Aulenbach (16) found that total phosphorus was reduced to less than 1 mg/L within 7 m of vertical transport through the sand. In another study of phosphate removal in the soil, Aulenbach et al. (17) traced a septic tank effluent in shallow soil and found the removal to be less than 1 mg/L within 35 ft of horizontal transport.

6. RECOVERY OF EUTROPHIC LAKES

The best way to prolong the life of a lake is to control the nutrient inputs to the lake before it progresses through the mesotrophic state to the eutrophic state. This is sometimes difficult or even impossible. If upon study of a lake recovery is considered possible, numerous methods are available (18–20).

6.1. *Aeration*

Several variations of aeration are available to prevent the hypolimnion from becoming anaerobic. This will tie up the phosphorus in an insoluble form and keep the surface of the bottom deposits aerobic to prevent resolubilization of the phosphorus. Aeration is generally more applicable to small lakes. The pressure to pump air to the bottom of a deep lake requires special equipment.

When air is used, the system is designed to create a circulation within the lake, so that anaerobic hypolimnetic water is brought to the surface where natural reaeration occurs. While some reaeration results from the addition of the air, the surface aeration is responsible for most of the reaeration. More than one air system may need to be placed in a lake depending upon the shape of the lake. A disadvantage of the complete circulation system is that the thermocline is destroyed and the lake becomes isothermal from top to bottom at a mean temperature. Air systems must be turned on before the hypolimnion becomes anaerobic. These systems are relatively inexpensive.

A modification of the plain aeration system is a hypolimnetic aeration system. This consists of two concentric vertical tubes normally placed entirely in the hypolimnion. The top of the larger tube is sealed. Water from near the bottom of the lake enters the smaller inner tube where an aerator both lifts the water and aerates it at the same time. At the top of the inner tube the water overflows into the larger outer tube and is carried back downward. The aerated discharge from the larger tube is generally above the intake to minimize short circuiting back to the inlet tube. Since the entire device is placed in the cold hypolimnion, there is little impact on the temperature in the hypolimnion. Judicious placement of the intake and the discharge minimizes the impact on the lake bottom, and the system maintains the normal thermal stratification of the lake.

Oxygen has also been used instead of air. In this case, the oxygen provides the source of the reaeration. This usually requires onsite generation of the oxygen.

6.2. *Weed Harvesting*

A common situation in eutrophic lakes is having a shallow (<2 m deep) shoreline filled with both submerged and emergent growths. These are considered unsightly, interfere with boating, make swimming undesirable, and make fishing nearly impossible. At the same time, they provide a breeding ground for fish. Weed harvesting has been used under the guise of reducing the nutrient inputs to a lake. However, it has been estimated that they represent only in the order of 1% of the phosphorus content of the lake. They are usually harvested by a special boat that may not be able to reach the shallowest portion or certain bays in a lake. Here, weeds may be removed by rake or hand pulling while wading in the shallow water. Also, the weeds harvested must be removed from the shore or the nutrients will return to the lake as the weeds decompose. Harvesting the extensive Eurasian watermilfoil in Lake Wingra, WI, resulted in the reduction of only a small fraction of the lake's total nutrient pool (21). This is a relatively expensive treatment for the amount of nutrient reduction accomplished. It does remove the unsightly and undesirable weeds.

Related to weed harvesting is the use of herbicides to kill the weeds. This must be applied before the weeds reach full growth, and may have to be repeated during the growing season. Any dead weeds should be removed. The use of herbicides may have other undesirable environmental impacts, and they are not recommended if the water is used as a drinking water supply.

6.3. *Dredging*

The principle of dredging is to remove the organic sediments on the bottom of the lake that add to the nutrient supply when the hypolimnion becomes anaerobic (22, 23). This is an expensive technology, and is impractical for deep lakes. It also destroys the natural bottom of the lake. It is somewhat practical in artificial lakes or reservoirs where the water level can be drawn down (usually during winter) and surface equipment such as bulldozers can be used for the dredging. Any dredged material must be handled in an environmentally safe way. If any hazardous contaminants are shown to be present, this could be costly.

6.4. *Sediment Fixation*

Eutrophic lakes are synonymous with significant organic bottom deposits. When these become anaerobic they release their nutrients, specifically phosphorus. As the lake overturns, these nutrients are distributed throughout the lake, enabling more biological growth, which ultimately dies and settles to the bottom. Instead of trying to remove these sediments, chemicals may be added to more permanently precipitate the phosphorus. Aluminum salts have been found to be most effective since the aluminum phosphate remains insoluble so long as the surface of the sediments, in contact with aerobic water, remains aerobic (24, 25). Iron salts are effective in precipitating phosphates, but in the deep anaerobic sediments, the iron combines with reduced sulfur to form ferrous sulfide that is more insoluble than the iron phosphate, thus releasing the phosphate back into solution. Calcium salts are also capable of forming precipitates of calcium phosphate; however, their high alkalinity may undesirably raise the pH of the water. This may be desirable in acid lakes. Thus, aluminum salts have been found to be most effective in tying up the phosphate permanently in the sediments. As more organic material settles to the bottom, reapplication may be necessary in future years. This becomes extremely expensive for large lakes.

One difficulty in binding the sediment phosphate is establishing adequate contact. The alum must be spread fairly uniformly over the bottom to be effective. This is usually achieved by the use of boats crisscrossing the lake. A novel system was set up in a sewage oxidation pond in California (26). A mechanical mixer was installed in the middle of the pond, providing both mixing and aeration. Alum was applied at the mixer, which was solar powered. This eliminated a long power cord. The alum combined with both the sediment phosphorus and the soluble or suspended phosphorus in the pond, settling to the bottom. Excessive biological growth was eliminated, and the upper liquid layer met the phosphorus discharge limits to the receiving water.

7. HYPOLIMNETIC PHOSPHORUS REMOVAL BY DAF

A different approach is to remove the excess phosphorus from the anaerobic hypolimnion. Here, the phosphorus level may be high enough to be removed by conventional precipitation by aluminum, iron, or calcium salts. A flocculation/filtration system located on the shore could accomplish this. Successful use of such a program at three lakes in Germany has been reported (27). Further, a DAF system could be installed at the lake shore without the cost and obstruction of a conventional sedimentation basin.

A preliminary study for phosphate removal using DAF was conducted by Kittler (28) using water from eutrophic Laurel Lake in Massachusetts. Samples were taken during the high algae period of summer and again near the end of the algae growth period. Adding 40 mg/L ferric chloride and subjecting it to DAF with sand filtration showed the removals of 96–98% of phosphate during these periods (Tables 13.1 and 13.2) with no iron residual.

This was used to set up a pilot study for the removal of hypolimnetic phosphorus in Devil’s Lake, Wisconsin. This lake was of concern to the Wisconsin Department of Natural

Table 13.1
Results of Laurel Lake bench scale DAF studies – summer (28)

Parameter	Units	Raw influent	DAF/filtration effluent	Removal efficiency
Temperature	°C	16		
pH	Unit	7.3	7.1	
Turbidity	NTU	7.9	0.7	91%
Color	PCU	48	<1	99%
Iron, Fe	mg/L			
PO_4^{3-}	mg/L	0.72	0.03	96%

Table 13.2
Results of Laurel Lake bench scale DAF studies – late fall (28)

Parameter	Units	Raw influent	DAF/filtration effluent	Removal efficiency
Temperature	°C	8		
pH	Unit	7.0	7.0	
Turbidity	NTU	17	0.3	99%
Color	PCU	132	3	98%
Iron, Fe	mg/L	0.61	0.47	[a]
PO_4^{3-}	mg/L	1.16	0.02	98%

[a] Iron residual after DAF is 23% below *influent* concentration.

Resources (WDNR) due to summer algae blooms attributed to high accumulations of phosphorus (29). In 1991, the WDNR began evaluating whether hypolimnetic withdrawal and phosphorus removal would reduce sediment phosphorus concentrations with concomitant lower sediment phosphorus release during anaerobic hypolimnion periods.

Devils Lake is surrounded by ancient bluffs in the east, west, and south (30). The preglacial Wisconsin River flowed through a gap between these bluffs in the South Range of the Baraboo Hills. Devils Lake was formed at the end of the last ice age by terminal moraines deposited at the north and the southeast ends of the gap, diverting the Wisconsin River to the east around the Baraboo Hills.

Figure 13.5 shows the depth profile of the lake (29). Its surface area is 149 ha and its maximum depth is 14.3 m. Its mean depth averages about 9.3 m. The east and west shorelines between the bluffs are steep, while the littoral zones of the lake are mostly at the north and south ends of the lake. The watershed area is relatively small, 6.86 km^2 and the ratio of watershed to lake surface area is only 4.6. Most of the watershed is forested (29). There is only one small inlet that drains through a small wetland, and no outlet. The lake water level is maintained by fluctuations in ground water level and the balance of precipitation and evapotranspiration (29).

WDNR measured iron-bound phosphorus concentrations in profundal sediments around the lake both before and after hypolimnetic anoxia occurred in order to estimate the amount of phosphorus released into the overlying water during each season. Similar long-term laboratory column studies were conducted to support those results. The U.S. Geological Survey (USGS) also studied lake level and water budgets to model the impact of the removal of water from the hypolimnion. Although a temperature-depth profile of the lake was not available, data from the phosphorus concentrations in Table 13.3 indicate that the thermocline was located at about 13 m depth on September 20, 1996. This indicates that the hypolimnion existed in only approximately 1.3 m of the bottom of the lake. It is likely that some lake cooling had occurred before September 20, and that during the warmer summer period the thermocline was higher.

A pilot DAF system with sand filtration was set up on the shore of Devils Lake (Fig. 13.6) and operated from September 25, 1996 through October 3, 1996 (28). A 150 hp pump brought

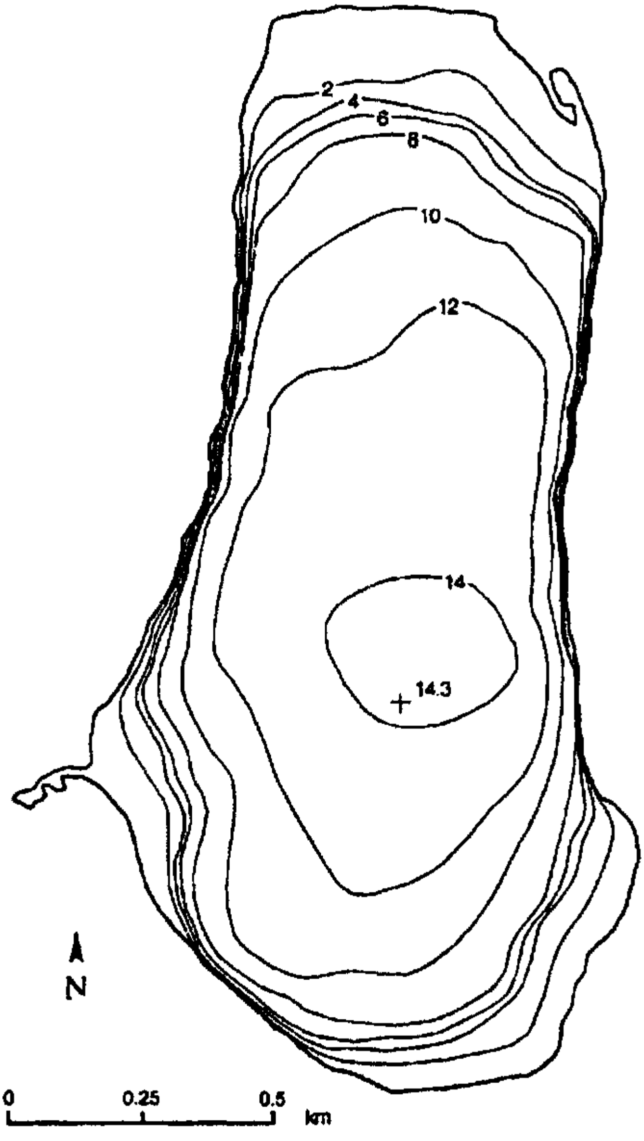

Fig. 13.5. Depth profile of Devils Lake, WI.

the hypolimnetic water to the treatment plant by means of an approximately 0.5 mile pipe that terminated approximately 14.5 m deep in the lake. The vertical water intake was covered with a screen mesh to keep out bottom debris. Treated water was returned to the surface of the lake.

The coagulants used were alum, aluminum chlorohydrate (ACH), and ferric chloride, with Percol added as a coagulant aid to all tests. Each coagulant was studied individually. Dosages were varied to provide a range of results that would indicate an optimum dose. Alum dosages varied between 13.2 and 49.5 mg/L, ferric chlorides varied between 5 and 50 mg/L, and ACH

Table 13.3
Profile of Devils Lake – September 20, 1966 (29)

Depth (m)	pH (unit)	TP (mg/L)	Fe (mg/L)
0 (surface)	7.9	0.007	–
4	–	0.007	–
10.3	–	0.013	–
11.3	–	0.018	0.09
12.3	–	0.021	0.13
12.8	–	0.077	0.84
13.3	–	0.216	2.6
13.8	6.9	0.408	3.9
14.1 (0.5 m off bottom)	–	0.432	4.1

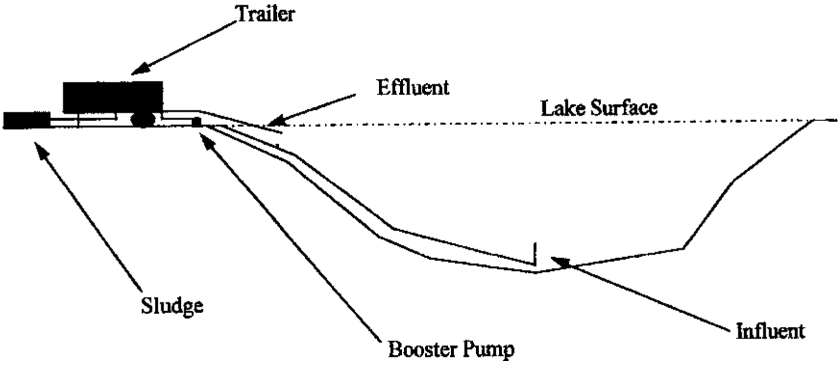

Fig. 13.6. Pilot plant setup for removal of phosphate from the hypolimnion of Devils Lake by DAF.

varied between 6.6 and 23 mg/L. The Percol dosages varied between 0 and 0.7 mg/L. Flows through the pilot plant were varied between 35 and 60 gpm.

The results of the 9-day operation of the pilot plant are shown in Table 13.4. Figures 13.7–13.9 depict the results for the use of ferric chloride, ACH, and alum, respectively. It may be seen that effective phosphorus removal required a minimum of 40 mg/L of ferric chloride. Doses as low as 7 mg/L ACH resulted in effective phosphorus removal. An alum dose of 25 mg/L or more is needed to achieve effective phosphorus removal. There did not seem to be any correlation of flow rate with treatment efficiency at the flow rates studied. Considering that flocculation is slower in the cold hypolimnion waters, this represents satisfactory operation for phosphorus removal.

Based upon WDNR's Table 13.1, the depth of the thermocline on September 20 was estimated to be at 13 m. Thus, at this time the volume of water in the hypolimnion was relatively small. However, the results of the phosphorus content of the inlet to the treatment

Table 13.4
Results of DAF pilot studies of phosphate removal from Devils Lake (28)

Chemical addition (mg/L)	Date (month/day/year)	Influent TP (mg/L)	Effluent TP (mg/L)	Flow rate (gpm)	Percent removal (%)
49.5 Alum	09/25/96	0.496	<0.007	40	99
47.6 Alum	09/25/96	–	<0.007	40	99
23.0 ACH	09/25/96	–	<0.007	40	99
20.8 Ferric	09/26/96	0.495	0.036	35	93
13.2 Ferric	09/26/96	–	0.045	35	93
19.8 Ferric	09/26/96	–	0.058	30	88
15.8 Ferric	09/26/96	–	0.204	50	59
5.0 Ferric	09/27/96	0.436	0.130	35	70
9.4 Ferric	09/27/96	–	0.222	35	49
10.2 Ferric	09/27/96	–	0.326	52	25
32 Ferric	09/27/96	0.411	0.096	45	77
29 Ferric	09/27/96	–	0.082	50	80
26.4 Alum	09/28/96	0.492	0.007	45	99
17.6 Alum	09/28/96	–	0.016	45	97
13.2 Alum	09/28/96	–	0.013	45	97
14.4 Alum	09/30/96	0.575	0.087	55	83
22.8 Alum	09/30/96	–	0.019	55	96
20.4 Alum	09/30/96	–	0.022	65	96
6.6 ACH	10/01/96	0.588	<0.007	60	98
8.8 ACH	10/01/96	–	0.008	60	98
7.5 ACH	10/01/96	–	0.011	55	98
35 Ferric	10/03/96	–	0.028	55	95
50 Ferric	10/03/96	–	<0.007	55	99
40 Ferric	10/03/96	–	<0.007	55	99
40 Ferric	10/03/96	0.516	<0.007	55	99
38.1 Ferric	10/03/96	–	<0.007	45	99

Alum aluminum sulfate, *Ferric* ferric chloride, *ACH* aluminum chlorohydrate.

system showed that hypolimnetic water was consistently used during this study. From the contour map of the lake (Fig. 13.5), the volume of the lake at its normal level would be 13,641 million m^3 (481,660 million ft^3 or 3,602,817 MG). The volume below 13 m depth was only 83,040 MG. Nevertheless, at an average pumping rate of the treatment system of 50 gpm, it would take 1,153 days to deplete the volume in the hypolimnion. Thus, it was considered that the water removed by the pilot study had minimal impact on the available water in the hypolimnion.

An estimate was made of the relative costs of the coagulants studied. Based on the cost and the concentration needed, the following comparison was made:

Coagulant	Cost, cents per 1,000 gal
Aluminum sulfate	0.78
Aluminum chlorohydrate	2.9
Ferric chloride	16.6

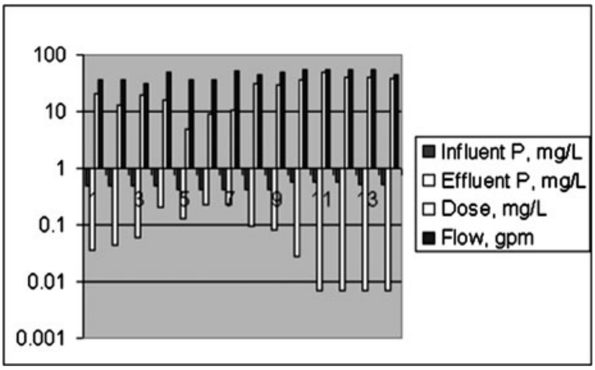

Fig. 13.7. Results of DAF pilot plant study for removal of phosphorus from the hypolimnion of Devils Lake using ferric chloride.

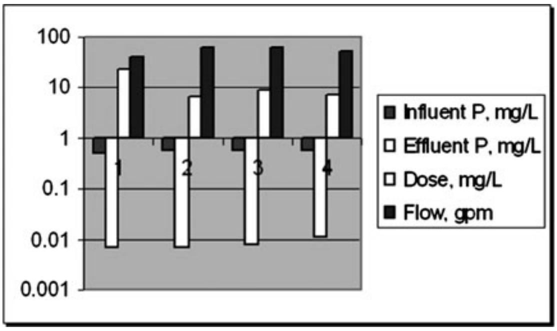

Fig. 13.8. Results of DAF pilot plant study for removal of phosphorus from the hypolimnion of Devils Lake using aluminum chlorohydrate (ACH).

An advantage of using ACH is that it does not result in any aluminum residual. Aluminum is toxic to some fish. Ferric chloride is not recommended due to its high cost and its potential to leave a residual color.

In order to apply the technique of phosphate removal from a hypolimnion, the first step would be to determine the volume of the hypolimnion. DAF/filtration systems of the type used in this study are available up to 13,000 gpm. Knowing the existing phosphorus concentration and the treated effluent concentration, a calculation can be made of how

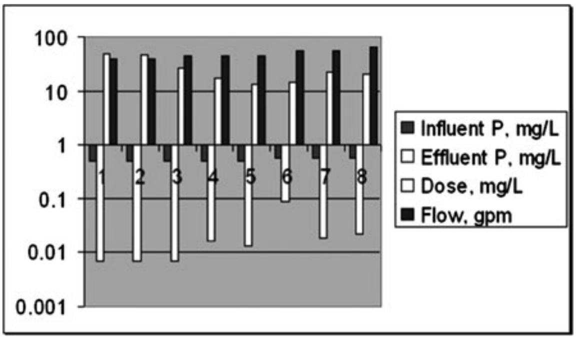

Fig. 13.9. Results of DAF pilot plant study for removal of phosphorus from the hypolimnion of Devils Lake using alum.

much volume of water would have to be treated to bring the phosphorus concentration down to an acceptable level. This may require several years of operation. However, if the lower nutrient level reduces the biological growth to a level where the hypolimnion may remain aerobic, there will be less release of phosphorus from the benthic deposits. A further consideration is that DAF involves aerating the water. If the effluent is discharged to the hypolimnion, it may provide sufficient additional oxygen to maintain aerobic conditions. This should enter into the calculation and influence the final decision to utilize DAF/filtration to control lake eutrophication.

8. CASE HISTORIES

8.1. Lake Brazos, Waco, TX

On the Brazos River, a few hundred yards downstream from the La Salle Avenue Bridge lies the Low Water Dam or more recently, the Lake Brazos Dam. About 40 years ago, city leaders decided that a dam below Waco would significantly widen the river and stabilize the river level. These improvements would enhance the natural beauty of the Brazos River through Waco. Additionally, the dam would create an impoundment from which up to 5,600 acre-ft of water can be withdrawn annually for municipal purposes (31).

Since the original dam was constructed, there have been many new developments. McLennan Community College has built the Bosque River Stage and Amphitheater. Baylor University has developed all along the eastern edge near the river, including a new law school, natural history museum, and a science building. These improvements along with a world-class athletic complex have been built immediately adjacent to the Brazos River. In addition, Baylor operates a marina on the Brazos River to facilitate sailing and canoeing opportunities. Other colleges from Colorado and Kansas routinely travel to Waco for early spring rowing practices.

The City of Waco has also made many improvements including; miles of riverwalk and various parkway improvements that include landscaping, lighting, and a boat dock in

Cameron Park. Recent improvements include the Texas Sports Hall of Fame and upgrades to the Texas Ranger Museum. There have also been many private developments such as the Brazos Queen (dining boat), the Spirit of the Rivers paddleboat, Lake Brazos Steakhouse, Dock's Restaurant and kayaking. Even with the enormous amount of improvements, the unmet potential remains tremendous.

With so much focus and activity along the Brazos River, there is a tremendous need to ensure a reliable, constant-level town lake. The existing dam was completed in 1970. The structure, which originally consisted of two drum gates, has quite a history for poor or nonperformance. The original design, despite several modifications, did not function as intended for a reliable town lake. In 1985, hydraulic cylinders were attached to the underside of the massive gates (117 ft each) to provide a positive control mechanism for maintaining the level of Lake Brazos. This modification, while expensive to maintain, has restored quite a bit of reliability. Through decades of modifications and expensive maintenance, it was time to replace the structure with a new dam, which offered reliability while requiring less maintenance. The new dam was a concrete labyrinth weir and was scheduled for completion in 2007 during the fall.

The City of Waco remains committed to providing a safe and plentiful supply of water for its citizens. Work has begun on 80 million USD in improvements to the water treatment system. The first phase has been completed with the completion of construction on the 42″ water distribution line and upgrades at the Mount Carmel Water Treatment Plant. This will increase the treatment plant capacity from 45 to 66 MGD. Similar improvements will take place at the Riverside Plant, and when the entire project is completed, the City of Waco will be able to treat a maximum of 130 MGD of water.

The City of Waco is also making the transition to a new DAF treatment process. This will address issues with the taste and odor problems caused by by-products of algae in the North Bosque River Watershed. The second phase of the Water Quality and Quantity project is designed to dramatically improve the taste of the finished water. In order to complete this task, the City of Waco is constructing a new clarification facility, featuring DAF for the removal of algae and other suspended particles from the raw water supply. DAF is particularly effective on waters with significant amounts of lightweight particles such as algae. Algae are the primary source of taste and odor causing compounds in Texas waters.

DAF works by attaching air bubbles to particles suspended in the raw water and floating them to the surface of a tank for removal. The process includes flocculation to bind particles suspended in the raw water into larger flocs that can more easily be removed; a saturator that entrains air into a side stream for injection into the process; an air nozzle header that releases extremely fine air bubbles that attach to the flocculated particles; a skimmer that removes the suspended particles after they float to the surface of the basin; and effluent laterals that collect the clarified water off the bottom of the basin.

The odor causing compounds MIB and Geosmin found inside the algae cells are released into the water when the algae are killed or damaged. Removing the algae within the lake before water intake pumping would lessen this problem. This could be accomplished by means of a DAF system mounted on a barge operated within the lake. A suggested design was

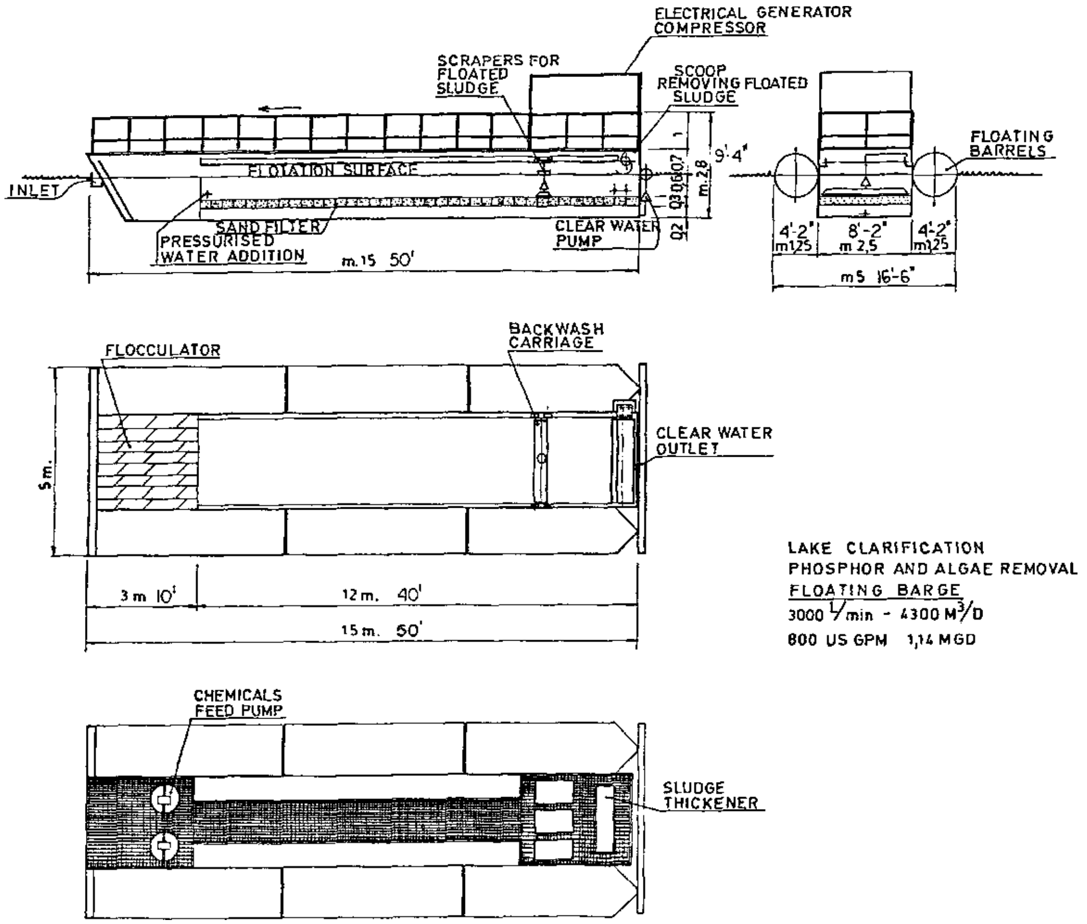

Fig. 13.10. Floating barge for algae removal from lake water.

prepared by Krofta and Wang (Fig. 13.10) (32). By removing the algae within the lake before it has a chance to be killed or damaged during pumping to the treatment plant or in the water treatment process itself, water quality will be significantly improved. The reduced levels of MIB and Geosmin in the raw water once the algae are removed will allow any residual taste and odor compounds to be more easily removed in later stages of the treatment process. This possible system was never constructed nor further studied.

8.2. Water Treatment from Lake Roine, Tampere, Finland

In the 1960s, the City of Tampere, Finland began drawing water from Lake Roine when the quality of water from its original lake source deteriorated. A horizontal sedimentation basin was constructed in the early 1970s, and a laminar flotation process was implemented in 1989.

Table 13.5
System performance (Lake Roine water temperature range = 0.1–17°C) (33)

Parameter	Raw influent	Clarified effluent	Filter effluent
Turbidity, NTU	0.40–0.60	0.15–0.90	0.05–0.20
Dissolved organic carbon (DOC), mg/L	4.5–5.9	<2.0	
pH, unit	6.2–7.5	5.0–7.0	

Activated carbon replaced sand filtration in 1996, but the City was still not satisfied with its drinking water quality (33).

In 1997, a pilot DAF (AquaDAF) system was retrofitted in one of the conventional sedimentation basin flocculators. The DAF pilot demonstrated much higher flotation rise rates than those previously achieved with the laminar DAF units. In 2000, retrofitting of all laminar DAF units was completed. Today, the plant uses only the AquaDAF for clarification. The system was retrofitted in the original basins and sludge channels. The new structure is constructed entirely of wood.

The AquaDAF™ system utilizes hydraulic flocculation underneath the flotation area. Two very small unpacked saturators operate at a design recycle rate of 10%. The only submerged moving part is the effluent weir used for desludging. Water quality and system performance are shown in Table 13.5.

8.3. Restoration of Lake Apopka, FL

Environmental problems led the governor of Florida on April 4, 1967, to appoint a technical committee to evaluate the restoration of Lake Apopka (34). Sixteen agencies, including the Federal Water Pollution Control Administration (FWPCA), agreed to participate in the project. An FWPCA study begun in 1968 revealed that 90% of the bottom was covered with unconsolidated bottom sediment (muck) averaging 1.5 m thick. These sediments and peat sediments found along the shoreline were anaerobic and provided limited suitable substrate for desirable biota. Only 5% of the bottom was covered with sand, clay, and shell. The top meter of lake sediment contained 225 million kg of total nitrogen and 2–4 million kg of total phosphorus. Chemical oxygen demand (COD) in the muck samples (dry weight) was 1,100 mg/g. The FWPCA also made a crude nutrient budget and emphasized that restoration of the lake must include reduction of nutrient input. Although direct rainfall on the lake and high nutrient input from citrus grove runoff were important, the principal controls on inputs emphasized by the FWPCA were point sources such as agricultural runoff pumped directly into the lake from muck farms, and municipal and industrial wastes. In addition to the control of external nutrient sources, several solutions for improving lake water quality are listed below. These include (35) the following:

1. Dredging to remove nutrient-rich unconsolidated bottom sediments to increase lake depth and reduce internal nutrient recycling

2. Using lake drawdown to expose and subsequently consolidate large areas of lake bottom by oxidation and compaction
3. Adding an inert sealing material to stabilize bottom sediments
4. Engaging in hydroponic farming to remove dissolved nutrients
5. Harvesting to remove algae by flotation, filtration, precipitation (not within the lake), or centrifugation (recovered algae could be used as a feed supplement)
6. Harvesting fish to remove nutrients "on a large scale." Harvested fish could be used as a protein supplement.

The governor of Florida assigned complete responsibility for a 1970 restoration of Lake Apopka to the Florida Air and Water Pollution Control Commission. This agency decided to proceed with the lake drawdown approach by allowing gravity drainage to lower the lake level to 60 cm beginning in December 1970. The effect of this lowering was to be evaluated, and the lake would then be drained further by pumping to 25% of its original area. This final drawdown would occur in the spring of 1971. It was anticipated that two beneficial effects would result from the drawdown:

1. Nutrient recycling would be reduced or eliminated from dried, compacted sediments.
2. Suitable substrate for rooted aquatic vegetation would also be a result.

This plan to lower the lake about 7 ft below normal water level was not implemented, however, because of the projected cost (20 million USD) and because of concern about environmental and economic impacts (36). For example, the loss of lake volume would minimize the freeze protection citrus growers received from the large heat capacity of the lake.

In the 1970s, additional studies were conducted on water quality problems and on restoration of Lake Apopka (37). Studies of techniques that might be used to restore the lake have continued. Biomanipulation of algal standing crops with gizzard shad may actually increase standing crops of undesirable algae. A multimillion dollar feasibility study on growing and harvesting water hyacinths to remove nutrients from the lake was launched (38). The field test of this project in Lake Apopka was abandoned when the enclosure that was to have been used for the experiment was destroyed by water movements in the lake.

The Saint Johns Water Management District began a feasibility study on using marsh restoration to improve water quality in the lake (39). The water management district purchased muck farmland that will be flooded to restore the wetland by using the wetland as a filter to remove nutrients. The hydrology of the wetland will be manipulated, so that highly nutrient-enriched water will flow from the lake into the wetland and nutrient-depleted water from the wetland will be directed back to the lake. If successful, this project will result in both a restored wetland and a restored lake.

There seem to be two divergent views about Lake Apopka. One group contends that the lake can be restored. This viewpoint is supported by the need to reduce nutrient inputs to prevent accelerated eutrophication. Schneider and Little (35) commented that the history of Lake Apopka "is not atypical" because other lakes in Florida and reservoirs all over the South were being subjected to similar attacks. They stated that the lake could be restored, but only with great expense and difficult decisions (e.g., the extent to which a ten million USD plus marginal muck farming operation could expend money for nutrient removal). "The technical capabilities to prevent accelerated eutrophication are and have been available for some time. The planning and foresight needed to prevent the early demise of our lakes, however, has come into being only lately. Today, we must consider the full ecological impact of all our resource development activities if we are to eliminate the Lake Apopka syndrome from our aquatic environment," they emphasized.

At the other extreme is the viewpoint that restoration should not be attempted because it will meet with failure or it is too expensive. This viewpoint can be supported to a certain extent with results of studies on Lake Tohopekaliga (Lake Toho), Florida. A number of restoration measures have been instituted on Lake Toho since 1971, with little evidence of improvement in water quality (39). In this lake, nutrient inputs have been reduced by sewage treatment and by storm water detention and filtration. In addition, drawdown has been used as a restoration measure. What is not known is whether water quality would have been degraded even more if remedial measures had not been instituted. Dierberg et al. (40) point out that evaluation of restoration practices in Florida lakes has been hampered by the lack of long-term data and the consequent limitation on the use of robust statistical approaches in evaluating effectiveness.

8.4. *Water Treatment from Lake DeForest in Clarkstown, NY*

United Water New York draws about 80% of its water supply from wells throughout Rockland County. The remaining 20% is supplied from a surface source, Lake DeForest in Clarkstown, NY (41).

The process of lake water treatment begins by pumping the water from the Lake DeForest Reservoir into the treatment plant. During the pumping process, chemical is added to oxidize inorganic material and the water passes through screens that remove large objects prior to entering the pumps. The water then proceeds to the new DAF system. A coagulant (aluminum sulfate) is added as the water enters the DAF system. This allows smaller particles to form larger flocs, getting the water ready to enter the final step of the DAF process. In this step, millions of micro bubbles are added to the water floating the flocs to the top. The float (residuals) is removed and the clean water proceeds to the filters. It is during this step that chlorine is added. Chlorine destroys bacteria and viruses in the water. The water passes through the filters (layers of coal, sand, and gravel) to remove the smallest remaining particles. Next, the water receives another small dose of chlorine to be sure that the water remains pure and safe. Finally, corrosion control chemicals are added. This step helps prevent corrosion of the water pipes and plumbing. It also reduces the chance of lead dissolving in the water from plumbing.

8.5. *Water Treatment from Lake Whitney, Hamden, CT*

Lake Whitney is a lake in Hamden, Connecticut that is a part of the Mill River. The lake was a water source for the New Haven, Connecticut metro area, until it was discontinued in the early 1990s. Now, with a new Lake Whitney Water Treatment Plant rated for up to 15 million gallons a day (15 MGD), Lake Whitney has been reconnected, restored, and utilized as a reserve water source for the Regional Water Authority. The plant treats surface water from Lake Whitney. The treatment train consists of DAF, ozonation, and granulated activated carbon filtration, along with appropriate chemical addition facilities. Residual solids from the treatment process will be dewatered in an onsite centrifuge (42, 43).

9. SUMMARY

A major factor in the death of a lake is eutrophication, which is the result of increased biological growth within the lake. Biological life may be controlled by limiting the nutrients in the lake. Phosphorus is generally the nutrient that is most easily and permanently removed. There are many ways to control the nutrients entering a lake, to control the existing nutrients within a lake, and to reduce the existing nutrients within a lake, and fully utilize the lake water for recreation or domestic water supply (39–44). Each lake must be studied individually to determine the best method to control eutrophication. DAF is one method that should be considered for removing existing excessive phosphorus nutrients and algae in a lake. This will be effective in extending the life of a lake (28–29).

REFERENCES

1. Sawyer CN (1966) Basic concepts of eutrophication. J Water Pollut Control Fed 38(5):737
2. Sakamoto M (1966) Arch Hydrobiol 62:1
3. Vollenweider RA (1968) The scientific basis of lake and stream eutrophication, with particular reference to phosphorus and nitrogen as factors in eutrophication. Technical Report to OECD, Paris, DAS/CSI/68.27, p 1
4. Vollenweider RA, Dillon PJ (1974) The application of the phosphorus loading concept to eutrophication research. Canada Centre for Inland Waters, NRCC 13690, Burlington, ON, Canada
5. Phelps EB (1944) Stream sanitation. Wiley, New York
6. Wilson TE (2006) Upgrades to BNR: optional approaches, Earth Tech. Presented at 78th NY water environment association conference. Alexandria, VA
7. Eberhardt TE (1997) Aluminum dose calculation. Sweetwater Technology, Aitkin, MN
8. Tabor CW (2006) Comparison of high rate clarifiers in tertiary phosphate removal applications. Presented at 78th NY water environment association conference. Stantec Consulting, Richmond, VA
9. Patoczka J (2006) Reducing phosphorus to 0.1 mg/L with existing facilities at the East Windsor Plant. Presented at 78th NY water environment association conference. Hatch Mott MacDonald, Millburn, NJ
10. FHA (2006) Stormwater best management practices in an ultra-urban setting: selection and monitoring. Federal Highway Administration, Washington, DC
11. Harper HH (1990) Long-term performance evaluation of the alum stormwater treatment system at Lake Ella. Final Report for FDER Project WM339, Florida
12. Pitt RF (1996) The control of toxicants at critical source areas. Proceedings of effects of watershed development and management on aquatic ecosystems symposium. Engineering Foundation, Snowbird, UT
13. Allard LA, Graham W, Platz W, Carr R, Wheeler J (1996) The storm treat system used as a storm water best management practice. Proceedings of watershed'96, a national conference on watershed management. Tetra Tech, Baltimore, MD
14. Claytor RA, Schueler TR (1996) Design of stormwater filtering systems. The Center for Watershed Protection, Silver Spring, MD

15. Sheepdrove Organic Farm – Sustainable Water Management Project (2008) Winner of national farmers union. UK. www.sheepdrove.com/206.htm
16. Aulenbach DB (1978) Chemical interactions in a rapid infiltration system accomplishing tertiary treatment of wastewaters. In: Rubin AJ (ed) Chemistry of wastewater technology. Ann Arbor Science Publishers, Ann Arbor, MI, pp 227–244
17. Aulenbach DB, Clesceri NL, LaDuc M, Peachy B, Sliwinski R (1982) Monitoring a septic tank Leaching field. In: Schadler MH (ed) The Lake George ecosystem, vol II. Lake George Association, New York, pp 142–149
18. US EPA (1980) Our nation's lakes. US Environmental Protection Agency, Washington, DC, EPA 440/5-80-009
19. NYS Museum (1986) Understanding New York's lakes. New York State Museum, Education Leaflet 26, Albany, NY
20. Barko JW, Adams MS, Clesceri NL (1986) Environmental factors and their consideration in the management of submersed aquatic vegetation: a review. J Aquat Plant Manag 24:1
21. Carpenter SR, Adams MS (1977) The macrophyte tissue nutrient pool of a hardwater eutrophic lake: Implications for macrophyte harvesting. Aquat Bot 3:239
22. US EPA (1980) Restoration of Lake Temescal. U.S. Environmental Protection Agency, Washington, DC, EPA-625/2–80-026
23. George CJ, Tobiessen PL, Snow D, Jewell TK (1982) The Monitoring of the restorational dredging of Collins Lake. U.S. Environmental Protection Agency, Scotia, NY, EPA-600/S3-81-017
24. US EPA (1980) Restoration of Medical Lake. US Environmental Protection Agency, Washington, DC, EPA-625/2-80-025
25. US EPA (1980) Lake restoration in Cobbossee watershed. US Environmental Protection Agency, Washington, DC. EPA-625/2-80-027
26. Myers J, Christensen M, Bleth J, Tormaschy W (2005) Evaluation of phosphorus reduction in wastewater ponds by injecting aluminum sulfate (alum) into a high flow solar powered circulator. Water Environ Technol 17(12):99
27. Clasen J, Bernhardt H (1987) Chemical methods of p-elimination in the tributaries of reservoirs and lakes. Schweiz Z Hydrol 49:249
28. Kittler RDI (1997) The use of dissolved air flotation to reduce the internal phosphorus supplies in utrophic Devils Lake, WI, Masters Thesis. Lenox Institute of Water Technology, Lenox, MA
29. WDNR (2010). Removing phosphorus and mercury from Devil's Lake State Park, WI. Wisconsin Department of Natural Resources, Madison, Wisconsin, USA. http://www.dnr.state.wi.us
30. Lillie RA, Manson JW (1986) Historical changes in water quality and biota of Devils Lake, Sauk County, 1866–1985. Trans Wis Acad Sci Arts Lett 74:81
31. City of Waco (2010) Lake Brazos Dam. City of Waco Water Utility Services. Waco, TX, http://www.wacowater.com/news.html
32. Krofta M, Wang LK (2000) Flotation engineering, 1st edn. Lenox Institute of Water Technology, Lenox, MA, Technical manual no. Lenox1-06-2000/368
33. Ondeo-Degremont, Inc. (2001) Water treatment case study, Rusko Water treatment works. Tampere, Finland, Richmond, VA, www.onedo-degremont-usa.com
34. CGER (1992) Restoration of aquatic ecosystems: science, technology, and public policy, commission on geosciences, environment and resources (CGER). http://www.nap.edu/books/0309045347/html/395.html

35. Schneider RF, Little JA (1973) Rise and fall of Lake Apopka: a case study in reservoir mismanagement. In: Ackerman C (ed) Man-Made Lakes: their problems and environmental effects. American Geophysical Union, Washington, DC, pp 690–694
36. Lowe EF, Adams J, Bateman J, Fell C, Graetz D, Hulbert J, Ingram W, Johnson W, Muller P, Nall L, Reddy R, Snyder L, Williams V (1985) Proposed scope of work for the Lake Apopka pilot project. report, p 55
37. Brezonik PL, Pollman CD, Crisman TC, Allenson JN, Fox JL (1978) Limnological and water quality studies on Lake Apopka and Downstream Lakes in the upper Oklawaha River Basin, historical trends and current status. Report to Florida Department of Environmental Regulation, Env-07–78–01, Department of environmental engineering science. University of Florida, Gainesville, FL, p 283
38. Amasek, Inc. (1985) A practical concept for the restoration of Lake Apopka. Report by Amasek, Inc., Cocoa, FL, p 38
39. Lowe EF, Stites DL, Battoe LE (1989) Potential role of marsh creation in restoration of hypereutrophic lakes. In: Hammer DA (ed) Constructed wetlands for wastewater treatment: municipal, industrial and agricultural. Lewis Publishers, Chelsea, MI, pp 710–717
40. Dierberg FE, Williams VP, Schneider WH (1988) Evaluating water quality effects of lake management in Florida. Lake Reserv Manage 4:101–111
41. United Water (2010) Surface water treatment processes. Lake DeForest in Clarkstown, NY, http://www.unitedwater.com/uwny/wtrspply.htm
42. RSRI (2010) Lake Whitney water treatment plant, Hamden, CT. Robinson, Stafford & Rude, Inc., St Petersburg, FL, http://www.rsri.net/water-supply.html
43. Wang LK, Wang MHS, Suozzo T, Dixon RA, Wright TL, Sarraino S (2009) Chemical and biochemical technologies for environmental infrastructure sustainability. 2009 National Engineers Week Conference, Albany Marriott, Albany, NY, 5–6 Feb
44. Klapper H (2003) Technologies for lake restoration. J Limnol 62(Suppl 1):73–91

14

Jiminy Peak, Hancock, Massachusetts Wastewater Treatment Plant: The First RBC-Flotation-UV Wastewater Treatment Plant in the USA

Lawrence K. Wang, Donald B. Aulenbach, and James P. VanDyke

CONTENTS

Abstract An innovative 0.1-MGD (378 m^3 per day) tertiary biological–physicochemical wastewater treatment plant (WWTP) consisting of equalization, rotating biological contactors (RBCs), secondary clarification (using both dissolved air flotation and gravity sedimentation), tertiary sand filtration and ultraviolet disinfection has been installed at Hancock, MA, USA, for treating the domestic sewage generated from the four-season Jiminy Peak timeshare resort. The influent raw sewage is collected and equalized in an equalization tank, then biologically treated by two RBCs. One portion of the RBC effluent passes to an innovative dissolved air flotation–filtration (DAFF) clarifier to simulate a two-stage biological and physicochemical treatment by RBC-DAFF. For parallel comparison, the remaining portion of the RBC effluent passes to a secondary sedimentation clarifier (SSC) to simulate conventional wastewater treatment by RBC-SSC. Both the DAFF effluent and the SSC effluent are then combined and treated by a tertiary sand filter and two UV disinfection units. The final WWTP effluent (or UV effluent) is discharged to a subsurface leach field for final disposal. The innovative RBC-DAFF system generally met the secondary effluent discharge standards on BOD_5, TSS, total coliform bacteria, pH, and oil and grease. The conventional RBC-SSC system did not produce an effluent meeting secondary effluent discharge standards. The tertiary filter and UV units upgraded the quality of the plant effluent to the tertiary treatment

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level. Jiminy Peak WWTP is the first RBC-Flotation-UV plant built in use for domestic sewage treatment.

Key Words Domestic sewage • rotating biological contactor • dissolved air flotation • sedimentation • tertiary sand filtration • ultraviolet • first RBC-flotation-UV sewage treatment plant • biological–physicochemical treatment • leach field • Jiminy Peak Wastewater Treatment Plant • small system • Lenox Institute of Water Technology • Krofta Engineering Corporation.

1. INTRODUCTION

1.1. The First RBC-Flotation-UV-Leach Field Sewage Treatment Plant in US

Jiminy Peak, Inc., is a timeshare resort located at a ski resort in a remote area in Hancock, MA, USA. In order to operate it must have its own wastewater treatment system that meets the approval of the Massachusetts Department of Environmental Quality Engineering (DEQE). To achieve this they have installed a tertiary biological wastewater treatment system consisting of preliminary/primary treatment facilities, two rotating biological contactors (RBCs), a dissolved air flotation–filtration (DAFF) clarifier, a conventional secondary sedimentation clarifier (SSC), a tertiary sand filtration (TSF) unit, and two ultraviolet (UV) disinfection units. The DAFF and the SSC were installed to compare the results of the two systems and decide which would provide the most satisfactory treatment. The total average wastewater flow is approximately 0.1 MGD (375 cubic meters per day) (1, 2).

The total wastewater stream is collected and equalized in an equalization tank, and then biologically treated by two RBC units. These are piped to allow for use of a single unit, both units in parallel, or the combined units in series. Of the RBC effluent, 84% is directed to the DAFF clarifier for combined biological–physicochemical treatment, while the remaining 16% is directed to the SSC for secondary clarification in order to simulate a conventional RBC-SSC wastewater treatment plant (WWTP). This enables the parallel comparison of the two systems. Both the DAFF effluent and the SSC effluent are then combined and discharged to the subsequent tertiary sand filter and UV disinfection units for final polishing. The final WWTP effluent (or UV effluent) is discharged to a subsurface leach field for final disposal. Subsurface disposal was required to satisfy requirements where no surface stream is available to accept the effluent. Figure 14.1 shows the flow diagram of the entire Jiminy Peak WWTP. Figure 14.2 shows an RBC-clarification system. This can be used in conjunction with a primary clarifier that can be either a primary flotation clarifier or a primary sedimentation clarifier and with a secondary clarifier that can be a DAFF, an SSC, or simply a secondary flotation clarifier (dissolved air flotation or DAF) (3).

The DAFF package plant (Krofta SASF-8) was designed and manufactured by the Lenox Institute of Water Technology and Krofta Engineering Corporation, respectively, under the leadership of four licensed professional engineers, Milos Krofta, Lawrence K. Wang, Daniel Guss, and Donald B. Aulenbach. The Jiminy Peak WWTP was completed in 1985 and was the first RBC-Flotation-UV wastewater treatment plant in North America (1).

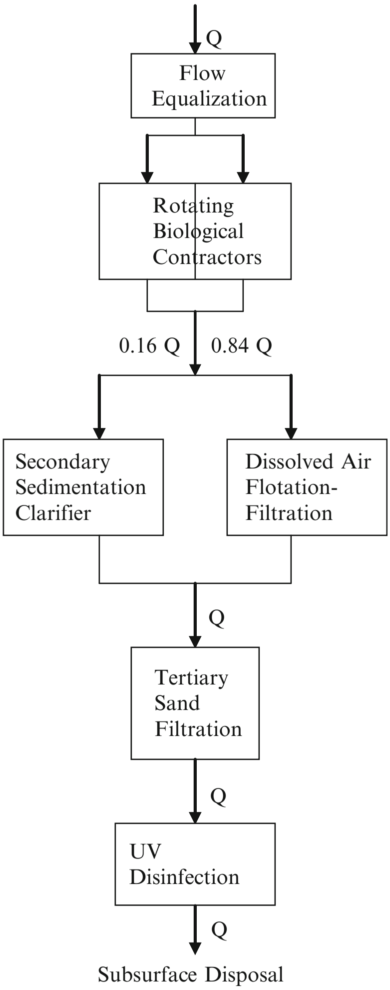


Fig. 14.1. Flow diagram of Jiminy Peak Wastewater Treatment Plant (1).

1.2. Wastewater Treatment Plant Effluent Limitations

The Massachusetts Clean Waters Act (M.G.L.c.21, sections 26–53) was amended by Chapter 246 of the Acts of 1973 to authorize the Massachusetts Department of Environmental Quality Engineering (DEQE), Division of Water Pollution Control, Boston, MA, to regulate domestic and industrial effluent discharges into all waters of the Commonwealth of Massachusetts, including ground water. The DEQE regulates discharges through the issuance of discharge permits that impose effluent discharge limitations on the amount of pollutants that may be discharged in the effluent, together with monitoring and reporting requirements and other conditions to insure adequate treatment of all liquid wastes prior to discharge. In 1984, the DEQE reviewed the application submitted by Jiminy Peak Inc. for a permit to discharge the treated effluent from the Jiminy Peak WWTP located off Brodie Mountain

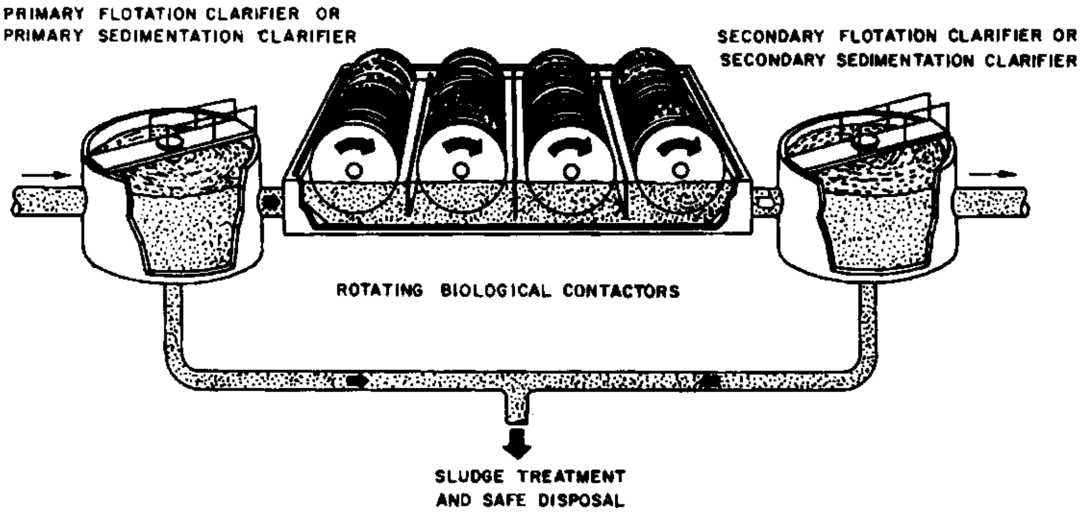


Fig. 14.2. Rotating biological contactor (Source: USEPA) (3).

Road, Hancock, MA, and subsequently developed the conditions contained in the Groundwater Discharge Permit No. 0-188.

More specifically, Jiminy Peak, Inc. (i.e., the permittee) was authorized to discharge the Jiminy Peak WWTP effluent into the ground water under the Permit No. 0-188, under the conditions that the characteristics of the Jiminy Peak WWTP effluent, within 1 month after start-up of the RBC-DAFF-UV facilities and continuing thereafter, shall not exceed the following values:

1. Flow discharge upper limitations = 375 m^3/day or 0.1 million gallons per day (MGD)
2. BOD_5 (5-day biochemical oxygen demand) discharge upper limitation = 30 mg/L
3. TSS (total suspended solids) discharge upper limitation = 30 mg/L
4. Settleable solids discharge upper limitation = 0.1 mL/L
5. TC (total coliform) discharge upper limitation = 1,000 organisms/100 mL
6. O&G (oil and grease) discharge upper limitation = 15.0 mg/L.

In addition, the pH of the Jiminy Peak WWTP effluent shall not be less than 6.5 or greater than 8.5 at any time. The discharge of the WWTP effluent shall not result in any demonstrable adverse effect on the ground water or violate any water quality standard that has been promulgated. The monthly average concentration of BOD_5 and total suspended solids in the discharge shall not exceed 15% of the monthly average concentrations of BOD_5 and total suspended solids in the influent to the Jiminy Peak WWTP. When the effluent discharged for a period of 90 consecutive days exceeds 80% of the permitted flow limitation, Jiminy Peak Inc. or its designated Consulting Engineer shall submit to the permitting authorities projected loadings and a program for maintaining satisfactory treatment levels consistent with the approved water quality management plans. The detailed WWTP design background information can be found from the literature (1–16).

1.3. RBC-Flotation-UV Plant Operation and Technology Verification

Director Lawrence K. Wang of the Lenox Institute of Water Technology (LIWT), which was formerly the Lenox Institute for Research Inc. (LIR,) was retained by Jiminy Peak Inc. as the Consulting Engineer-Operator to design, install and operate the plant and later to monitor the performance of the RBC-DAFF-UV system for a period of 1 year. The Jiminy Peak Secondary Treatment Plant was installed and operational in November 1985 (1). J. J. Johnson & Associates (Park City, UT) was also involved in the engineering design.

The secondary objective of this sponsored engineering research project was to compare the performance data of its RBC-DAFF effluent quality with that of its conventional RBC-SSC effluent quality, under the same wastewater flow conditions, for a period of at least six consecutive months.

1.4. Secondary and Tertiary Treatment Levels

Based on the operational and performance data generated during the period of November 1985 to April 1986, it was concluded that the RBC-DAFF system performed better than the conventional RBC-SSC system.

It was further concluded that the innovative RBC-DAFF system generally met the secondary effluent discharge standards on BOD, TSS, total coliform bacteria, pH, and oil and grease. The conventional RBC-SSC system did not produce an effluent that met the secondary effluent discharge standards. The tertiary sand filter and UV units further upgraded the quality of the Jiminy Peak WWTP effluent to meet the tertiary treatment standards.

2. PROCESS DESCRIPTION OF A TERTIARY BIOLOGICAL–PHYSICOCHEMICAL WASTEWATER TREATMENT PLANT

2.1. Equalization

Wastewater flows into treatment facilities are subject to diurnal and seasonal fluctuation in both quality and in quantity. Most waste treatment processes are sensitive to such changes. An equalization basin serves to balance these fluctuations to allow more uniform contact time in the treatment facility. This section addresses an equalization basin used only to equalize flow; however, the quality of the wastewater will also be equalized, thereby reducing variations in feed concentration and lessening any toxic shocks to some degree. In a small system, cleaning a toilet with chemicals can create a shock loading.

Equalization basins may be designed as either in-line or side-line units. In the in-line design, the basin receives the wastewater directly from the collection system, and the discharge from the basin through the treatment plant is kept essentially at a constant rate, usually by means of a pump. In the side-line design, flows in excess of the average are diverted to the equalization basin. When the plant flow falls below the average, wastewater is withdrawn from the basin to bring the flow back to the average value. Both types of basins must be sufficiently sized to hold the peak flows and designed to maintain a constant rate of flow to the treatment system.

Pumps may or may not be required to discharge into or out of the equalization basin, depending upon the available head. Where pumping is found necessary, the energy requirements will be based on total flow for in-line basins and on excess flow for side-line basins.

Aeration of the wastewater in the equalization basin is normally required for mixing and maintaining aerobic conditions for odor control.

The in-line equalization basin installed at Jiminy Peak WWTP is used to equalize the extremes of diurnal and wet weather flow fluctuations. The secondary benefits are equalization of quality and the potential for the protection from toxic upsets. Additional technical information on equalization basin design, applications, and operation can be found in the literature (4)

2.2. *Rotating Biological Contactor*

The RBC process is a fixed film biological reactor consisting of circular plastic media mounted on a horizontal shaft and partially submerged in a trough containing the wastewater. Common media forms are disc type made of Styrofoam, and a denser lattice type made of polyethylene. While wastewater flows through the trough, the media are slowly rotated, about 40% immersed, for contact with the wastewater. Biological slimes grow on the wetted media. These adsorb soluble organic matter from the wastewater as the disc dips into the wastewater trough. As the discs rotate, aerobic conditions prevail that break down the organic matter (BOD and COD) aerobically. Excess biomass on the media is stripped off by rotational shear forces and the stripped solids are maintained in suspension by the mixing action of the rotating media in the trough. Multiple staging of RBCs increases treatment efficiency and aids in achieving nitrification year round. A complete RBC system may consist of two or more parallel trains with each train consisting of multiple stages in series.

The RBC process has only been in use in the USA since 1969. Its use is growing due to its characteristic modular construction, low hydraulic head loss, and shallow excavation, which make it adaptable to new or existing treatment facilities. The process is suitable for treatment of domestic and compatible industrial wastewater amenable to aerobic biological treatment in conjunction with suitable pre and posttreatment. RBC can be used for nitrification, roughing, secondary treatment, and polishing. It is particularly tolerant of varying organic loading, as in small systems.

RBC can be vulnerable to climatic changes and low temperatures if not housed or covered. Performance may diminish significantly at temperatures below 55°F. Enclosed units can result in considerable wintertime condensation if heat is not added to the enclosure. High organic loadings can result in first-stage septicity and supplemental aeration in the trough may be required. Use of dense media for early stages can result in media clogging. Alkalinity deficit can result from nitrification; supplemental alkalinity source may be required.

The two RBC units installed at Jiminy Peak WWTP are housed, therefore are not vulnerable to climatic changes and low winter temperatures. Besides, the source of the wastewater is strictly domestic sewage that is amenable to aerobic biological treatment. Equalization is the RBC pretreatment, while SSC or DAFF clarifier, TSF, and ultraviolet disinfection (UV) constitute the posttreatment. Addition technical information on RBC can be found from the literature (1–3, 5).

2.3. Secondary Sedimentation Clarification

The purpose of secondary clarification is to separate the sloughed biosolids from the RBC effluent.

Circular secondary sedimentation clarifiers (SSCs) have been constructed with diameters ranging from 12 to 200 ft (3.7–61 m) and depths of 12–15 ft (3.7–4.6 m). The SSC installed at the Jiminy Peak WWTP is the smallest one (diameter = 12 ft) commercially available. There are two standard types (a) the center-feed and (b) the rim-feed. Both utilize a rotating mechanism to transport and remove the sludge from the bottom of the clarifier. Sludge removal mechanisms are of two types (a) those that scrape or plow the sludge to a center hopper similar to the types used in primary sedimentation tanks (6), and (b) those that remove the sludge directly from the tank bottom through suction orifices that sweep the entire bottom of the tank in each revolution. Variations in the type of suction removal of the sludge include (a) suction is maintained by reduced static head on the individual draw-off pipes and (b) suction is provided through a manifold either hydrostatically or by pumping. Common circular SSC design may locate the effluent overflow weir either near the center of the tank or around the perimeter of the tank. Surface skimming facilities are required on all federally funded projects.

Although the design of a SSC is similar to primary sedimentation clarifiers, when used in conjunction with a conventional activated sludge treatment system, the large volume of flocculent solids in the mixed liquor requires that special consideration be given to the design of SSC for biosolids separation (14). Generally, the reliability of SSC is very high. However, rising sludge due to denitrification and sludge bulking may cause problems, which may be overcome by proper operational techniques. The sludge pump capacity and the size of the sedimentation tank are larger.

The circular SSC installed at Jiminy Peak is of a common type in widespread use. Circular SSC units require a greater footprint than rectangular sedimentation clarifiers (6).

2.4. Dissolved Air Flotation and Dissolved Air Flotation–Filtration

DAF is used to remove suspended solids by flotation (rising) by decreasing their apparent density. DAF consists of saturating a portion or all of the wastewater feed, or a portion of recycled effluent, with air at a pressure of 25–70 psi (gage). The pressurized wastewater is held at this pressure for 0.5–3.0 min in a retention tank and then released to atmospheric pressure in the flotation chamber. The sudden reduction in pressure results in the release of microscopic air bubbles, which attach themselves to oil and suspended solid particles in the wastewater in the flotation chamber. This results in an agglomeration of the solids with the entrained air having a greatly increased vertical rise rate of about 0.5–2.0 ft/min (15–60 cm/min). The floated materials rise to the surface to form a froth layer. Specially designed flight scrapers or other skimming devices continuously remove the froth. The retention time in the flotation chambers is usually about 20–60 min for conventional rectangular DAF units. Modern circular DAF units may require only about 10–15 min of detention time for flotation clarification. The effectiveness of DAF depends upon the attachment of bubbles to the suspended oil and other particles that are to be removed. The attraction between the air bubble and particle is primarily a result of the particle surface charges and bubble-size distribution. The more uniform the distribution of water and microbubbles, the shallower the flotation unit can be. Generally, the depth of effective flotation units is between 4 and 9 ft (1.2 and 3 m). The surface sludge layer can in certain cases attain a thickness of several inches (cm) and can be relatively stable for a short period. The layer thickens with time, but undue delays in removal will cause a release of particulates back to the liquid.

DAF units can be round, square, or rectangular. In addition, gases other than air can be used. The petroleum industry has used nitrogen, with closed vessels, to reduce the possibilities of fire. DAF has been used for many years to treat industrial wastewaters. It has commonly been used to treat sludges generated by municipal wastewaters. However, it is not widely used to treat municipal wastewaters (7).

DAF systems have been found to be reliable. However, chemical pretreatment is essential, without which DAF units are subject to variable influent conditions, resulting in widely varying performance. Alum, ferric chloride, and polymers can be added to aid in the coagulation and precipitation process prior to the actual flotation step (8–9).

DAF requires very little use of land. The air released in the unit is unlikely to strip volatile organic material into the air. The air compressors will need silencers to control the noise generated. The sludge generated will need additional treatment for final disposal. This sludge will contain high levels of the chemical coagulants used.

The Jiminy Peak WTP has adopted a circular DAF with a filter attached at the bottom of the tank. The combination of DAF and filtration is technically known as a DAFF clarifier. The Krofta Sandfloat SASF-8 installed at Jiminy WWTP is a DAFF clarifier.

There are many DAF and DAFF reputable manufacturers around the world. All properly designed and installed DAF and DAFF clarifiers should be equally effective for treating the RBC effluent.

2.5. *Tertiary Sand Filtration*

Gravity filtration through dual media is one of the most economical forms of tertiary treatment for wastewater treatment applications. Granular media filtration involves the passage of pretreated wastewater through a bed of filter media with resulting removal of solids. Dual media filtration involves the use of both sand and anthracite as filter media, with the anthracite being placed on top of the sand. Gravity filters operate by either using the available head from the previous treatment unit, or pumping to a higher elevation from which the wastewater can flow by gravity to the filter cells. Pressure filters require a closed tank and utilize pumping to increase the available head to force the liquid through the sand.

A filter unit generally consists of a containing vessel, the filter media, structures to support the media, distribution, and collection devices for influent, effluent, and backwash water flows, supplemental cleaning devices, and necessary controls for flows, water levels, and backwash sequencing. Filtration systems can be constructed of concrete or steel, with single or multiple compartment units. Steel units can be either horizontal or vertical and are generally used for pressure filters. Systems can be manually or automatically operated. Normally filter systems include multiple filter compartments. This allows for the filtration system to continue operating while one compartment is being backwashed.

With continued use the filtered solids clog the filter, creating a pressure drop across the bed and/or impairing the ability of the bed to remove suspended solids. Cleaning by backwashing is then necessary to restore the operating head and effluent quality. The time in service between cleanings is termed the run length. The head loss at which filtration is interrupted for cleaning is called the terminal head loss, and this head loss is maximized by the judicious choice of media sizes. Backwash sequences can include air scour or surface wash steps. Backwash water can be stored separately or in chambers that are integral parts of the filter unit. Backwash water pressure can be provided by pumps or through gravity head tanks.

Sand filtration and dual-media filtration have been used for many years in the potable water industry, and have been used in the wastewater treatment field for 35–45 years (10). The applications of tertiary wastewater filtration include (a) removal of residual biological solids in clarifier effluents (SSC) from secondary treatment and (b) removal of residual chemical–-biological flocs after alum, iron, or lime coagulation/precipitation in DAF or DAFF clarifiers.

At the Jiminy Peak WWTP TSF serves to remove fine particles as well as a preliminary process to prepare the wastewater for further treatment by UV disinfection (17–19).

2.6. *Ultraviolet Disinfection*

Ultraviolet (UV) radiation disinfection uses a special lamp to transfer electromagnetic energy to the target organism cells in the wastewater. The most efficient and widely used device is the mercury arc lamp. It is popular because approximately 85% of its energy output is at the 253.7-nm wavelength, within the optimum germicidal range of 250–270 nm. The lamps are long thin tubes. When an electric arc is struck through mercury vapor, the energy discharge generated by the mercury excitation results in the emission of UV radiation. This radiation then destroys the cell’s genetic material and the cell dies (11–12).

The effectiveness of radiation is a direct function of the energy dose absorbed by the organism, measured as the product of the lamp’s intensity and the time of exposure. Intensity is the rate at which photons are delivered to the target. The intensity in a reactor is governed not only by the power of the lamp, but also by the placement of the lamps relative to the water, and by the presence of other energy sinks that consume UV radiation.

The radiation dose absorbed by the wastewater is the wastewater’s UV demand, which is analogous to chlorine demand and is quantified as the absorption of UV energy (at a wavelength of 253.7 nm) in a given depth of wastewater. In addition to the intensity and the UV demand of the water, the exposure time also affects the energy dosage that the target organisms absorb. Exposure time is controlled by the residence time of the water in the reactor. Continually maintaining the required residence time is not always possible, but the system design should maximize plug-flow operation.

If the energy dosage is not sufficient to destroy the target organisms’ DNA macromolecules, disinfection is not effective. Photoenzymatic repair occurs if the genetic material is only damaged during irradiation. This repair mechanism, called photoreactivation, occurs with exposure to light from the sun or most incandescent and fluorescent lights (at wavelengths between 300 and 500 nm). Photoreactivation does not occur with all bacterial species and is therefore difficult to predict. To prevent photoreactivation, the rule of thumb is to increase the dosage necessary to meet a required reduction in organism numbers. For example, if the disinfection criteria require a 3-log reduction of microorganism concentrations, the UV radiation system should be designed to provide a 4-log reduction (18).

Wastewater with suspended solids, color, turbidity, and soluble organic matter can react with or absorb the UV radiation, reducing the disinfection performance. Therefore, water with high concentrations of these substances may receive inadequate disinfection (15). Since the DAFF clarifier at the Jiminy Peak WWTP had removed most of the suspended solids, color, turbidity, soluble organic matter, etc., the clarity of DAFF effluent was excellent resulting high UV efficiency.

2.7. *Leach Field*

A septic tank followed by a leach field (or soil absorption bed) is a traditional on-site system for the treatment and disposal of domestic wastewater from individual households or establishments. The conventional septic tank system consists of a buried tank where wastewater is collected and scum, grease, and settleable solids are separated by gravity, and a subsurface drainage system where clarified effluent percolates into the soil. Precast concrete tanks with a capacity of 1,000 gallons (3.75 cubic meters) are commonly used for household systems (13, 14).

The leach field can be one of three basic types of subsurface system (a) adsorption trenches, (b) seepage beds, or (c) seepage pits. Sizes are usually determined by percolation rates, soil characteristics, and site, size, and location. For adsorption trenches, distribution pipes are laid in a field of absorption trenches in order to leach the tank effluent over a large area. Required absorption areas are dictated by state and local codes. Trench depth is commonly about 24 in. (0.6 m) to provide minimum gravel depth and earth cover. Clean, graded gravel, or similar aggregate, varying in size from ½ to 2½ in. (1–6 cm) should surround the distribution pipe and extend at least 2 in. (5 cm) above and 6 in. (9 cm) below the pipe. The maintenance of at least a 2 ft (0.6 m) separation between the bottom of the trench and the high water table is required to minimize groundwater contamination. Piping typically consists of agricultural drain tile, vitrified clay sewer pipe, or perforated, nonmetallic pipe. Absorption systems having trenches wider than 3 ft (1 m) are referred to as seepage beds. Given the appropriate soil conditions (sandy soils), a wide bed makes more efficient use of available land than a series of long, narrow trenches. Seepage pits may consist of a variety of surface depressions in the land that hold excess water and allow it to drain into the soil.

The ability of the soil to absorb liquid, the depth to ground water, the nature of and depth to bedrock, seasonal flooding, and the distance to wells or surface water are all dependent on soil and site conditions. A percolation rate of 60 min/in. (60 min/2.5 cm) is often used as the lower limit of permeability. When a soil system loses its capacity to absorb the effluent, there may be a potential for effluent surfacing, which often results in odors and, possibly, health hazards. If this occurs, it must be quickly corrected.

The performance of a leach field is a function of the system components, construction techniques employed, rate of hydraulic loading, areal geology and topography, physical and chemical composition of the soil mantle, and care given to periodic maintenance. It must be pointed out that these restrictions for a leach field are based on the effluent from a conventional septic tank. This still contains a significant amount of oxidizable organic matter and variable amounts of suspended solids depending upon maintenance of the tank. To allow for the aerobic decomposition of the organic matter with a minimum formation of biological solids, the liquid to be leached should be maintained under aerobic conditions. In a typical household system this is established by the intermittent flow, such as no flow when the residents are sleeping at night. Properly designed, constructed, and operated, a leach field has been demonstrated to be an efficient and economical alternative to public sewer systems, particularly in rural and sparsely developed areas. System life for properly sited, designed, installed, and maintained leach field may equal or exceed 20 years and operate satisfactorily in most climates.

The type of leach field used at Jiminy Peak WWTP is of the seepage beds. The properly installed leach field requires a minimum of maintenance and can be operated in all climates. However, the Jiminy Peak WWTP effluent is different from the conventional septic tank system effluent described above. The innovative biological–physicochemical treatment system (including equalization, RBC, DAFF, SSC, and ultraviolet disinfection) replaces the simple septic tank in order to meet the stringent effluent limitations imposed by the Commonwealth of Massachusetts. Any residual trace pollutants in the Jiminy Peak WWTP effluent are removed from the effluent by natural adsorption and biological processes in the soil. BOD_5, suspended solids, bacteria, and viruses, along with heavy metals and complex organic compounds, are adsorbed by soil. However, chlorides and nitrates may readily penetrate coarser aerated soils and reach the ground water (16).

Based on the field monitoring data in 1985–1986, it was found that leachate did not contaminate the ground water, because the pollutants in the sewage were effectively removed by the Jiminy Peak WWTP. The leach field was only used for ultimate disposal of the plant effluent to the environment.

3. PLANT DESIGN, INSTALLATION, OPERATION, AND VERIFICATION

The Jiminy Peak WTP was designed in 1984 and completed in November 1985.

On behalf of Jiminy Peak Inc., Hancock, MA, the Lenox Institute of Water Technology (LIWT) staff monitored and recorded the daily average wastewater flows and pH values, and analyzed the other wastewater parameters to evaluate the performance of the treatment system. Samples were secured from the RBC influent in Distribution Box A (see Sect. 4) the RBC effluent in Distribution Box B (see Sect. 4), the SSC effluent, the DAFF effluent, the sand filter effluent near Distribution Box C and the ultraviolet disinfection chamber effluent (see Sect. 4), according to the schedule and other provisions in Table 14.1.

Jiminy Peak installed five monitoring wells: one up gradient and four down gradient of the subsurface discharge. Detailed plans of the wells, the locations thereof, and the methods and means for sampling were submitted by Jiminy Peak's Consulting Engineer (J. J. Johnson & Associates, Park City, UT 84060) and approved by the Massachusetts Department of

Table 14.1
Sampling, analysis, and reporting required by the Commonwealth of Massachusetts, USA

Parameter[a,b]	Minimum frequency of analysis	Sample type
Flow	Daily	Average
BOD_5	Monthly	8-h composite[c]
TSS and Total Solids	Monthly	8-h composite[c]
Total Coliform	Monthly	Grab[c]
pH	Daily	Grab[d]
Nitrate as N	Monthly	8-h composite[c]
Ammonia as N	Monthly	8-h composite[c]
Settleable solids	Monthly	8-h composite[c]
Oil and grease	Monthly	8-h composite[c]

[a] Parameters analyzed for seven wastewater samples (plant influent, RBC influent, RBC effluent, sedimentation clarifier effluent, Sandfloat effluent, Sand filter effluent and UV chamber effluent) for a total of 6 months.

[b] Analysis of BOD, TSS, TS, total coliform, nitrate, ammonia, settleable solids, and oil and grease shall be done by LIR chemists.

[c] Sampling of exactly 1 L of each representative sample shall be done by Jiminy Peak every 2 h in order to generate an 8-h composite sample for each of the seven wastewater samples.

[d] Sampling and measurement of wastewater flow, and pH values shall be done by Jiminy Peak personnel.

Environmental Quality Engineering, Division of Water Pollution Control. On behalf of Jiminy Peak, LIWT operated and monitored the plant facilities and recorded and reported the quality of water in the monitoring wells according to the following schedule and other provisions:

1. Chloride = once quarterly
2. Nitrate nitrogen = once quarterly
3. pH = once monthly
4. Specific conductance = once monthly
5. Static water level = once monthly

Any grab samples or composite samples required to be taken less frequently than daily were taken during the period of Monday through Friday inclusive. Eight-hour composites and grab samples were taken between 8:00 A.M. and 6:00 P.M. All composite samples were taken over the operating day.

4. JIMINY PEAK WASTEWATER TREATMENT PLANT DESIGN AND INSTALLATION

Preliminary design of the Jiminy Peak WWTP was completed jointly by Jiminy Peak's Consulting Engineer, J. J. Johnson & Associates, (Park City, UT), Lenox Institute of Water Technology (Lenox, MA), and Krofta Engineering Corporation (Lenox, MA), based on an average design flow of 100,000 gpd (375 m^3/d), and a peak design flow of 300,000 gpd (1,100 m^3/d).

The entire WWTP includes a weir box, a flow equalization tank, two feed pumps, two RBCs, a dissolved air flotation–filtration clarifier (DAFF clarifier), a SSC, a tertiary sand filter, two ultraviolet disinfection units, and a subsurface disposal system as shown in Fig. 14.1. A previous engineering report (1) documented the design calculations, and the design criteria of the wastewater transportation and treatment facilities.

Two mechanical clarifiers were installed for parallel treatment of the RBC effluent:

1. A standard 12 ft. (3.6 m) diameter circular SSC
2. An 8 ft. (2.4 m) diameter dissolved air flotation–filtration clarifier (DAFF clarifier), also commercially known as Krofta Sandfloat Model SASF-8.

The performances of both the SSC and the DAFF clarifier were evaluated and compared by LIWT in this engineering program for a period of 1 year under the supervision of Director Lawrence K. Wang, Superintendent James P. Van Dyke, and Professor Donald B. Aulenbach.

The top view (PLAN), three side views (VIEW A, VIEW B and VIEW C), and the hydraulic grade line of the Jiminy Peak system are presented in Figs. 14.3–14.7, respectively, for the purpose of illustration and documentation.

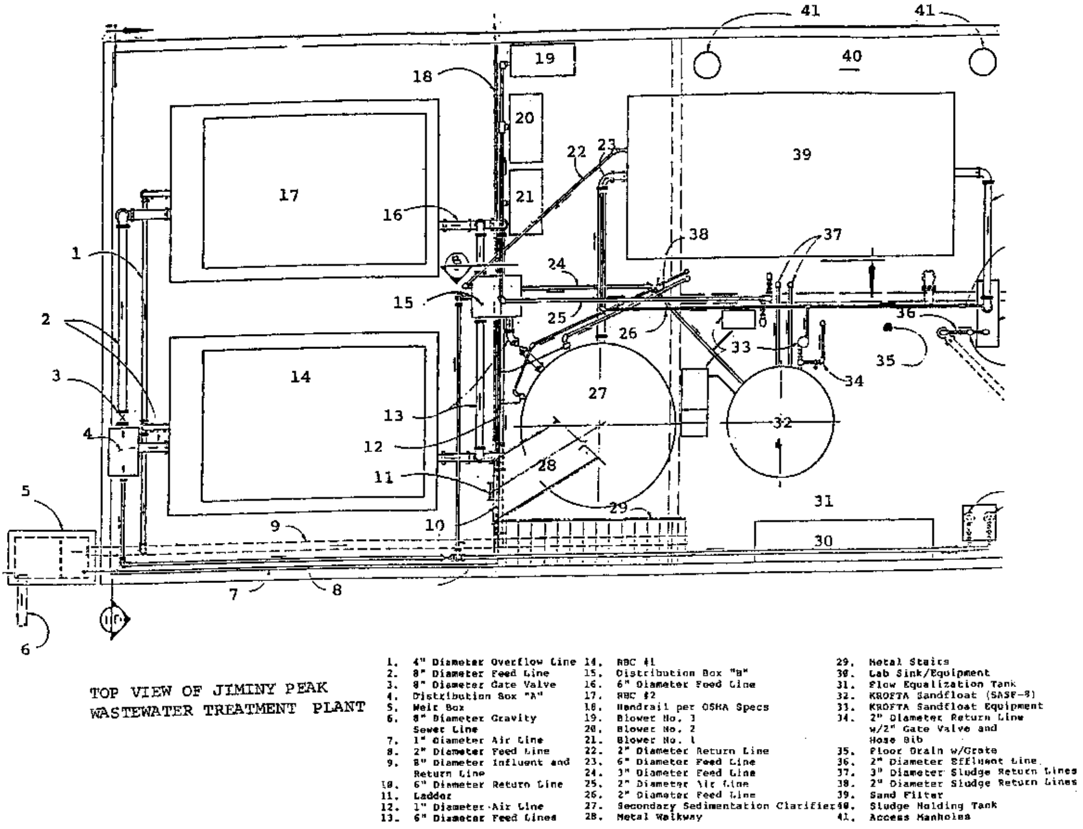


Fig. 14.3. Top view of Jiminy Peak Wastewater Treatment Plant.

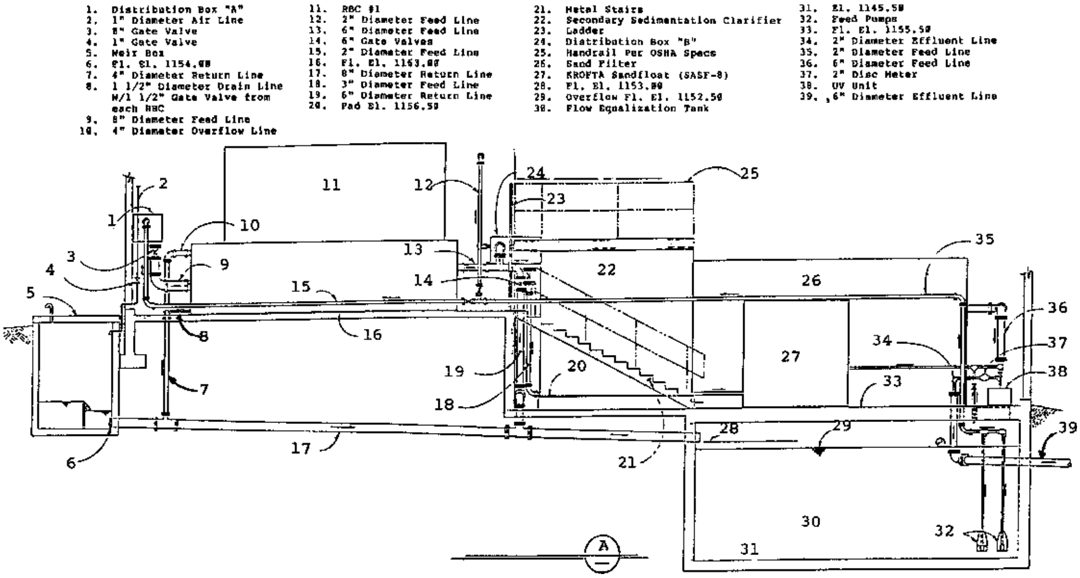


Fig. 14.4. Side view of Jiminy Peak Wastewater Treatment Plant.

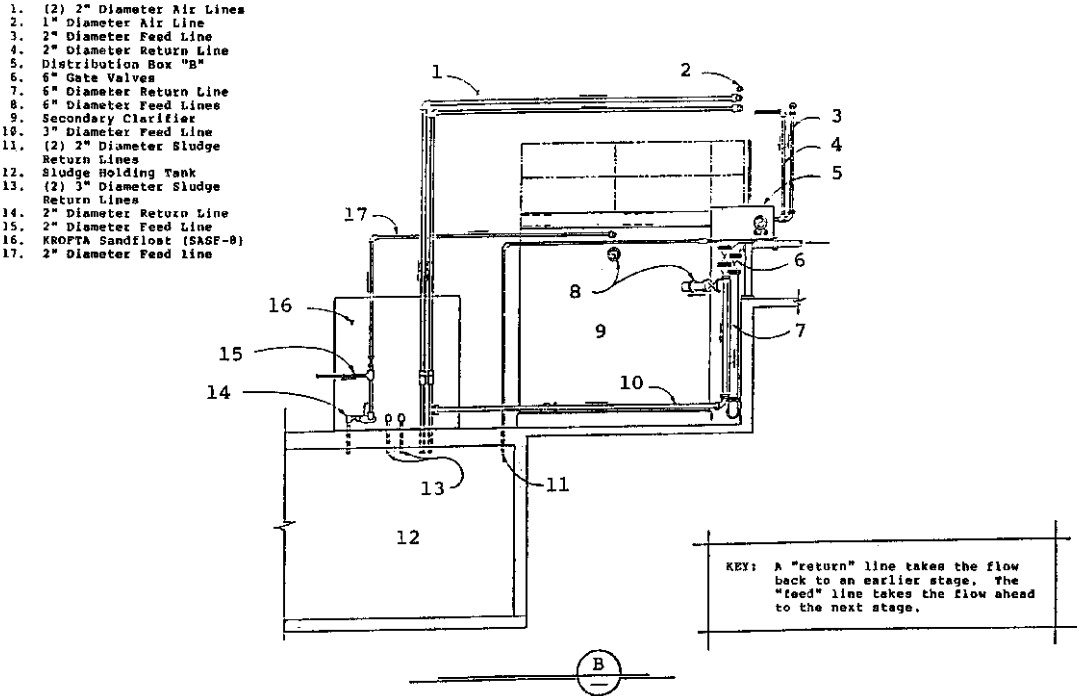
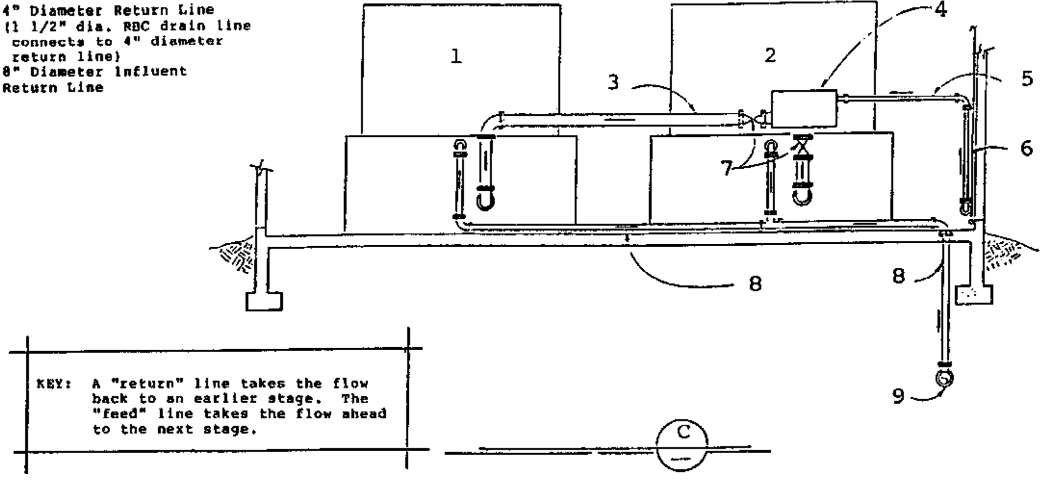


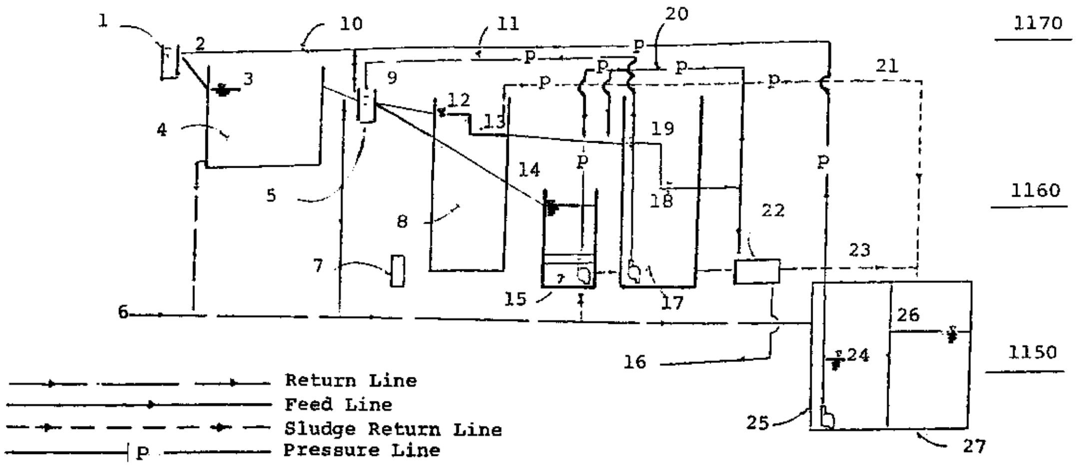
Fig. 14.5. Side view B of Jiminy Peak Wastewater Treatment Plant.

1. RBC #1
2. RBC #2
3. 8" Diameter Feed Line
4. Distribution Box "A"
5. 2" Diameter Feed Line
6. 1" Diameter Air Line
7. 8" Gate Valve
8. 4" Diameter Return Line (1 1/2" dia. RBC drain line connects to 4" diameter return line)
9. 8" Diameter Influent Return Line



KEY: A "return" line takes the flow back to an earlier stage. The "feed" line takes the flow ahead to the next stage.

Fig. 14.6. Side view C of Jiminy Peak Wastewater Treatment Plant.



1. Distribution Box "A"
2. W.S. 70.0
3. W.S. 67.67
4. RBC's
5. Distribution Box "B"
6. Influent
7. Blowers
8. Secondary Clarifier
9. W.S. 66.75
10. Influent
11. Backwash
12. W.S. 66.8
13. W.S. 64.75
14. W.S.± 60.5
15. KROFTA Sandfloat (SASF-8)
16. Effluent to Leach Trenches
17. Sand Filter
18. W.S. 61.67
19. W.S. 64.42
20. KROFTA Sandfloat (SASF-8) Effluent
21. Sludge
22. UV Unit
23. Sludge
24. W.S. Variable
25. Flow Equalization Tank
26. W.S. 52.5
27. Sludge Holding Tank

ELECTRICAL REQUIREMENTS

RBC's	(2)	20	HP	Sandfilter	(2)	3.0	HP
Blowers	(2)	3.0	HP		(2)	2.0	HP
		5.0	HP		(2)	0.4	HP
Clarifier		0.5	HP	Ultraviolet	(No Pumps)		
Sandfloat	(2)	0.25	HP		115 Volt		
		7.5	HP		Connection		
		0.5	HP	Feed Pumps	(2)	2.0	HP
		2.0	HP				

Notes: 1. Voltage at site is 208 volts, 3-phase.
2. Other electrical requirements include lighting, power outlets, heating & ventilation.

Fig. 14.7. Hydraulic grade line and electrical requirements of Jiminy Peak Wastewater Treatment Plant.

The monitoring/recording of the quantity and quality of wastewater in Distribution Boxes A, B, and C (Figs. 14.3–14.7) was mandatory by the Commonwealth of Massachusetts. A Jiminy Peak Facility Plan is presented elsewhere (1).

5. PERFORMANCE OF THE JIMINY PEAK WWTP

Technically speaking, the 0.1 MGD (375 cubic meter per day) Jiminy Peak WWTP in Hancock, MA, USA is a two-stage biological physicochemical treatment plant. The plant consists of a 30,000 gal (100 m^3) raw wastewater equalization tank, two RBCs, one circular secondary sedimentation clarifier (SSC, Diameter = 12 ft; 3.6 m), one circular dissolved air flotation–filtration (DAFF, Diameter = 8 ft; 2.4 m), one 34.7 ft^2 (3.2 m^2) tertiary sand filter, and two ultraviolet (UV) disinfection units, with ultimate subsoil disposal of the final purified effluent.

The first-stage biological wastewater treatment is accomplished utilizing the RBC, which is a fixed film bioreactor consisting of plastic media discs mounted on a horizontal shaft and partially submerged in a trough containing the wastewater. While wastewater flows through the trough, the discs coated with a biological film are slowly rotated about 40% immersed in the wastewater. As the discs emerge from the wastewater, aerobic conditions in the thin film break down both BOD and COD. Excess biomass produced on the media is stripped off by rotational shear forces in the trough, and the stripped solids are subsequently separated by a secondary clarifier such as either an SSC or a DAFF system (2, 3).

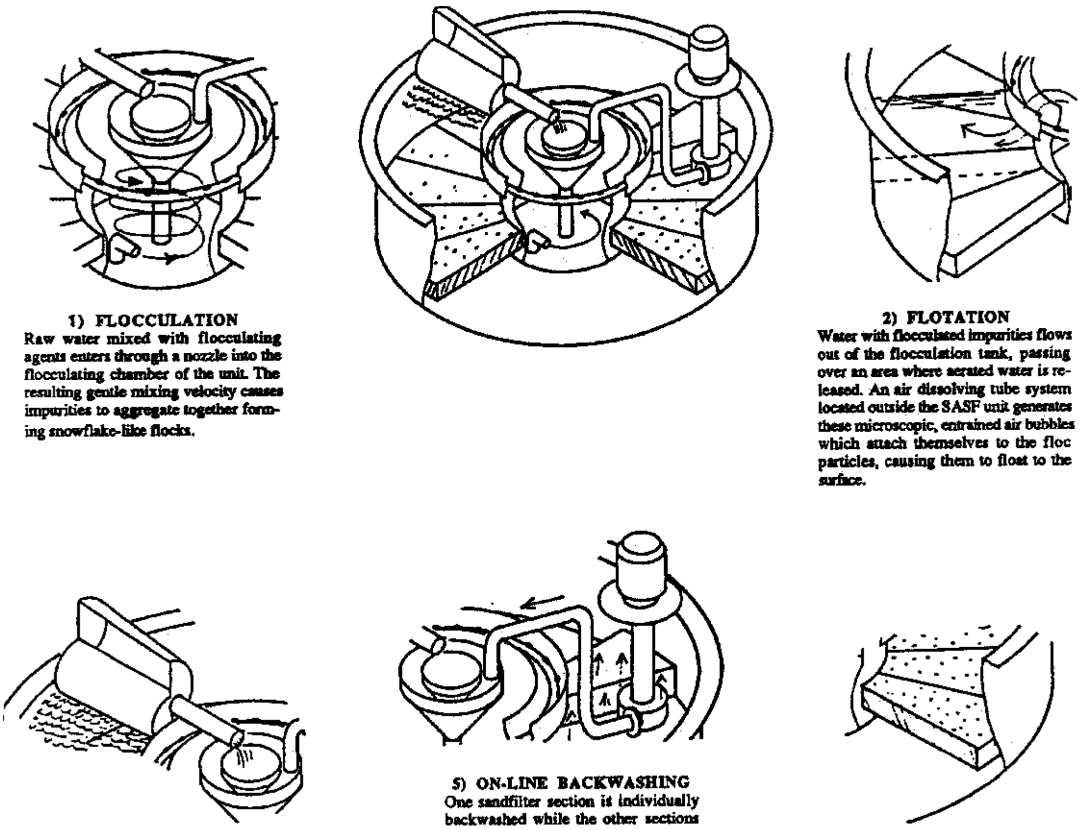
The combination of RBC and circular SSC constitutes a conventional secondary biological wastewater treatment system (Figs. 14.1 and 14.2). The combination of RBC and flotation clarifier DAFF) makes this an innovative two-stage biological physicochemical process system (Fig. 14.1). RBC is the first-stage biological unit process, and DAFF is the second-stage physicochemical unit process.

The commercial DAFF (Sandfloat) is a package waste treatment unit consisting of flocculation, DAF, and automatic backwash filtration, specifically designed for small wastewater treatment systems (17–20) (Fig. 14.8).

In normal operation, raw sewage flows through the equalization tank and the two RBC. About 14% of the RBC effluent is diverted to the SSC for separation of the solids. The remaining about 86% of the RBC effluent is diverted to the DAFF for physicochemical treatment (Fig. 14.1). Both the DAFF effluent and the SSC effluent are combined and are then sent to the subsequent tertiary sand filter and the UV disinfection unit for final polishing.

The monitoring data generated during the period of November 1985 to April 1986 are documented in Tables 14.2–14.8, which are all self-explanatory. The pollutant ranges of seven sampling events are summarized in Table 14.9. The average pollutant concentrations are presented in Table 14.10. The abbreviations used in Tables 14.2–14.10 are defined below:

BOD_5	5-day biochemical oxygen demand
COD	Chemical oxygen demand
DAFF	Dissolved air flotation–filtration clarifier



1) FLOCCULATION
Raw water mixed with flocculating agents enters through a nozzle into the flocculating chamber of the unit. The resulting gentle mixing velocity causes impurities to aggregate together forming snowflake-like flocks.

2) FLOTATION
Water with flocculated impurities flows out of the flocculation tank, passing over an area where aerated water is released. An air dissolving tube system located outside the SASF unit generates these microscopic, entrained air bubbles which attach themselves to the floc particles, causing them to float to the surface.

3) SLUDGE REMOVAL
The rotating KROFTA Spiral Scoop circulates around the SASF unit, gently lifting the floated impurities from the water surface. The sludge is emptied into the central collector for removal from the SASF unit.

5) ON-LINE BACKWASHING
One sandfilter section is individually backwashed while the other sections continue to filter water. Filtered water from below is drawn up through the sand, washing out impurities. Backwash water is normally recycled back to the flocculation chamber for reflocculation.

4) FILTRATION
Water is given a final cleansing through an eleven inch deep bed of fine sand which traps any impurities not removed by the flotation process. After filtration, the clarified water is held in the Clearwell compartment under the sand for final removal from the SASF unit.

Fig. 14.8. Process description of a dissolved air flotation–filtration (DAFF) clarifier (Krofta Sandfloat SASF-8).

NA	Not available
NH_3	Ammonia nitrogen
NO_3	Nitrate nitrogen
O&G	Oil and grease
PI	Plant influent
RBC	Rotating biological contactor
SASF	Dissolved air flotation–filtration clarifier (Sandfloat SASF-8)
SF	Sand filter
SS	Settleable solids
SSC	Secondary sedimentation clarifier

Table 14.2
Jiminy Peak Wastewater Treatment Plant data on November 18, 1985

Wastewater parameters	PI	RBC Inf.	RBC Eff.	SSC Eff.	SASF Eff.	SF Eff.	UV Eff.
BOD_5 (mg/L)	NA	12	24	5.4	NA	7.2	4.8
COD (mg/L)	NA	80	35	29	NA	30	49
TSS (mg/L)	NA	16	8	3	NA	3	9
TS (mg/L)	NA	279	303	270	NA	301	300
NO_3 (mg/L-N)	NA	0.3	0.3	0.3	NA	0.1	0.1
NH_3 (mg/L-N)	NA	30.5	31.3	25.0	NA	26.5	27.5
SS (mL/L-h)	NA	<1	0	0	NA	0	0
O&G (mg/L)	NA	0	0	0	NA	0	0
pH (unit)	NA	7.0	7.0	7.0	NA	7.0	7.0
Total coliforms (#/100 mL)	NA	400,000	200,000	14,000	NA	9,400	5,000

Table 14.3
Jiminy Peak Wastewater Treatment Plant data on November 22, 1985

Wastewater parameters	PI	RBC Inf.	RBC Eff.	SSC Eff.	SASF Eff.	SF Eff.	UV Eff.
BOD_5 (mg/L)	NA	12.6	9.0	NA	2.1	4.2	1.8
COD (mg/L)	NA	55	40	NA	25	20	20
TSS (mg/L)	NA	26	19	NA	4	0	0
TS (mg/L)	NA	354	316	NA	238	294	294
NO_3 (mg/L-N)	NA	0.2	0.2	NA	0.2	0.2	0.1
NH_3 (mg/L-N)	NA	30.0	30.0	NA	25.0	22.5	21.3
SS (mL/L-h)	NA	0.4	.07	NA	0	0	0
O&G (mg/L)	NA	0	0	NA	0	0	0
pH (unit)	NA	7.0	7.0	NA	6.5	6.5	6.5
Total coliform (#/100 mL)	NA	35,000	21,000	NA	9,000	8,000	3,000

TSS	Total suspended solids
TS	Total solids
TNTC	Too numerous to count
UV	Ultraviolet unit
WWTP	Wastewater treatment plant

In order to evaluate any impact, the leachate may have on the adjacent ground water, five monitoring wells were installed around the leaching area. After estimating the expected groundwater flow direction, one monitoring well was placed upstream from the leachate discharge, and four in the potential impacted area downstream. Table 14.11 shows the results of this monitoring.

The chemical dosages used in the DAFF were varied in order to find the optimum dose to provide the best treatment. In addition, this provided information on the cost of the chemicals

Table 14.4
Jiminy Peak Wastewater Treatment Plant data on December 9, 1985

Wastewater parameters	PI	RBC Inf.	RBC Eff.	SSC Eff.	SASF Eff.	SF Eff.	UV Eff.
BOD$_5$ (mg/L)	NA	72.0	37.5	30	15.0	24.0	15.0
COD (mg/L)	NA	94	63	49	15	39	31
TSS (mg/L)	NA	19	7	13	4	1	1
TS (mg/L)	NA	315	319	305	256	297	275
NO$_3$ (mg/L-N)	NA	0.3	0.3	0.3	0.1	0.1	0.1
NH$_3$ (mg/L-N)	NA	50.0	50.0	37.5	40.0	35.0	35.0
SS (mL/L-h)	NA	<0.05	<0.05	0	0	0	0
O&G (mg/L)	NA	0	0	0	0	0	0
pH (unit)	NA	7.0	7.0	7.0	6.5	6.5	6.5
Total coliform (#/100 mL)	NA	340,000	251,000	194,000	171,000	146,000	400

Table 14.5
Jiminy Peak Wastewater Treatment Plant data on January 9, 1986

Wastewater parameters	PI	RBC Inf.	RBC Eff.	SSC Eff.	SASF Eff.	SF Eff.	UV Eff.
BOD$_5$ (mg/L)	96	84.0	70.0	52.5	24.6	27.6	15.6
COD (mg/L)	240	224	216	144	70	80	75
TSS (mg/L)	31	120	116	21	10	39	21
TS (mg/L)	682	700	706	534	546	532	NA
NO$_3$ (mg/L-N)	74	52.5	36.0	32.5	32.5	33.7	32.5
NH$_3$ (mg/L-N)	0.06	0.05	0.05	0.04	0.04	0.03	0.02
SS (mL/L-h)	<1	2	4.5	0	0	0	0
O&G (mg/L)	108	51	29	30	27	22	24
pH (unit)	7.0	6.0	6.0	7.0	6.0	6.0	6.0
Total coliform (#/100 mL)	TNTC	TNTC	TNTC	TNTC	65,000	280,000	4

needed to achieve these dosages. A goal is to achieve the best treatment at the lowest chemical cost, not just from the standpoint of the initial chemical cost, but also from the standpoint of managing the residuals from the treatment utilizing these chemicals. Results of these studies are shown in Table 14.12.

Near the start of the actual WWTP operation, samples were taken of the RBC effluent and returned to the laboratory for bench-scale studies to optimize the chemicals needed to best operate the DAFF. RBC effluent was collected from the Jiminy Peak WWTP for treatment by a bench-scale DAFF with various chemical dosages. The results of the bench-scale experimentation are recorded in Table 14.13.

The results of the daily monitoring of the flow and the pH of the effluent from the Jiminy Peak WWTP for the entire period of the study are shown in Table 14.14. These values were provided by treatment plant operators from recorders at the plant.

Table 14.6
Jiminy Peak Wastewater Treatment Plant data on February 9–10, 1986

Wastewater parameters	PI (2/9)	RBC Inf. (2/9)	RBC Eff. (2/9)	SSC Eff. (2/9)	SASF Eff. (2/9)	SF Eff. (2/10)	UV Eff. (2/10)
BOD_5 (mg/L)	375	324	102	92	26	27	12
COD (mg/L)	398	390	105	95	63	75	70
TSS (mg/L)	62	102	89	32	10	18	16
TS (mg/L)	420	556	444	450	422	414	410
NO_3 (mg/L-N)	92	86	58.5	36.7	36.0	38.5	36.0
NH_3 (mg/L-N)	0.09	0.06	0.05	0.05	0.03	0.04	0.02
SS (mL/L-h)	NA	2	3.7	0	0	0	0
O&G (mg/L)	381	273	196	106	83	92	80
pH (unit)	7.2	7.2	7.2	7.2	7.7	7.2	7.2
Total coliform (#/100 mL)	TNTC	TNTC	TNTC	460,000	112,000	430,000	0

Table 14.7
Jiminy Peak Wastewater Treatment Plant data on March 14, 1986

Wastewater parameters	PI	RBC Inf.	RBC Eff.	SSC Eff.	SASF Eff.	SF Eff.	UV Eff.
BOD_5 (mg/L)	232.5	306	174	57	10.8	22.8	5.4
COD (mg/L)	360	430	350	107	81	77	80
TSS (mg/L)	87	381	312	34	30	15	20
TS (mg/L)	526	804	746	552	598	524	562
NO_3 (mg/L-N)	23.8	70	77.5	82.5	77.5	80	77.5
NH_3 (mg/L-N)	39.5	7	0.8	3.85	0.82	1.83	4
SS (mL/L-h)	0.1	20	15	<0.1	0.5	<0.1	<0.1
O&G (mg/L)	391	381	206	44	0	0	0
pH (unit)	6.7	6.6	6.5	6.5	6.5	6.5	6.5
Total coliform (#/100 mL)	1.75×10^6	1.60×10^6	1.63×10^6	1.7×10^6	1,000	1,500	0

6. DISCUSSION AND CONCLUSIONS

Tables 14.2–14.8 document the monthly monitoring data at the Jiminy Peak WWTP. The plant influent (PI) was initially equalized in an equalization tank ($L \times W \times D = 26$ ft × 19 ft × 9 ft; 8 m × 6 m × 3 m). The equalization tank was equipped with a 3-HP air blower (manufactured by Clow Engineering) capable of delivering sufficient air to maintain the entire tank under aerobic conditions. The flow equalized waste was then treated by two RBC.

The RBC effluent was then normally split between the SSC and the DAFF unit. However, during the November 1985 startup low sewage flow period, only one clarifier was required for

Table 14.8
Jiminy Peak Wastewater Treatment Plant data on April 3, 1986

Wastewater parameters	PI	RBC Inf.	RBC Eff.	SSC Eff.	SASF Eff.	SF Eff.	UV Eff.
BOD_5 (mg/L)	210	198	150	78	4.3	8.0	1.7
COD (mg/L)	240	200	150	90	12.8	19.2	6.4
TSS (mg/L)	37	119	131	28	12	21	15
TS (mg/L)	398	532	568	376	730	580	554
NO_3 (mg/L-N)	12.5	30	25	35	35	37.5	32.5
NH_3 (mg/L-N)	24.2	1.6	1.28	0.4	0.13	2.2	2.3
SS (mL/L-h)	0	7	6	0.5	0	0	0
O&G (mg/L)	54	40	10	0	0	0	0
pH (unit)	8.0	8.0	8.0	7.5	6.5	6.5	6.5
Total coliform (#/100 mL)	TNTC	5,600,000	600,000	450,000	0	0	0

Table 14.9
Range of Jiminy Peak Wastewater Treatment Plant data from November 1985 to April 1986

Wastewater parameters	PI	RBC Inf.	RBC Eff.	SSC Eff.	SASF Eff.	SF Eff.	UV Eff.
BOD_5 (mg/L)	96–375	12–324	9–174	5.4–92	2.1–26	4.2–27.6	1.7–15.6
COD (mg/L)	240–398	55–430	35–350	29–144	12.8–81	19.2–88	6.4–80
TSS (mg/L)	31–87	16–381	7–312	3–34	4–30	0–39	0–21
TS (mg/L)	398–682	279–804	303–746	270–552	238–730	294–580	275–562
NO_3 (mg/L-N)	12.5–92	0.2–86	0.3–77.5	0.3–82.5	0.1–77.5	0.1–80	0.1–77.5
NH_3 (mg/L-N)	0.06–39.5	0.05–50	0.05–50	0.04–37.5	0.03–40	0.03–35	0.02–35
SS (mL/L-h)	$<$1–0.1	0–20	0–15	0–0.5	0–0.5	0–0.1	0–0.1
O&G (mg/L)	54–391	0–381	0–206	0–106	0–83	0–92	0–80
pH, unit	6–8	6–8	6–8	6.5–7.5	6–7.7	6–7.2	6–7.2
Total coliform (#/100 mL)	TNTC	35,000–TNTC	21,000–TNTC	14,000–TNTC	0–171,000	0–430,000	0–5,000

clarification of the RBC effluent (Tables 14.2 and 14.3) with the SSC used during the sampling period on November 18 and the DAFF used during the November 22 sampling period.

From December 1985 to April 1986, an average of 84% of the total RBC effluent flow was treated by the DAFF clarifier (diameter = 8 ft; 2.5 m), and 16% of the total RBC effluent flow was treated by the larger SSC (diameter = 12 ft; 3.6 m).

No obnoxious malodors were attributed to the Jiminy Peak WWTP. A test taken on December 9, 1985 showed the Threshold Odor Number (TON) of the RBC effluent was specifically measured to be 7 TON, which was considered to be negligible.

Table 14.10
Average of Jiminy Peak Wastewater Treatment Plant data from November 1985 to April 1986

Wastewater parameters	PI	RBC Inf.	RBC Eff.	SSC Eff.	SASF Eff.	SF Eff.	UV Eff.
BOD_5 (mg/L)	228	144	81	52	14	17	8
COD (mg/L)	310	210	137	86	44	50	47
TSS (mg/L)	54	110	97	22	12	14	12
TS (mg/L)	507	506	486	415	405	420	399
NO_3 (mg/L-N)	51	34	28	31	30	27	26
NH_3 (mg/L-N)	16	17	16	11	11	13	13
SS (mL/L-h)	0.4	4.6	4	0.1	0.08	0.02	0.02
O&G (mg/L)	234	115	63	30	18	16	15
pH (unit)	7.2	7.1	6.9	7.0	6.6	6.6	6.6
Total coliform (#/100 mL)	TNTC	TNTC	TNTC	>753,000	59,700	125,000	1,200[a]

[a] Average coliform count in UV effluent was 1/100 mL from January to April 1986.

Table 14.11
Monitoring of groundwater at Jiminy Peak Wastewater Treatment Plant in 1986

Water quality parameters	Date:	3/13	4/30	4/30	4/30	4/30
	Well No:	1	1	2	3	4
	Gradient:	Down	Down	Down	Down	Up
pH (unit)		7.3	6.8	7.0	6.8	7.2
Chloride (mg/L)		7.5	12.0	5.5	12.0	11.5
NO_3 (mg/L-N)		0.6	0.2	0.3	0.5	0.3
Spec. Cond. (μmho/cm)		129	180	176	105	350

The two UV units (Model 8500; total design capacity = 83 gpm; 300 L/min) were supplied by Atlantic UV. The UV units initially did not perform satisfactorily in November–December 1985. After the UV units were adjusted in January 1986, no total coliforms (TC) were detected in the UV effluent from February to April 1986.

The performance of the Jiminy Peak WWTP during the period November 1985 to April 1986 (Tables 14.2–14.8) is summarized in Tables 14.9 and 14.10. Table 14.9 presents the pollutant ranges at the various sampling locations (a) plant influent (PI), (b) RBC influent, (c) RBC effluent, (d) SSC effluent, (e) DAFF effluent, (f) sand filter (SF) effluent, and (g) ultraviolet (UV) effluent. Table 14.10 presents the average performance results during the same period.

The UV effluent of the Jiminy Peak WWTP is the final effluent, which is discharged to a leach field for ultimate disposal. Accordingly, four groundwater monitoring wells were installed for monitoring the groundwater quality up gradient and down gradient of the plant effluent discharge. Results in Table 14.11 indicate that there were no noticeable changes in

Table 14.12
Continuous treatment of rotating biological contactor (RBC) effluent by dissolved air flotation–filtration (DAFF) clarifier

Date	Chemical dosages	Cost ($/1,000 Gal.)
11/22/85	Alum = 9.7–21.9 mg/L (Al_2O_3)	0.0510
	Nalco 2PD-462 = 1.2–1.7 mg/L	0.1059
12/09/85	Alum = 20.5 mg/L (Al_2O_3)	
	Nalco 7533 = 1.3 mg/L	0.1009
01/09/86	Alum = 60 mg/L (Al_2O_3)	
	Nalco 7533 = 1.3 mg/L	0.2569
02/10/86	Alum = 90.22 mg/L (Al_2O_3)	
	Nalco 2PD-462 = 0.03 mg/L	0.3670
03/14/86	Alum = 43.12 mg/L (Al_2O_3)	
	Nalco 2PD-462 = 0.004 mg/L	0.1750
04/03/86	Alum = 10.5 mg/L (Al_2O_3)	
	Nalco 7533 = 1.2 mg/L	0.1750
		Ave. 0.1586

the pH, chloride, and nitrate nitrogen of the groundwater due to the plant effluent discharge, whereas the specific conductivity of the groundwater became slightly lower.

The operational conditions of DAFF during the recorded testing period (November 1985 to April 1986) were:

1. Influent domestic sewage flow, gpm = 22–35 (average 31) [L/min = 83–130, average 120]
2. ADT inlet water pressure, psi = 69–73 (average 71)
3. ADT tube water pressure, psi = 62–64 (average 63)
4. ADT air pressure, psi = 80–82 (average 81.8)
5. Air flow (2 flow meters), SCFH = 5 × 2 to 8 × 2 (average 6.8 × 2)

where *gpm* gallon per minute, *psi* pounds per square inch pressure, and *SCFH* standard cubic feet per hour.

Table 14.12 documents the chemical dosages applied to the DAFF at the Jiminy Peak WWTP. The results show that the chemical cost is affordable. The average chemical treatment cost of DAFF from November 1985 to April 1986 was only 15.86 cents per 1,000 gallons of wastewater. Using a Cost Index for the cost conversion from 1986 to 2007, the estimated 2007 cost is 24.86 cents per 1,000 gallons of wastewater treated (14). The results of additional bench-scale experiments conducted in 1985 (Table 14.13) indicate that the sodium aluminate, alum, and polymer Nalco 2PD-462 together can also effectively treat the RBC effluent.

The Jiminy Peak plant effluent flow and effluent pH were monitored daily as recorded in Table 14.14. The effluent pH met the Commonwealth of Massachusetts' effluent standards. The total volume of raw sewage treated by Jiminy Peak WWTP from November 1, 1985 to

Table 14.13
DAFF treatment of RBC effluent from Jiminy Peak Wastewater Treatment Plant

Test No.	Sampling & testing date	Chemical treatment (mg/L)		Wastewater quality				
				pH unit	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	BOD (mg/L)
1	10/25/85	None		7.4	40	125	172.8	135
2	10/25/85	15 1	AS 2PD-462	6.6	2.2	8	41.5	20.4
3	10/25/85	20 2	AS 2PD-462	6.4	2.6	10	55.3	15.0
4	10/25/85	30 2 10	AS 2PD-462 SA	6.4	2.0	8	48.4	12.0
5	10/25/85	15 10 1	AS SA 2PD-462	6.6	2.4	10	48.4	12.0
11	11/1/85	None		7.6	NA	180	92.2	42.0
12	11/1/85	15 1	AS 2PD-462	7.3	NA	5	41.4	4.2
13	11/1/85	20 2	AS 2PD-462	6.7	NA	6	NA	6.6
14	11/1/85	30 2	AS 2PD-462	6.4	NA	6	34.5	4.8
15	11/1/85	15 10 1	AS SA 2PD-462	6.6	2.0	10	27.0	6.6

AS aluminum sulfate as Al_2O_3, *SA* sodium aluminate as Al_2O_3, *2PD-462* anionic polymer.

April 30, 1986 was calculated to be 2,784,446 gallons (105 m^3). The overall average daily flow in the period was 15,565 gpd (60 m^3/d).

Several conclusions can be drawn from the Jiminy Peak sewage treatment and monitoring data in Tables 14.10–14.12 (17–19).

1. The complete Jiminy Peak WWTP including flow equalization, RBC, SSC or DAFF, TSF, and ultraviolet light can adequately treat the wastewater from the resort to meet the secondary effluent discharge standards established by the Commonwealth of Massachusetts DEQE (Permit No. 0-188) (a) flow = 0.1 MGD or less; (b) BOD_5 = 30 mg/L or below; (c) TSS = 30 mg/L or below; (d) settleable solids = 0.1 mL/L or below; (e) total coliform = 1,000 organisms or less per 100 mL; (f) O&G = 15 mg/L or below; and (g) pH = between 6.5 and 8.5. After the UV units were adjusted in January 1986, no coliform bacteria were detected in the UV effluent in the entire period of February to April 1986 (see the footnote on Table 14.10).
2. A conventional secondary biological wastewater treatment system consisting of flow equalization, RBC, and SSC without the DAFF (see Fig. 14.1 and, the column of SSC Eff. in Table 14.10) is not

Table 14.14
Daily monitoring of effluent flow and pH from November 1985 to April 1986

Date	Effluent (gpd)	pH	Date	Effluent (gpd)	pH	Date	Effluent (gpd)	pH
11/1	10,560	8	12/1	21,720	7.8	1/1	31,260	7.7
11/2	6,890	8.2	12/2	19,200	8	1/2	30,980	7.5
11/3	8,880	8.2	12/3	16,800	7.7	1/3	9,360	7.4
11/4	7,680	8.2	12/4	15,280	7.8	1/4	21,150	7.3
11/5	9,240	8	12/5	13,720	7.8	1/5	21,600	7.5
11/6	8,760	7.8	12/6	12,840	7.8	1/6	14,900	7.7
11/7	7,320	7.8	12/7	23,280	8.2	1/7	9,720	7.2
11/8	9,360	8	12/8	23,520	8.2	1/8	9,240	7.4
11/9	9,840	8	12/9	25,080	8.2	1/9	10,680	7.2
11/10	9,240	8	12/10	16,320	7.8	1/10	10,440	7.2
11/11	22,080	8.2	12/11	17,400	7.8	1/11	16,920	7.2
11/12	9,000	8.2	12/12	16,920	7.5	1/12	14,028	7.2
11/13	12,600	8	12/13	17,520	7.2	1/13	12,120	7.4
11/14	18,240	7.9	12/14	18,120	7.3	1/14	9,360	7.4
11/15	16,800	8	12/15	17,760	7.2	1/15	10,200	7.2
11/16	21,000	8	12/16	13,080	7.6	1/16	12,480	7.4
11/17	24,120	8	12/17	12,960	8.2	1/17	14,040	7.4
11/18	18,600	8	12/18	14,280	8.2	1/18	28,320	7.0
11/19	18,360	8	12/19	14,400	8.2	1/19	25,800	7.4
11/20	17,520	8	12/20	16,320	8.2	1/20	19,440	7.4
11/21	16,920	8	12/21	21,600	8.2	1/21	10,920	7.2
11/22	17,040	8	12/22	20,280	8.2	1/22	9,480	6.8
11/23	16,680	8	12/23	19,320	8.3	1/23	10,920	6.9
11/24	17,160	8	12/24	18,840	8	1/24	18,360	6.8
11/25	14,760	7.8	12/25	18,600	7.9	1/25	19,560	7.4
11/26	18,360	8	12/26	25,680	7.8	1/26	16,080	7.4
11/27	21,240	7.8	12/27	27,200	8	1/27	13,440	7.0
11/28	25,320	8	12/28	36,820	7.8	1/28	11,880	7.0
11/29	31,560	7.8	12/29	39,600	7.8	1/29	11,280	7.2
11/30	28,080	8	12/30	38,460	7.8	1/30	12,320	7.0
			12/31	39,420	8.1	1/31	15,480	7.0
Ave.	15,772	8	Ave.	22,334	7.9	Ave.	15,540	7.4
2/1	18,620	7.6	3/1	27,960	7.0	4/1	9,480	6.8
2/2	19,800	7.0	3/2	21,840	7.0	4/2	9,120	7.0
2/3	10,200	7.2	3/3	13,920	7.2	4/3	8,520	7.0
2/4	10,920	7.2		11,880	7.2	4/4	7,440	6.8
2/5	13,260	7.2	3/5	9,960	7.2	4/5	8,760	6.8
2/6	15,420	7.0	3/6	8,880	7.2	4/6	7,560	6.8
2/7	19,240	7.4	3/7	11,880	7.2	4/7	6,840	7.4
2/8	20,680	7.4	3/8	21,120	7.0	4/8	6,840	7.4
2/9	22,560	7.3	3/9	15,600	7.4	4/9	7,920	7.4

(*Continued*)

Table 14.14 (Continued)

Date	Effluent (gpd)	pH	Date	Effluent (gpd)	pH	Date	Effluent (gpd)	pH
2/10	13,800	7.4	3/10	9,000	6.0	4/10	8,040	7.4
2/11	12,960	7.4	3/11	12,360	6.0	4/11	7,800	7.4
2/12	13,080	7.0	3/12	9,000	7.2	4/12	7,560	7.4
2/13	12,000	7.0	3/13	9,670	7.0	4/13	7,440	7.6
2/14	15,720	7.0	3/14	7,360	6.0	4/14	7,080	7.0
2/15	24,960	7.4	3/15	24,960	7.0	4/15	7,200	7.4
2/16	32,640	7.4	3/16	16,440	7.0	4/16	7,920	7.4
2/17	23,280	7.4	3/17	13,560	6.6	4/17	7,490	7.4
2/18	15,120	7.0	3/18	8,090	6.6	4/18	7,320	7.4
2/19	16,320	7.2	3/19	9,560	6.8	4/19	7,440	6.4
2/20	18,432	7.2	3/20	15,360	6.8	4/20	8,400	6.6
2/21	18,360	7.3	3/21	17,400	6.8	4/21	7,320	6.8
2/22	21,000	7.4	3/22	22,920	7.0	4/22	8,520	6.8
2/23	19,080	7.0	3/23	17,880	7.0	4/23	7,800	6.8
2/24	11,760	6.8	3/24	12,840	7.0	4/24	8,400	6.8
2/25	12,120	6.8	3/25	10,200	7.0	4/25	7,920	7.0
2/26	12,000	6.8	3/26	9,240	7.0	4/26	12,360	6.9
2/27	9,360	6.8	3/27	11,160	7.0	4/27	10,440	7.0
2/28	12,480	7.0	3/28	14,160	7.0	4/28	8,160	7.0
			3/29	12,600	6.8	4/29	8,280	7.0
			3/30	11,400	6.8	4/30	8,760	7.2
			3/31	9,120	7.0			
Ave.	16,614	7.1	Ave.	13,803.87	7.0	Ave.	8,136	6.8

Conversion factor : 1 gpd = 3.785 L/d.

sufficient to produce an effluent meeting the aforementioned secondary effluent discharge standards for BOD_5, O&G, and total coliforms.

3. The innovative biological–physicochemical wastewater treatment system consisting of flow equalization, RBC, and DAFF or Sandfloat (see Fig. 14.1 and the column of SASF Eff. in Table 14.10) will meet the secondary effluent discharge standards for BOD_5, TSS, settleable solids, and pH. The DAFF or Sandfloat removed some oil and grease, but did not meet the effluent oil and grease standard of 15 mg/L or below at all times. To achieve this, constant process optimization and/or operator's attention will be required.
4. Both DAFF and UV are excellent processes for removal of total coliforms (Tables 14.6–14.8 and 14.10). To ensure 100% removal of total coliforms, the UV unit is required.
5. The innovative DAFF clarifier is superior to the SSC not only in removal of coliforms, O&G, COD, TSS, and BOD but also in land space requirement and capital cost. The RBC-DAFF combination makes an efficient biological–physicochemical waste treatment system. The estimated 2007 average physicochemical treatment cost was only USD 0.2486 per 1,000 gallons of wastewater.
6. There was no noticeable groundwater contamination due to the Jiminy Peak Plant's subsurface effluent discharge.

REFERENCES

1. Wang LK (1985) Monitoring and testing program of Jiminy peak secondary wastewater treatment facilities. Lenox Institute of Water Technology (formerly Lenox Institute for Research Inc.), Technical Report No. LIR/06-85/l46, pp 21, June 1985
2. Wang LK, Wang MHS, Poon CPC (1984) Rotating biological contactors. Effluent Water Treat J 24(3):93–95
3. Wang MHS, Wang LK, Poon CPC (1986) Rotating biological contactors. In: Wang LK, Pereira NC (eds) Handbook of Environmental Engineering, vol 3. Biological Treatment Processes Humana Press, Totowa, NJ, pp 427–448
4. Goel RK, Flora JRV, Chen JP (2005) Flow equalization and neutralization. In: Wang LK, Hung YT Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ, pp 21–46
5. Wang LK, Wu Z, Shammas NK (2009) Rotating biological contactors. In: Wang LK, Pereira NC, Hung YT Shammas NK (eds) Biological treatment processes, Humana Press, Totowa, NJ, pp 435–458
6. Shammas NK, Kumar IJ, Chang SY, Hung YT (2005) Sedimentation. In: Wang LK, Hung YT Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ, pp 379–430
7. Wang LK, Fahey EM, Wu Z (2005) Dissolved air flotation. In: Wang LK, Hung YT Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ, pp 431–500
8. Shammas NK (2005) Coagulation and flocculation. In: Wang LK, Hung YT Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ, pp 103–140
9. Wang LK, Vaccari D, Li Y, Shammas NK (2005) Chemical precipitation. In: Wang LK, Hung YT Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ, pp 141–198
10. Chen JP, Chang SY, Huang JYC, Baumann ER, Hung YT (2005) Gravity filtration. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ, pp 501–544
11. Chen JP, Yang L, Wang LK, Zhang B (2006) Ultraviolet radiation for disinfection. In: Wang LK, Hung YT Shammas NK (eds) Advanced physicochemical treatment processes. Humana Press, Totowa, NJ, pp 317–366
12. Ray MB, Chen JP, Wang LK, Pehkonen SO (2006) Advanced oxidation processes. In: Wang LK, Hung YT Shammas NK (eds) Advanced physicochemical treatment processes. Humana Press, Totowa, NJ, pp 463–486
13. Aulenbach DB, Clesceri NL (2009) Treatment by application onto land. In: Wang LK, Pereira NC, Hung YT Shammas NK (eds) Biological treatment processes. Humana Press, Totowa, NJ, pp 29–74
14. Wang LK, Shammas NK, Hung YT (eds) (2008) Biosolids engineering and management. Humana Press, Totowa, NJ, pp 800
15. Wang LK (2008) Recent advances in ultraviolet technology. The 2008 National Engineers Week Celebration Meeting, Marriott, Albany, NY, 13–15 February 2008
16. Clesceri NL, Aulenbach DB, Roetzer JF (2009) Treatment by subsurface application. In: Wang LK, Pereira NC, Hung YT (eds) Biological treatment processes. Humana Press, Totowa, NJ, pp 75–112
17. Wang LK, Wang MHS (2007) Emerging induced gas flotation and dissolved gas flotation processes. 2007 National Engineers Week Conference, Albany Marriott, Albany, NY, 15–16 Feb 2007

18. Wang LK, Wang MHS (2008) Recent advances in ultraviolet technology. 2008 National Engineers Week Conference, Albany Marriott, Albany, NY, 14–15 Feb 2008
19. Wang LK, Wang MHS, Suozzo T, Dixon RA, Wright TL, Sarraino S (2009) Chemical and biochemical technologies for environmental infrastructure sustainability. 2009 National Engineers Week Conference, Albany Marriott, Albany, NY, 5–6 Feb 2009
20. Wang LK, Shammas NK, Guss DB (2010) Flotation biological systems. In: Wang LK, Ivanov V, Tay JH, Hung YT (eds) Environmental biotechnology. Humana Press, Totowa, NJ

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Pittsfield Water Treatment Plant: Once the World's Largest Flotation–Filtration Plant

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CONTENTS

Abstract When the 37.5 MGD (142 million liters per day) Pittsfield, MA, USA water treatment plant was installed in 1986 it became the world's largest water treatment plant using dissolved air flotation (DAF) and automatic backwash filtration (ABF) technologies. Design features are presented in detail along with the plant's performance data, and special features on total wastewater recycle. Total detention time of the innovative flotation–filtration (DAFF) plant is less than 20 min compared with a conventional sedimentation–filtration plant requiring 7–9 h of detention time.

Key Words Pittsfield • water treatment • dissolved air flotation • total wastewater recycle • design • performance.

1. INTRODUCTION

When the 37.5 MGD Pittsfield, MA, USA water treatment plant was installed in 1986, it became the world's largest water treatment plant using dissolved air flotation (DAF) and automatic backwash filtration (ABF) technologies. The first potable water flotation–filtration treatment plant in USA with 1.2 MGD capacity has been serving the Town of Lenox, MA since July 1982 (1–3). DAF was originally developed for treatment of industrial waste waters,

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before being used, together with separate filtration, for water treatment. The historical importance of the Lenox plant is that it pioneered the use of dissolved air flotation–filtration in water treatment.

Based on the design of the Lenox first generation demonstration plant, the 37.5 MGD potable flotation–filtration system in Pittsfield was built. The heart of the Pittsfield water supply system is two potable flotation–filtration plants: the Ashley Plant has two flotation–filtration clarifiers, and the Cleveland Plant has four flotation–filtration clarifiers. Each flotation–filtration clarifier has a capacity of 6.25 MGD. The flotation–filtration clarifier is 49 ft in diameter and 6 ft in depth, and is a package clarifier consisting of mainly dissolved air flotation and sand filtration (4).

This chapter briefly introduces the overall Pittsfield water supply system, design criteria, and operational procedures. Another paper (5) presents the City of Pittsfield's water system improvements, performance data, optimum chemical combination, and chemical treatment costs of Pittsfield's two advanced flotation–filtration plants.

2. PITTSFIELD WATER RESOURCES SYSTEM, ITS PROBLEMS AND ENGINEERING SOLUTION

The City of Pittsfield is located in Berkshire County, MA, USA. The area is about 7 miles east of the New York State border (30 miles from Albany, NY), 150 miles North of New York City, and 150 miles West of Boston. The altitude is about 1,035 ft above sea level. The average yearly total precipitation is 44.24 in.

The water of the City of Pittsfield has been supplied from three principal reservoir systems:

1. Cleveland System:
   Cleveland Reservoir (10 MGD yield; 155 MG capacity)
2. Millbrook System:
   Farnham Reservoir (2 MGD yield)
   Sandwash Reservoir (1.4 MGD yield)
3. Ashley System:
   Upper Sackett Reservoir (0.7 MGD yield; 155 MG capacity)
   Ashley Lake. (0.5 MGD yield)

All three are located at higher elevations in the hills east of the city. Total average dependable yield of the three systems is 14.7 MGD. The City's average daily demand is 15 MGD, of which General Electric, at the time, used about 6 MGD. Since the water demand slightly exceeds the total dependable yield, there has been a need for water conservation, and development of additional water supply, such as groundwater.

Before 1986, the City of Pittsfield believed that the surface reservoirs in Berkshire County provided the community with quality water that required only disinfection by chlorination before delivery to the consumers.

Extensive water quality analyses were carried out by the State of Massachusetts, the City, and consulting engineers after the promulgation of the US and Massachusetts Drinking Water Regulation in 1977. The trihalomethane (THM) formation potentials determined by

Metcalf & Eddy, Inc. in 1981 were 336 μg/L for Cleveland Reservoir, 178 μg/L for Ashley Lake, 235 μg/L for Upper Sackett Reservoir, and 418 μg/L for Farnham Reservoir, which were all substantially higher than the limit at that time of 100 μg/L permitted by the US Environmental Protection Agency (US EPA) Primary Drinking Water Regulation. THM precursors therefore had to be removed by appropriate pretreatment.

In March 1981, raw water samples from Farnham, Cleveland, Ashley, and Upper Sackett Reservoirs were collected and analyzed by Metcalf & Eddy, Inc., Energy Resources, Inc. and Interex Corporation. Their results showed that the raw water quality parameters of Farnham, Cleveland, Ashley, and Upper Sackett reservoirs were all within the maximum contaminant levels (MCL) of the US EPA Primary Drinking Water Standards and the Massachusetts Drinking Water Regulations, except for turbidity and coliforms. In addition to turbidity and coliforms, the US EPA Primary Standards on THM was violated when the raw water was chlorinated. Both the Federal and the State Drinking Water Standards are intended to protect health to the maximum extent feasible using available treatment methods and considering the costs. They are applicable to all public water systems in the State of Massachusetts and are enforceable by the governmental officials. Since turbidity and THM could not be removed by the original chlorination facilities of the City of Pittsfield, additional water treatment facilities were definitely needed.

The Secondary Standards include those contaminants that primarily deal with aesthetic qualities of drinking water and are federally enforceable only when necessary. They are intended only as guidelines for consideration by the State officials and planning engineers. A comparison between the US EPA Secondary Standards and the raw reservoir water quality data in 1982 further indicated the following:

1. The maximum color in Farnham, Cleveland, Ashley, and Upper Sackett reservoirs exceeded the recommended Secondary limit of 15 color units.
2. The maximum concentration of iron in Farnham and Cleveland reservoirs exceeded the recommended secondary limit of 0.3 mg/L.
3. The maximum concentrations of manganese in Farnham, Cleveland, and Ashley reservoirs exceeded the recommended secondary limit of 0.05 mg/L.

In addition to the aforementioned water quality problems, the City of Pittsfield also experienced Giardiasis outbreaks in the late 1970s and early 1980s before the new water treatment facilities were installed and when only minimal chlorination was practiced.

Giardiasis is characterized by moderate to severe diarrhea and other unpleasant symptoms. It is caused by a microscopic single-celled animal (protozoan), *Giardia lamblia* and is transmitted by a fecal-oral transmission cycle. Many animals, such as beavers, elk, cows, dogs, sheep, etc., are known to serve as a reservoir or carrier of Giardia in their intestines although humans are also one of the main carriers for this organism.

G. lamblia itself is a fragile organism and can be readily destroyed by minimal chlorination or equivalent. Fecal discharges from apparently healthy carriers may harbor Giardia cysts. These cysts are tough, long-lasting, can slip through inefficient filters, and are resistant to normal chlorination. Only superchlorination will affect the cysts. The negative effect of superchlorination is an increase in THMs concentrations in the chlorinated product water (6). Both color-causing substances and organic matter react with chlorine to produce THMs. THMs are cancer-causing substances. THM concentration would be more severe with heavy doses of chlorine, so superchlorination was not recommended in 1982. Instead, it was suggested that the advanced water treatment technologies (i.e., flotation and filtration) be adopted for removal of color, THMs, THMFP (THM formation potential), turbidity, iron, manganese, coliforms, and Giardia cysts.

New water treatment technologies for removal of the target impurities (turbidity. iron, manganese, coliforms, color, THMs, THMFP, and Giardia cysts) include chemical coagulation, dissolved air flotation clarification, and filtration.

Any one of the following two water treatment systems is technically feasible for removal of color, turbidity, THMs, THMFP, Giardia cysts, coliforms, iron, and manganese from Pittsfield raw water:

1. Individual coagulation/flocculation, dissolved air flotation, and filtration.
2. A package unit including flocculation, dissolved air flotation, and sand filtration.

The new Pittsfield Water Treatment Facilities utilize six flotation–filtration package clarifiers for water purification.

3. NEW PITTSFIELD WATER TREATMENT FACILITIES

3.1. *System Description*

The new water treatment system of the City of Pittsfield, MA, USA served, at the time, the City's population of 55,000 and supplied 6 MGD industrial water demand mainly for the General Electric Company. The water system consists of the Ashley Water Treatment Plant, the Cleveland Water Treatment Plant and a water distribution system. Both the Cleveland and Ashley Plants serve the same water distribution system as shown in Fig. 15.1. The entire Pittsfield water treatment facilities include four major reservoirs, chemical feed equipment, six flotation/filtration clarifiers, two chlorination stations, two flow control stations, distribution

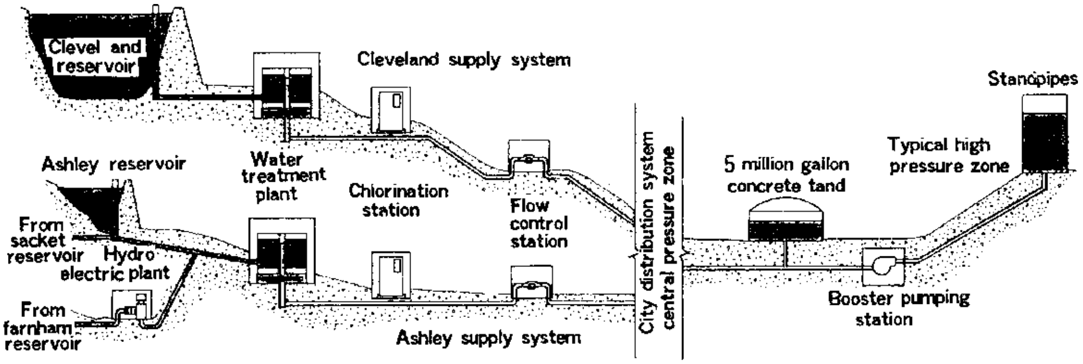

Fig. 15.1. Pittsfield water treatment system (Cleveland and Ashley plants).

pipes, one hydroelectric plant, one 5 MG concrete water storage tank, one standpipe, two pumping stations, and one central data acquisition system.

Each flotation–filtration clarifier consists of chemical feeders, mixing chamber, flocculation module, dissolved air flotation chamber, ABF module, and clearwell.

The average daily design flow and maximum daily design flow are 15 MGD and 25 MGD, respectively. The maximum daily design flow is expected to occur in the year 2015. The maximum peak capacity of the entire system, however, is 37.5 MGD, which is not ever expected to be exceeded.

The Ashley Plant is equipped with two 49-ft diameter flotation–filtration clarifiers treating an average of 5 MGD raw water from the Ashley Reservoir and/or the Farnham Reservoir. Farnham Reservoir water is low in alkalinity, high in color, and moderately turbid. Ashley Reservoir water contains sufficient alkalinity, but is also high in color and is moderately turbid.

The Cleveland Plant, which is equipped with four 49-ft diameter flotation–filtration clarifiers, treats an average of 10 MGD from the Cleveland Reservoir. The Cleveland Reservoir water contains high alkalinity, moderate color, and low turbidity.

During normal water treatment operation, one flotation–filtration clarifier at each plant is a standby unit. The flow distribution between the Cleveland and Ashley Plants has been established as shown in Table 15.1.

The Cleveland and Ashley plants have internal controls for automatic operation of the flotation/filtration package clarifiers during normal water quality and flow fluctuations. Plant operators visit each plant daily to perform necessary operating procedures and record plant data. As part of the overall improvement program, a Supervisory Control and Data Acquisition (SCADA) System has been provided to allow for remote observation and control of the treatment plants, flow control of the treatment plants, flow control stations, storage tanks, and booster pumping stations throughout the system. This computer-based SCADA system, which alerts the remote operator of problems occurring in the system, reduces the staff required for continuous operation of the water system. In addition to providing observation and control of the various remote stations, the SCADA system collects, stores, and reports the various parameters required for system operation.

Table 15.1
Flow distribution between Cleveland and Ashley plants

Flotation–filtration and flow distribution	Cleveland plant	Ashley plant
Total flotation–filtration clarifiers	4	2
Standby flotation–filtration clarifiers	1	1
Operating flotation–filtration clarifiers	3	1
Ave. daily flow, MGD	10	5
Ave. flow per clarifier, MGD	3.33	5
Max. daily flow, MGD	18.75	6.25
Max. flow per clarifier, MGD	6.25	6.25

Conversion factors: 1 MGD = 1 million gallons per day = 3.785 million liters per day.

The newly improved Pittsfield water treatment facilities include a raw water pipeline from the Farnham Reservoir to the Ashley Water Treatment Plant. Because the Farnham Reservoir is considerably higher than the Ashley Reservoir, a hydroelectric power plant has been constructed on this raw water line at the Ashley Plant site. The hydroelectric plant utilizes the available flow and head to generate power for operation of the Ashley Plant. The turbine generator operates between 5 and 12 ft^3/s and generates up to 225 kW of power.

Treated water from the Cleveland and Ashley Plants flows by gravity to the City's distribution system as shown in Fig. 15.1. Water is disinfected at the chlorination stations that existed prior to construction of the improved facilities, just downstream of each plant. The rate of flow from the treatment plants is controlled by throttling valves on each of the main supply lines just within the City limits. The Cleveland supply is throttled by a flow control station that replaced an existing valve station under the improvements program. A new flow control station was also constructed at the Ashley Plant as part of the improvements program.

Treated water entering the City of Pittsfield is delivered to customers through an extensive distribution piping network. Most of the system demands are located within the Central Pressure Zone. The pressure gradient for this zone is established by a new 5-MG concrete water storage tank. This tank supplements the flow delivered through the flow control stations and permits the maintenance of a relatively constant rate through each treatment plant. The concrete tank effectively serves as a clearwell for the plants, thereby eliminating the need for significant storage at the plant sites.

The northern, western, and southern parts of the City of Pittsfield are at higher elevations and require water pressure gradients greater than those created by the 5-MG tank. In each of the areas, separate high pressure zones have been established for servicing customers at higher elevations. Six booster pumping stations service these areas in conjunction with three new standpipes, one standpipe being located within each zone. Suction pressure is provided to five high pressure zone booster stations from the Central Pressure Zone gradient established by the 5-MG concrete tank, shown in Fig. 15.1. A sixth station is supplied directly from the pipeline leading from the Cleveland Plant immediately upstream of the Flow Control Station. The unique booster pump stations employ inline submersible pumps and motors equipped with a variable speed (variable frequency) drive to permit pumping against a variable head.

3.2. *Flotation–Filtration Package Clarifiers*

The maximum daily flow (6.25MGD) is the design flow of each flotation–filtration clarifier. Figure 15.2 shows the top and side views of a flotation–filtration clarifier (7–10). The dimensions of a typical clarifier are presented in Table 15.2.

At the manufacturer's design flow, the recommended operational parameters are:

- Maximum influent flow = 6.25 MGD
- Range of filter backwash rate = 12–20 gpm/ft^2
- Diameter of flotation/filtration clarifier = 49 ft I.D
- Diameter of clearwell = 15 ft
- Area of flotation chamber = 996 ft^2
- Area of sand filter = 1,709 ft^2

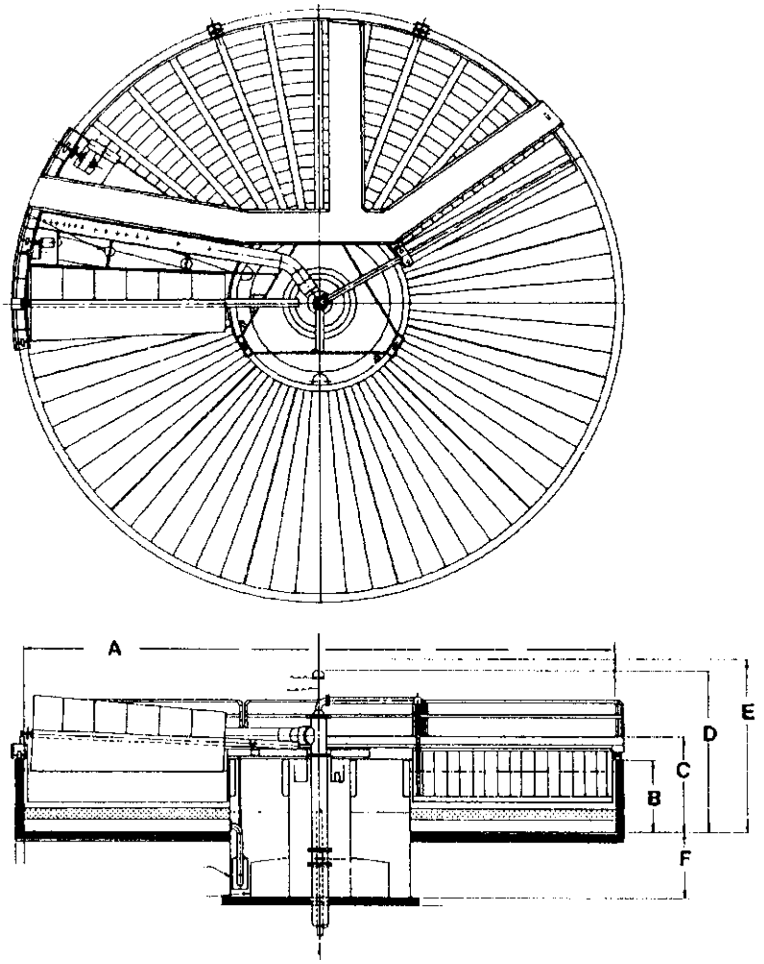

Fig. 15.2. Top and side view of a flotation–filtration clarifier (see Table15.2 for dimensions).

Table 15.2
Dimensions of a typical flotation–filtration clarifier

Package clarifier description	Notation in Fig. 15.2	Dimensions ft – in
Inside tank diameter	A	49 – 0
Height of tank	B	6 – 2
Height of carriage walkway	C	8 – 2
Maximum height of equipment	D	13 – 6
Minimum head clearance height	E	14 – 6
Tank depth	F	3 – 6

Conversion factors: 1 ft = 0.3048 m; 1 in = 2.54 cm.

- Effective filter area during backwash = 1,663 ft^2
- No. of filter compartments = 37
- No. of compartments being backwashed = 1
- Max. backwash wastewater flow = 855 gpm
- Total flow to clarifier during backwash = 5,195 gpm
- Max. flotation overflow between backwash = 4.06 gpm/ft^2
- Max. flotation overflow during backwash = 4.86 gpm/ft^2
- Max. filtration rate between backwash = 2.54 gpm/ft^2
- Max. filtration rate during backwash = 3.04 gpm/ft^2

Each flotation/filtration clarifier is designed in accordance with the latest standards, as applicable. Conversion factors for converting the above US customary units to the SI units are: 1 gpm = 3.785 L/min; 1 ft^2 = 0.0929 m^2; 1 gpm/ft^2 = 40.7 Lpm/m^2; 1 MGD = 3.785 MLD; 1 ft = 0.3048 m. Figure 15.3 shows a bird's view of a flotation/filtration clarifier to illustrate the clarifier's operation.

The notations in Fig. 15.3 identify the operating parts of the system:

A – raw water inlet
B – hydraulic joint
C – inlet distributor
D – rapid mixing
E – moving carriage
F – static hydraulic flocculator
G – backwash feed pump
H – backwash suction pumps (three required)

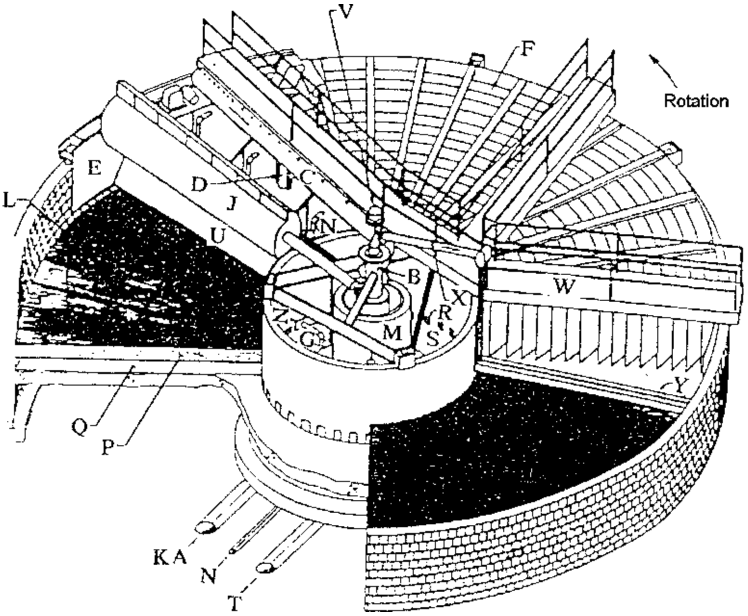

Fig. 15.3. Bird's view of flotation–filtration clarifier.

J – spiral scoop
K – chemical addition
L – flotation chamber
M – center sludge collector
N – sludge outlet
P – sand filter beds
Q – individual clear wells
R – clear water outlets
S – center clear well
T – clear effluent outlet
U – traveling hood
V – electrical contact
W – walkway with hand rail
X – dissolved air inlet
Y – dissolved air addition
Z – backwash shoe

The important parts are described below:

Moving carriage (E): The moving carriage (including inlet structure, air dissolving tube, and sludge scoop) is fabricated of 1/16 in. minimum thickness stainless steel plate, stiffened and reinforced as required to withstand normal handling and operational stresses. Stiffening of partition walls is provided to allow for draining of adjacent modules in the water treatment tank. Marine aluminum is used instead of stainless steel for the flocculation chamber.

Flocculation module (F): Each flocculation module is divided into a specified number of compartments of identical capacity by means of baffles with an adjustable opening, extending to the entire depth of the module. Each section of baffle is manually adjustable to provide for adequate slow mixing.

Flotation chamber (L): The flocculated water is saturated at several times atmospheric pressure (45–85 psig) by a pressurizing pump. The pressurized feed stream is held at this high pressure for at least 10 s in an air dissolving tube (ADT) to provide efficient dissolution of air into the water stream to be treated. The pressurized stream enters the ADT tangentially at one end and is discharged at the opposite end. During the short passage, the water cycles inside the tube and passes repeatedly by an insert, fed by compressed air. Very thorough mixing under pressure then dissolves the air in the water.

A radial distribution pipe with small holes covered by a deflector feeds the pressurized water at the bottom of the flocculator outlet. The sudden reduction pressure in the flotation chamber results in the release of microscopic air bubbles (with diameter of 80 μm or smaller) that attach themselves to suspended or colloidal particles in the process water in the flotation chamber. This results in agglomeration, which, due to the entrained air, gives a net combined specific gravity less than that of water and causes the flotation action. The floated materials rise to the surface of the flotation chamber to form a floated layer that is carried away by a spiral scoop (J). Clarified water (flotation effluent) is near the bottom of the flotation chamber and is further polished by automatic backwash filters.

The design of the dissolved air flotation chamber (main tank) (L) is of circular shape and made possible by use of the principle of "zero velocity." The influent distribution duct (part of the moving carriage) moves backward with the same velocity as the forward incoming flotation influent. A nearly “zero velocity” quiescent state in the flotation chamber is created for flotation.

Automatic backwash filtration module (G, H): Each filtration module is fabricated of 1/4 in. minimum thickness fiberglass plate of 1/16 in. minimum thickness marine aluminum plate. The filter module (P) is placed between the flotation chamber (L) and the clears well (Q).

The filter underdrains (P) are fabricated of stainless steel grid and a heavy duty screen and placed to assure uniform wash water distribution and filtrate collection. Alternatively, the filter media can be supported by 3 in. of coarse garnet and graded gravel.

***Filter media**:* The filter media can be either a single medium system comprised of 12 in. of fine silica sand (ES = 0.36 mm; UC = 1.6) or a dual media system comprised of 3 in. of fine garnet in the bottom portion of the bed and 9 in. of fine silica sand in the upper portion to provide the necessary polishing action. Dual media are provided, in size-identified bags, in sufficient volume by type and grade to enable a total depth of 12 in. after skimming of fines. All filter media conform to the physical and chemical standards of AWWA B100-80.

Inlet valve and filter level controls: Each water treatment unit is furnished with a float type level sensing system that transmits a 3–15 psig signal to control the 18-in. influent valve (modulate) and maintains a level over approximately 6 in.

The level controller is arranged to decrease the inlet flow on the rising water level and decrease the inlet valve opening. Conversely, inlet flow increases on a lowering filter level and increases the valve opening.

Air compressors: Two air compressors and tanks are provided, each of a sufficient size to provide air to the pneumatic sensor and the 18 in. influent modulating valves in each flotation/filtration clarifier. The compressors are equipped with a lead lag switch, an on/off switch, and a low air alarm light in the instrument control panel.

***Instrument control panel**:* Each flotation–filtration clarifier has one floor mounted (in the base) electrical control panel. The panel contains all timers, switches, relays, air compressor appurtenances and associated components to carry out the manually initiated, automatic chemical feed, turbidity monitoring meter, filter wash, and backwash cycles. Each automatic valve, program timer, and electrically driven accessory is furnished with a panel-mounted status light and hands-off/automatic switch. The duration of the filter backwash, chemical feed, and water quality monitoring is adjustable by the setting of individual timer mechanisms mounted on the front of the panel or on the carriage. All face mounted components are identified with engraved plastic nameplates. The panel is completely shop wired and tested prior to shipment and installation.

4. FLOTATION–FILTRATION CLARIFIER OPERATION

The location of the steps in the operational sequence may be referred to in Fig. 15.3. The operation of the treatment units is divided into two automatic cycles: service and backwash. Each cycle and the manual operation modes are summarized herein.

4.1. *Automatic Service Cycle*

The influent raw water enters the inlet at the center near the bottom (A) and flows through a hydraulic rotary joint (B) and an inlet distributor (C) into the rapid mixing section (D) of the slowly moving carriage (E). The entire moving carriage (E) consists of a rapid mixer (D), a static hydraulic flocculator (F), a backwash feed pump (G), backwash suction pumps (H), and a sludge discharge spiral scoop (J). To flocculate colloids and suspended solids, alum and/or an equivalent coagulant is added at (K) at the inlet (A). For additional improvement of flocculation, polyelectrolytes or other coagulant aids can be added at the same inlet (A) or elsewhere.

From the rapid mixing section (D), the water enters the static hydraulic flocculator (F) gradually building up the flocs by gentle mixing during the passage through the flocculator (11). The flocculated water moves from the flocculator into the flotation chamber (L) clockwise with the same velocity as the entire carriage (E), including flocculator (F), which moves counter-clockwise simultaneously. The outgoing flocculator effluent velocity is compensated by the opposite velocity of the moving carriage (E), resulting in a "zero" horizontal velocity of the flotation chamber influent. The flocculated water thus stands still in the flotation chamber (L) with minimum turbulence for optimum clarification.

At the outlet of the flocculator on the moving carriage, pressurized water with dissolved air comes through the dissolved air inlet (X) and is added at (Y). A small amount of water is taken from the inlet (A) before flowing through the hydraulic rotary joint (B) and is taken by a pressure pump (not shown) that feeds an ADT (not shown) where compressed air is added from an air compressor (not shown). The air is dissolved under pressure in the water and mixed with the flocculated raw water at the outlet of the flocculator.

The flocs and suspended solids are floated to the water surface in the flotation chamber (L). The floating scum or sludge accumulated on the water surface is scooped off by a sludge discharging spiral scoop (J) and discharged into the center sludge collector (M), where there is a sludge outlet (N) to an appropriate sludge treatment facility.

The bottom of the flotation–filtration unit is composed of multiple sections of sand filter beds (P) with individual clear wells (**Q**) below them. The outlets (R) from the individual clear wells discharge into a center clear well (S) where there is an outlet for the clear well effluent (T).

4.2. *Automatic Backwashing Cycle*

For backwashing the sand beds, four pumps (G) (H) are mounted on the carriage. During the backwash cycle, one pump sends clear water back into the individual clear well compartments (Q), which then enters the sand filter beds (P) cleaning the fluidized sand. By the use of a backwash shoe (Z), two compartments are washed simultaneously through one opening. The dirty backwash is collected with a traveling hood (U), where three backwash suction pumps (H) collect the dirty water and return it into the rapid mix inlet section (D) for repeated flocculation, flotation, and filtration. The backwash water is immediately recycled to the inlet distributor (C) for reproduction of drinking water.

Filter backwashing can be initiated automatically by predetermined high headloss, or a 0.5–3 h reset time, set for selected periods of treatment, or manually. The backwash sequence can be controlled by adjustable stop fingers on the tank wall to provide automatic stop and go over each filter's section.

4.3. *Manual Operation*

The treatment unit is provided with a manual control to allow optional manual operation, should it be required.

More detailed design features and specifications for the Pittsfield water treatment facilities can be found elsewhere (12).

5. ENCOURAGING ENGINEERING DEVELOPMENT AND PROGRESS

The conceptual design of the Pittsfield flotation–filtration system was conceived in 1981 and published by the American Water Works Association in 1982 (13, 14). Considering the nation's first 1.2-MGD potable flotation filtration plant (2. 3) built in 1982 in Lenox, Massachusetts (diameter 22 ft, depth 6 ft) as the demonstration plant for the City of Pittsfield, the State of Massachusetts eventually approved the manufacturer's plant design after careful evaluation. The ground breaking ceremony of both the Ashley and Cleveland Plants was held in March 1985. The first flotation–filtration clarifier at Ashley was started up for on-line service in October 1986, and the sixth (also the last) flotation–filtration clarifier at Cleveland was turned on for service in January 1987. The world's largest potable flotation–filtration system was thus born (see Fig. 15.4).

The combined Pittsfield Water Treatment Facilities including both Cleveland and Ashley Plants has a peak capacity of 37.5 MGD (142 MLD).

At the same hydraulic capacity and treatment efficiency, the capital cost of Pittsfield's potable flotation–filtration plant is only about one-third that of a comparable conventional

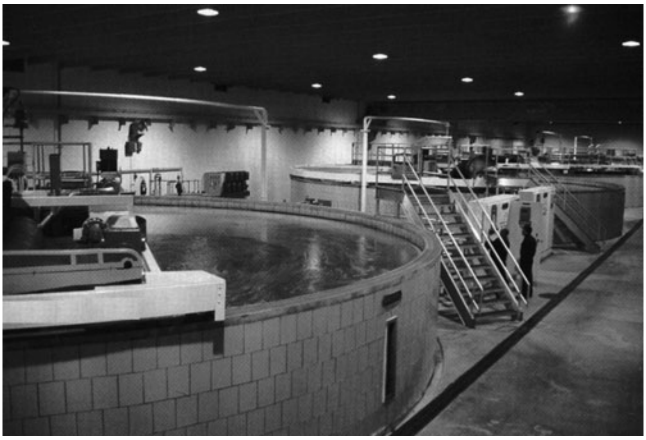

Fig. 15.4. Flotation–filtration clarifiers at Cleveland plant.

water treatment plant (including mixing, flocculation, clarification, filtration, clear well, and disinfection). Water conservation and chemical cost saving are added advantages. Flotation–filtration technology has been shown to be applicable to removal of color and turbidity, arsenic, volatile organic compounds, algae, odor, coliform bacteria, surfactants, hardness, iron and manganese, particulates, Giardia cysts, THM formation potential, and heavy metals. Flotation–filtration is technically and economically feasible for treatment of surface water, ground water, or storm runoff water, for large and small communities, institutions, and even single families (15–23).

A paper by Forestell and Wang (5) presents the City of Pittsfield' s detailed water system improvements, performance data, optimum chemical combination, and chemical treatment costs.

Tables 15.3 and 15.4 present the winter performance data from the Ashley Plant for treatment of Farnham reservoir raw water with high color (12–41 color units) and for treatment of Ashley reservoir raw water with moderate color (3–19 color units), respectively. Although the Farnham reservoir raw water temperature was very cold (1–6°C), 100% color reduction was still accomplished without any difficulty. It is important to note that Farnham water (Table 15.3) had a low temperature, low alkalinity, low pH, and high color; therefore, it had to be treated with poly aluminum chloride (Ultrion 8157) and using DAF's recycle flow pressurization mode. On the other hand, the Ashley reservoir water (Table 15.4) that had a low temperature, moderate alkalinity, neutral pH, and moderate color could be treated with common chemicals for 50% cost saving and by DAF's partial flow pressurization mode (i.e., using raw water as the ADT water source) for further cost saving.

It is also interesting to note that without the use of any chlorine the DAF-filter removed over 99% of total coliform bacteria from the raw water (Table 15.3). Accordingly, the chlorine dosage can be reduced in the final stage of disinfection.

The results in Tables 15.3 and 15.4 further demonstrate that up to 100% of the filter backwash water was successfully recycled for reproduction of drinking water. The only waste produced from each 6.25-MGD flotation–filtration unit was about 162 gpm of floated sludge. Considering the actual influent flow of 5.56 MGD per unit and the actual sludge flow of 162 gpm per unit (Table 15.3), the wastewater flow was less than 0.01% of the total raw water pumped into the plant. A conventional sedimentation–filtration process system's wastewater flow is about 10–15% of the total raw water flow because it is difficult for a conventional system to directly recycle its filter backwash wastewater for reproduction of drinking water. (25–27)

6. CITY OF PITTSFIELD DRINKING WATER QUALITY FOR YEAR 2004

In 2004, the City conducted regular and repeated tests for numerous potential contaminants (24). This section provides a complete listing of contaminants found and the level at which each contaminant was detected (see Table 15.5).

The City owns most of the land around its reservoirs and restricts the use of the land and the reservoirs to prevent contamination of its drinking water supply sources. Water from these reservoirs is treated to remove sediment and other contaminants at either the Cleveland Water

Table 15.3
Removal of high color from Pittsfield Farnham water in Massachusetts, USA by dissolved air flotation and sand filtration (December 4–7, 1986)

Parameters	Testing frequency	Range	Average
Raw water, influent			
Temperature	73	4–6	4.8
pH, unit	73	6.4–7.5	5.97
Turbidity, Grab NTU	73	1.0–1.2	1.11
Color, unit	73	12–41	32.7
Aluminum, mg/L Al	10	0.04–0.18	0.13
Alkalinity, mg/L $CaCO_3$	73	4–12	5.49
Chemical treatment			
Magnifloc 1849A, mg/L	73	0.14–0.25	0.176
Sodium aluminate, mg/L	73	25.4–28.0	26.5
Ultrion 8,157, mg/L	73	82.5–93.8	87.9
DAF/filter effluent			
Flow, MGD	73	3.5–3.7	3.57
pH, unit	73	6.6–7.5	7.05
Turbidity, Grab NTU	73	0.17–0.57	0.29
Color, unit	73	0–0	0
Alkalinity, mg/L $CaCO_3$	73	4–12	7.05
Aluminum residue, mg/L Al	18	0.07–0.18	0.1
Floated sludge			
Sludge flow, gpm	1	162–162	162
DAF/filter operational conditions			
ADT air feed rate, scfh	NA	45 × 5–45 × 5	45X5
ADT water source	–	DAF	DAF
Backwash frequency	73	1–1	1
Backwash duration, s	73	60–60	60
Percent backwash recycle	73	100–100	100

Testing frequency indicates the number of samples tested. 1 MGD = 3.785 MLD; 1 scfh = 0.0283 m^3/h.

Treatment Plant or the Ashley Water Treatment Plant. Before it is piped to the City for use, the filtered water is made less corrosive to pipes by adding caustic soda (sodium hydroxide) and polyphosphate, and it is disinfected by adding chlorine.

Contaminants that may be present in source water include microbial contaminants, such as viruses and bacteria, which may come from wastewater treatment plants, septic systems, agricultural livestock operations, and wildlife; inorganic contaminants, such as salts and metals, which can be naturally occurring or result from urban stormwater runoff, industrial or domestic wastewater discharges, and farming; pesticides and herbicides, which may come from a variety of sources such as agriculture, urban stormwater runoff, and residential uses; organic chemical contaminants, including synthetic and volatile organic chemicals from gas stations, urban stormwater runoff, and septic systems.

Table 15.4
Removal of moderate color from Pittsfield Ashley water by dissolved air flotation and sand filtration (March 11, 1987)

Parameters	Testing frequency	range	Average
Raw water, influent			
Temperature°C	14	1–1	1
pH, unit	14	6.8–7.1	6.9
Turbidity, Grab NTU	14	0.67–0.90	0.79
Color, unit	4	3–19	9
Total coliform, No./100 mL	1	5–5	5
Alkalinity, mg/L $CaCO_3$	4	24–28	25
Chemical treatment			
Magnifloc 1849A, mg/L	14	0.09–0.11	0.09
Sodium aluminate, mg/L	14	0–0.49	3.8
Alum, mg/L	14	0–48.8	36.9
DAF/filter effluent			
Flow, MGD	11	5.49–5.78	5.65
pH, unit	14	6.6–7.6	6.7
Turbidity, Grab NTU	14	0.20–0.48	0.29
Color, unit	4	0–0	0
Alkalinity, mg/L $CaCO_3$	4	14–18	15
Aluminum residue, mg/L Al	1	0.12	0.12
Total coliform, No./100 mL			
Chlorinated sample	1	0	0
Unchlorinated sample	1	0	0
Floated sludge			
Sludge flow, gpm	1	162–162	162
DAF/filter operational conditions			
ADT air feed rate, scfh	14	40 × 5–40 × 5	40 × 5
ADT water source	–	Raw	Raw
Backwash frequency	14	1–1	1
Backwash duration, s	14	60–60	60
No. of filter cells skipped	–	None	None
Percent backwash recycle	13	25–100	82

Testing frequency indicates the number of samples tested. 1 MGD = 3.785 MLD; 1 scfh = 0.0283 m^3/h.

Some people may be more vulnerable to contaminants in drinking water than the general population. Immuno-compromised persons, such as those with cancer undergoing chemotherapy, those who have undergone organ transplants, people with HIV/AIDS or other immune system disorders, some elderly, and infants, can be particularly at risk from infections. These people should seek advice from their health care providers about drinking water.

The City received an Administrative Order from the US EPA for not conducting the assessment monitoring in accordance with the original deadline set by the Unregulated

Table 15.5
Regulated contaminants found in city water in calendar year 2004

Contaminant	MCL	MCLG	Concentration	Units	Range	Number of samples
Turbidity	TT	None	0.35	NTU	0.04–0.35	4,391
Antimony	6	6	ND	μg/L	ND–ND	2
Barium	2	2	0.011	mg/L	0.009–0.013	2
Copper	AL = 1.3	1.3	0.156	mg/L	0.00057–0.309	30
Cadmium	5	5	ND	μg/L	ND–ND	2
Fluoride	4	4	0.08	mg/L	0.01–0.08	2
Lead	AL = 15	0	34.0	μg/L	ND–103.0	30
Nickel	None	None	ND	mg/L	ND–ND	2
Nitrate-N	10	10	0.09	mg/L	0.08–0.10	2
THMs	80	0	35.64	μg/L	24.89–59.36	36
Haloacetic acids	60	0	23.35	μg/L	19.11–28.40	36
Unregulated contaminant						
Chloroform	None	None	33.0	μg/L	17.0–73.1	36
Bromodichloromethane	None	None	26.5	μg/L	ND–7.38	36
Bromochloromethane	None	None	ND	μg/L	ND–ND	36
Sodium	None	None	11.6	mg/L	9.6–13.6	2

ND not detected, *AL* action level. That concentration of a contaminant, which, if exceeded, triggers treatment or other requirements which a water system must follow, *TT* treatment technique. A required process intended to reduce the level of a contaminant in drinking water. For turbidity reduction, the city is required to filter its water, *MCL* maximum contaminant level. The highest level of a contaminant that is allowed in drinking water, MCLs are set as close to the MCLGs as feasible using the best available treatment technology, *MCLG* maximum contaminant level goal. The level of a contaminant in drinking water below which there is no known or expected risk to health, *NTU* Nephelometric turbidity units.

Contaminant Monitoring Regulation (UCMR). The City has since completed three quarters of the monitoring requirements to date, and nothing has been detected.

Additional information concerning the data presented, and the City water system, may be obtained by contacting the City Hall office of the Commissioner of Public Utilities (28). The public may participate in decisions that affect the quality of City drinking water by contacting their local elected representatives or the Commissioner of Public Utilities or by attending the regular meetings of the City Council.

REFERENCES

1. Wang LK, Kolodziej PJ (1983) Removal of trihalomethane precursors and coliform bacteria by Lenox flotation-filtration plant. Proceedings of the water quality and public health conference, Worcester Polytechnic Institute, Worcester, MA, NTIS-PB83–244053, 17–29
2. Krofta M, Wang LK (1985) Application of dissolved air flotation to the Lenox, Massachusetts water supply: water purification by flotation. J New Engl Water Works Assoc, 99(3):249–264

3. Krofta M, Wang LK (1985) Application of dissolved air flotation to the Lenox, Massachusetts water supply: sludge thickening by flotation or lagoon. J New Engl Water Works Assoc, 99(3): 265–284
4. Shammas NK (2010) Flotation-filtration system for wastewater reuse. In: Wang LK, Shammas NK, Selke WA, Aulenbach DB (eds) Flotation technology, Humana Press, Totowa, NJ
5. Forestell W, Wang LK (1991) Air flotation and sand filtration: a success for Innovation in Pittsfield, MA. J New Engl Water Works Assoc, 105(3): 223–243
6. Wang LK (2006) Water chlorination and chloramination. In: Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical treatment processes, Humana Press, Inc., Totowa, NJ, pp 367–402
7. Wang LK (1988) Potable water treatment by flotation and filtration. Technical Report No.LIR/04-88/301, Lenox Institute of Water Technology, Lenox, MA
8. Krofta M, Wang LK (1984) Development of innovative flotation-filtration systems for water treatment. Part B: dissolved air flotation plants for small communities. Proceedings of the America water works association water reuse symposium III, Vol 3, pp 1238–1250
9. Krofta M, Wang LK (2000) Flotation engineering, 1st edn. Lenox Institute of Water Technology, Lenox, MA, Technical Manual No. Lenox/1–06–2000/368
10. Shammas NK (1997) Physicochemically-enhanced pollutants separation in wastewater treatment. Proceedings of the international conference: rehabilitation and development of civil engineering infrastructure systems – upgrading of water and wastewater treatment facilities, organized by The American University of Beirut and University of Michigan, Beirut, Lebanon, 9–11 June 1997
11. Shammas NK (2005) Coagulation and flocculation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes, Humana Press, Inc., Totowa, NJ, pp 103–140
12. Krofta M, Wang LK (1987) Winter operation of nation's largest potable water flotation plant. U S Department of Commerce, National Technical Information Service, Springfield, VA., No. PB88-200563/AS
13. Krofta M, Wang LK (1982) Potable water treatment by dissolved air flotation and filtration. J Am Water Works Assoc, 74(6):304–310
14. Wang LK (1982) Monitoring and analysis of potable water for the city of Pittsfield, Massachusetts. US Department of Commerce, National Technical Information Service, Springfield, VA., No.PB82-l82072
15. Wang LK, Wang MHS, Hoagland FM (1989) Reduction of color, odor. humic acid, and toxic substances by adsorption, flotation and filtration. American Institute of Chemical Engineers 1989 Summer National Meeting, Philadelphia, PA
16. Wang LK (1989) Using air flotation and filtration in removal of color, trihalomethane precursors and Giardia cysts. The state of New York workshop on water treatment chemicals and filtration, Marriott Thruway Hotel, Rochester, NY
17. Wang LK, Wang MHS (1989) Bubble dynamics and air dispersion mechanisms of air flotation process systems, Part A: material balances. Proceedings of the 44th industrial waste conference, Purdue University, W. Lafayette, IN, pp 9–11
18. Krofta M, Wang LK (1980) Bubble dynamics and air dispersion mechanisms of air flotation process systems, Part B: air dispersion. Proceedings of the 44th industrial waste conference, Purdue University, W. Lafayette, IN, pp 505–515
19. Wang LK, Wang MHS, Mahoney WJ (1989) Treatment of storm runoff by oil-water separation, flotation, filtration and adsorption, Part A: wastewater treatment. Proceedings of the 44th industrial waste conference, Purdue University, W. Lafayette, IN, pp 655–666

20. Wang LK, Wang MHS, Mahoney WJ (1989) Treatment of storm runoff by oil–water separation, flotation, filtration and adsorption. Part B: waste sludge management. Proceedings of the 44th industrial waste conference, Purdue University, W. Lafayette, IN, pp 667–673
21. Wang LK, Wang MHS (1990) Decontamination of groundwater and hazardous industrial effluents by high-rate air flotation processes. Great Lakes 90 conference proceedings, Hazardous Materials Control Research Institute, Silver Spring. MD, pp 26–28
22. Wang LK, Wang MHS (1990) Modern technologies for prevention and control of groundwater contamination. Proceedings of New York – New Jersey environmental exposition, NYNJEE, Belmont, MA
23. Wang LK, Wu BC, Meier A, Marshall J, Zepka J, Foote R, Janas J, Mulloy M (1984) Removal of arsenic from water and wastewater. Technical Report, NITS-PB86-169299, US Department of Commerce, National Technical Information Service, Springfield. VA
24. City of Pittsfield (2005) City of Pittsfield drinking water quality report for year 2004, Pittsfield, MA
25. Wang LK, Wang MHS (2007) Bubble dynamics of adsorptive bubble separation processes. 2007 National Engineers Week Conference, Albany Marriott, Albany, NY, 15–16 Feb 2007
26. Wang LK, Wang MHS (2007) Emerging induced gas flotation and dissolved gas flotation processes. 2007 National Engineers Week Conference, Albany Marriott, Albany, NY, 15–16 Feb 2007
27. Wang LK, Wang MHS, Suozzo T, Dixon RA, Wright TL, Sarraino S (2009) Chemical and biochemical technologies for environmental infrastructure sustainability. 2009 National Engineers Week Conference, Albany Marriott, Albany, NY, 5–6 Feb 2009
28. City of Pittsfield Department of Public Works and Utilities (2010) Drinking water system. http://www.pittsfield-ma.org/departments.asp?ID=47

16
Pretreatment of Meat-Processing Waste

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and William A. Selke

CONTENTS

Abstract In any effort to improve the quality of the wastewaters from a meat-processing plant, the first step must be a complete evaluation of in-plant waste-conservation opportunities. The cost of purchased water, the cost of waste treatment, and possibly the value of recoverable byproducts offer economic incentives for waste conservation. After all feasible steps in waste conservation have been taken, the degree of pretreatment of the various waste flows must be determined, first to satisfy regulations, and second to determine whether pretreatment beyond that required legally will produce economic advantages. The basic pretreatment is required by law; any pretreatment beyond this base is an economic decision. There follows an outline suggesting procedures for developing a decision matrix for waste conservation and pretreatment before discharge to a public sewer. Finally an investigation of the DAF process, its effective parameters, and its performance in the treatment of meat-processing wastewater are described and discussed in detail.

Key Words Meat-processing waste • conservation • reuse • regulations • pretreatment • decision matrix • DAF • flotation • case histories.

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1. INTRODUCTION

1.1. Background

In-plant process modification is the first step in pollution reduction in the meat-processing industry. It is a simple economic fact that conservation and in-plant waste saving, along with water recycle and reuse (1, 2), must be considered before any plant decides (a) to build pretreatment facilities for discharge to a public sewer, (b) to pay a municipal charge for wastewater treatment, or (c) to build a complete treatment plant for discharge to a watercourse.

The importance of pretreatment of meat-processing wastewaters for discharge to municipal systems becomes evident in the light of a US Environmental Protection Agency (US EPA) survey showing that 70% of the wastewater from the meat-processing industry was discharged to municipal facilities (3). Although more recent data are lacking, it is likely that this percentage may now be slightly lower with the continuing trend toward decentralization into small plants discharging into independent lagoon systems in semirural areas.

This chapter deals with waste conservation and pretreatment in existing and new plants. Many of the conservation methods discussed are applicable to new plants and can not readily be retrofitted into existing plants because of space limitations and layout. Thus, each manager and engineer can use the study as a guide and checklist, evaluating each water conservation concept as it applies to a particular plant.

Wastes from the meat-processing industry stem from a number of operations within the industry (see Fig. 16.1). The principal operations are those related to stockyards, slaughterhouses, and packinghouses (4). Stockyard wastes consist principally of manure, hay, straw, and dirt. These wastes are high in organic materials and high in nutrients. Stockyard wastes are suitable for land disposal and should be segregated and hauled or piped away for that purpose.

Slaughterhouse wastes are those resulting from the killing of animals and the preparation of the carcasses. Principal wastes are blood, grease, manure, body fluids, hair, and flesh and fat particles. These wastes, in undiluted form, are extremely high in organic content. For example, blood has the highest biochemical oxygen demand (BOD) of any liquid meat-processing material, that is, 400,000 mg/L. Paunch manure has a 5-day BOD of 100,000 mg/L. Therefore, unrecovered losses to the waste stream should be kept to a minimum.

Packinghouse wastes are those resulting from preparation of carcasses into saleable products. Processes involved are smoking, cooking, curing, pickling, and sausage making. Wastes are principally grease, blood, and flesh and fat particles. Waste streams from slaughterhouses and packinghouses tend to be high in BOD, averaging 1,000–2,000 mg/L and high in suspended solids, averaging 500–1,500 mg/L. They will also contain high amounts of nitrogen and grease that will tend to have a neutral pH. Average water use in slaughterhouses and packinghouses is from 1,000 to 5,000 gal (3,800–19,000 L) of water per 1,000 lb (455 kg) of live weight killed (LWK). Water conservation should be practiced to reduce both the water requirements and the waste flow. Recovery of much of the waste material for use as byproducts such as glue, soap, animal feed, and fertilizer is often economical.

Pretreatment of wastes in the meat-packing industry often proves economical from the dual standpoints of recovery of the byproducts and reduced sewer-use charges. Pretreatment

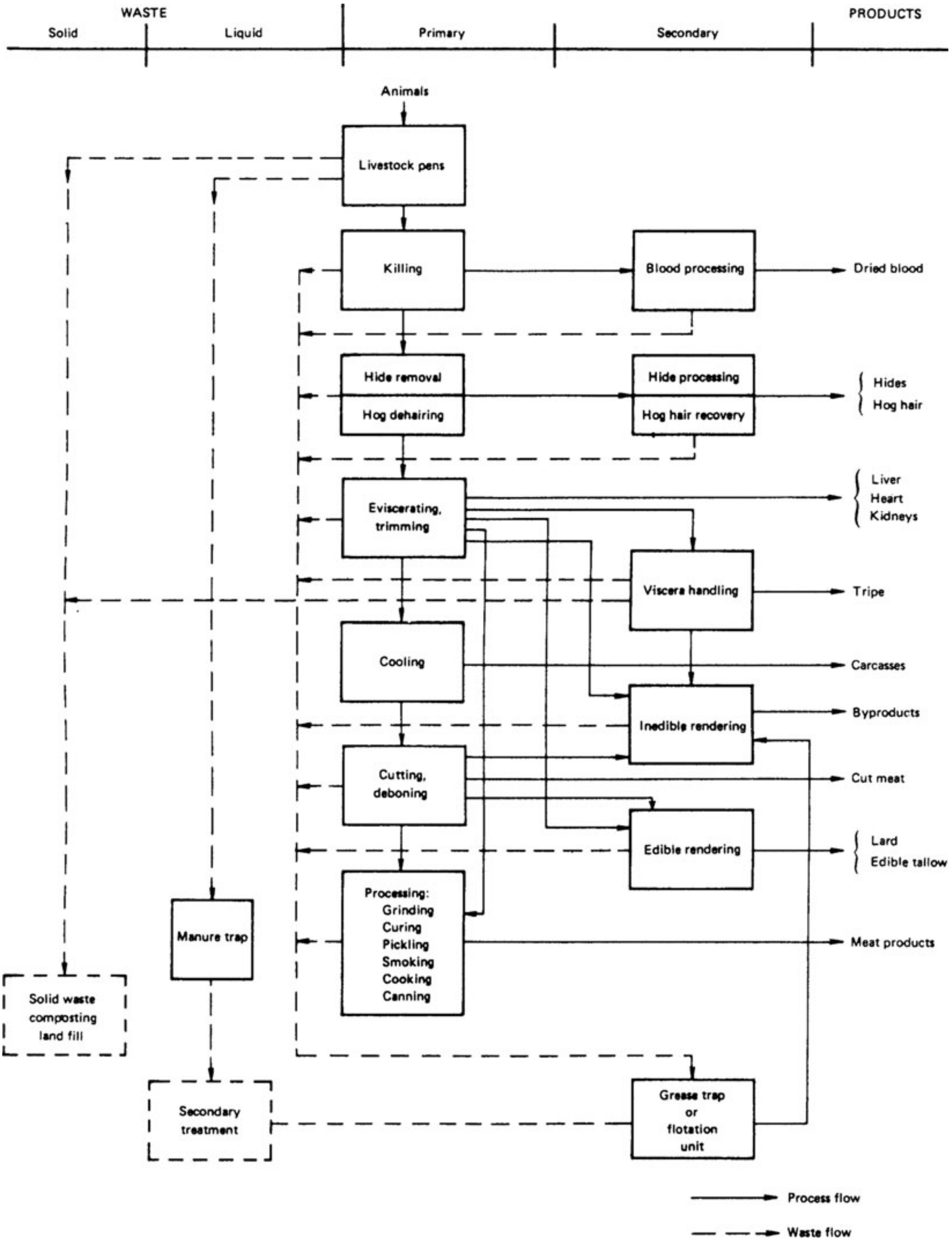


Fig. 16.1. Flow chart for meat-processing industry.

processes include flow equalization. This is usually economically advantageous because it permits smaller subsequent treatment units and averages the flow into the sewer, which often minimizes user charges. Screening is another common pretreatment process because a great deal of the waste material in meat-packing waters is in solid form. Screens should be checked frequently and cleaned as needed. Centrifuging is used to a lesser extent to remove residual grease and fine solids from waste streams.

Another widely used type of pretreatment process is the practice of grease and suspended solids separation, either by gravity and/or dissolved air flotation (DAF). Gravity grease recovery systems can remove up to 30% of the BOD, 50% of the suspended solids, and 60% of the grease from the waste stream. DAF systems will remove up to 35% of the BOD, 60% of the suspended solids, and up to 90% of the grease from waste streams (4).

1.2. Regulatory Considerations

1.2.1. Federal

Public Law 92-500, amending the Federal Pollution Control Act, that was passed by Congress on October 18, 1972 and amended in 1977, 1980, 1981, and 1987 contains several points of direct interest to industry. In providing grants for new or expanded municipal treatment plants (amounting to 75% of the construction cost), the Federal Government requires that the municipality "has made provision for the payment... by the industrial user of the treatment works, of that portion of the cost... allocable to the treatment of such industrial wastes... for which he is responsible (5)."

The law also provides that the US EPA shall "issue guidelines applicable to payment of waste treatment cost by industrial and nonindustrial recipients of waste treatment services which shall establish

1. Classes of users of such services, including categories of industrial users
2. Criteria against which to determine the adequacy of charges imposed on classes and categories of users reflecting factors that influence the cost of waste treatment, including strength, volume, and delivery flow rate characteristics (surges and maximum flows) of wastes
3. Model systems and rates of user charges typical of various treatment works serving municipal-industrial communities."

Thus, the US EPA is involved in the rate structure or formula developed for wastewater charges for all municipalities (including sanitary districts) where grant funds are allocated, in order to insure repayment of the Government's cost in proportion to the cost of the treatment works attributable to the industry's wastewater discharged to the municipal sewer. The following is excerpted from *Federal Guidelines – Equitable Recovery of Industrial Waste Treatment Costs in Municipal Systems* (6).

Quantity or quality formulas based on total cost or average unit costs: This method of cost allocation or derivation of industrial charge is computed by several forms of the generalized formula:

$$C_\mathrm{i} = v_\mathrm{o}V_\mathrm{i} + b_\mathrm{o}B_\mathrm{i} + w_\mathrm{o}W_\mathrm{i}, \tag{1}$$

where C_i is charge to industrial users, US\$/year; v_o is average unit cost of transport and treatment chargeable to volume, US\$/gal; b_o is average unit cost of treatment, chargeable to BOD, US\$/lb; w_o is average unit cost of treatment (including sludge treatment) chargeable to suspended solids, US\$/lb; V_i is volume of wastewater from industrial users, gal/year; B_i is weight of BOD from industrial users, lb/year; W_i is weight of suspended solids from industrial users, lb/year. The principle applies equally well with additional terms (e.g., chlorine feed rates) or fewer terms (e.g., v_oV_i only). The terms b_o and s_o may include charges (surcharges) for concentrated wastes above an established minimum based on normal load criteria.

In as much as it is an objective of the Guidelines to encourage the initiation and use of user charges, this general method of allocation is both preferable and acceptable.

Pretreatment before discharge to publicly owned (municipality, sanitary district, county, etc.) treatment works (POTW) is also regulated under the act. It requires that the US EPA "publish proposed regulations establishing pretreatment standards for introduction of pollutants into treatment works…, which are publicly owned, for those pollutants which are determined not to be susceptible to treatment by such treatment works or which would interfere with the operation of such treatment works."

The act allowed a maximum of 3 years for compliance by industry and also provides for revision of these standards as new technology warrants.

The limits are in two general categories:

1. Prohibited items (such as ashes, hair, whole blood, paunch manure, and similar materials untreatable in municipal plants).
2. Maximum concentrations of such items as BOD, suspended solids, and other constituents that, in excess, could interfere with the operation of the municipal plant.

The general Pretreatment Regulations, 40 CFR 403, were promulgated in 1978 and amended in 1981, 1986, and 1991. In these regulations, industries were categorized based on effluent characteristics, and national limitations were developed. Two types of regulatory programs were established by the 40 CFR 403 Regulations as follows (7, 8).

1. The Prohibitive Discharge Standards:
   (a) General prohibitions disallow industrial wastewater introduced into POTWs that
      - Passes through the POTWs untreated, and/or
      - Interferes with the operation or performance of the POTWs
   (b) Specific Prohibitions disallow the introduction of specific categories of pollutants into POTWs as follows:
      - Pollutants that may create a fire or explosion hazard in the POTWs sewer system or at the treatment plant; this includes waste streams with a closed up flash point of less that 140°F (60°C).
      - Pollutants that are corrosive, including any discharge with a pH lower than 5.0, unless the POTW is specifically designed to handle such discharges.
      - Solid or viscous pollutants in amounts that will obstruct the flow in the collection system and treatment plant, resulting in interference with operations.
      - Any pollutant discharged in quantities sufficient to interfere with POTW operations (including BOD).

  - Discharges with temperatures above 104°F (40°C) when they reach the treatment plant, or hot enough to interfere with biological processes at the WWTP.
  - Discharges to a POTW that may result in toxic gases, vapors, or fumes in quantities that could cause acute worker health and safety problems.
  - All industrial users are prohibited from discharging petroleum oil, nonbiodegradable cutting oil, or products of mineral oil origin in amounts that cause pass through or interference.
  - Trucked or hauled wastes are prohibited from discharge, except at discharge points designated by the POTW.
2. The Categorical Discharge Standards:

Originally, US EPA's focus was on the conventional pollutants. The most common conventionals are BOD, total suspended solids (TSS), fecal coliform, pH, and fats, oils, and grease (FOG). After many lawsuits, US EPA agreed to undertake a major review of industrial effluent discharge limitations. What they found was there were many pollutants that were not being regulated that were often damaging to the environment. There was a shift in direction from monitoring the conventionals to the toxic pollutants. A toxic pollutant is defined as being harmful to one or more forms of plant or animal life. US EPA has established standards for many industrial categories that have been determined to discharge toxic pollutants. These toxic pollutants are defined as the "priority pollutants." There are 126 identified organic and inorganic toxic pollutants (8).

Treatment plants are not designed to treat toxics. For example, heavy metals are harmful to the bacteria. Any industry that generates any of these chemicals in its wastewater is regulated by Federal pretreatment standards, as well as local regulations. These are called *categorical discharge standards* and are enforced in addition to the Prohibited Discharge Standards (8).

In 2001, US EPA published an Environmental Management System (EMS) Guide (9), a systematic approach to achieve a meat-processing plant's environmental and other organizational goals. The aim of the Guide is to improve a meat-processing plant's ability to comply with environmental laws and regulations, find ways to improve environmental performance, provide protection against significant liability, and manage its environmental obligations effectively.

Effluent guidelines are the national regulations that control the discharge of pollutants from industrial facilities to surface waters. US EPA sets effluent limitations based on process or treatment technologies that are technically feasible and affordable. Since 1974, US EPA has promulgated effluent guidelines for more than 50 industrial categories. On February 26, 2004, US EPA established new wastewater discharge limits for the Meat and Poultry Products (MPP) industry (10, 11). The MPP regulation affects about 170 facilities that discharge wastewater from slaughtering, rendering, and other processes such as cleaning, cutting, and smoking.

The new rule reduces discharges of conventional pollutants, ammonia, and nitrogen to rivers, lakes, and streams. The new estimates are that compliance with this regulation will reduce discharges of nitrogen up to 27 million lb/year, ammonia by 3 million lb/year, and conventional pollutants by 4 million lb/year.

Nutrients, including nitrogen, are the fifth leading type of pollutants contributing to the impairment of rivers and streams. Nutrients are the leading contributor of pollutants to impaired lakes. Nitrogen occurs in MPP discharges in several forms, including ammonia and nitrate. Ammonia is toxic to aquatic life and reduces the level of oxygen in the waterbody. Too much ammonia and other forms of nitrogen can lead to fish kills, reduced biodiversity, and growth of toxic organisms.

1.2.2. State

This discussion will be limited to the state's role in in-plant conservation and pretreatment before discharge to public sewers. Recycling and reuse of water, and any other major in-plant changes, should be reviewed with the State meat inspection agency if the plant is under State, rather than federal, inspection.

Most states require approval of plans for pretreatment of wastewaters before discharge to public sewers. Some states require a state-licensed wastewater-treatment plant operator for such pretreatment facilities.

State pollution control authorities generally review municipal ordinances relating to wastewater.

If a city has not passed the legislation required by the US EPA for a federal grant for wastewater treatment plant construction, the state that allocates these funds may advise US EPA to withhold a portion of the grant until all requirements are met (5).

When a new plant is planned for connection to a public sewer, and such connection substantially will increase the flow or pollutional characteristics of wastewaters reaching the municipal wastewater treatment plant, the agency owning the sewer is required by federal law to advise the state of such change.

1.2.3. Municipal

Municipal ordinances and regulations covering discharge to the public sewers vary widely. Ordinances commonly contain an extensive list of limiting characteristics applicable to meatpacking wastewaters discharged to public sewers. They generally cover the subject under two headings, limitations and surcharges (5).

1. Limitations

Prohibition of objectionable matter: Various minerals, toxic materials, and waste characteristics and materials that are difficult to treat, as has been required by federal regulations, are excluded.

Concentration of pollutional characteristics: Limits are included in many municipal ordinances. The following is an example from The Ordinance of the Metropolitan Sanitary District of Greater Chicago. It provides no top limits for BOD or suspended solids, but does include surcharges for these items. It does, however, limit temperature to a maximum of 150°F (65°C) and fats, oils, or greases to a maximum of 100 mg/L. Other cities may limit BOD_5 to possibly 300 mg/L and suspended solids to 350 mg/L, more or less. Catchall clauses also are common; for example, "The Town Board of Trustees is authorized to prohibit the dumping of wastes into the Town's wastewater system which, in its discretion, are deemed harmful to the operation of the wastewater works of said Town" (5).

2. Surcharges

The Metropolitan Sanitary District of Greater Chicago charges are based on cent/1,000 gal, cent/lb of BOD, and cent/lb of suspended solids, after deducting the first 10,000 gal/day (and the BOD and suspended solids it would contain). Also deducted are the sewer district tax (a property-type tax) plus an allowance for sanitary wastewater discharged during the working day.

Most of the simpler wastewater billing systems are, based on the water use, ranging from about 50% to as high as 125% of the water billing, with maximums for BOD, suspended solids, grease, and sometimes other ingredients. These are basic sewer charges applicable to all users – domestic, commercial, and industrial – and are not classified as surcharges unless they include escalation for BOD, suspended solids, grease, and so forth, and possibly flows, in excess of a “domestic” base. Thus, the surcharge portion of the ordinance might be similar in structure to the Chicago ordinance, but with a charge for flow in excess of a base and a charge per pound of ingredients above a base represented by discharge from a single residence.

In general, the Federal act has radically modified municipal ordinances and regulations. It should also be noted that recycle and reuse of wastewater must be checked by the US Department of Agriculture and by any other agency having jurisdiction over product sanitation. For help on environmental compliance by a meat-processing plant the reader is referred to the US EPA checklist publication (12).

2. IN-PLANT MODIFICATIONS TO REDUCE POLLUTION

2.1. Waste Conservation Practices

Except for very small slaughtering plants, most plants recover blood, screenable solids, and grease by various in-plant systems and devices. Many small packers without blood-drying facilities or inedible-rendering departments recover such materials for local tank truck pickup operated by specialized byproducts plants in the area.

The quantity of water used varies widely, based on waste-conservation practices, blood- and solids-handling methods, and the amount of processing done in the plant. This quantity may range from about 0.5 to 2 gal/lb LWK.

The degree of wastewater conservation, recycle and reuse and solids, and blood recovery in each individual plant depends on many factors (5, 13):

1. Age of the plant
2. Views of management
3. Whether markets or final disposal facilities for recovered blood, solids, and grease are readily available
4. Market prices of the recoverable materials
5. Local regulations regarding effluent quality and surcharge costs for plants discharging to public sewers
6. The first cost and operating costs of independent treatment if the packer discharges to a watercourse

The low market price for recovered inedible grease in some localities has forced many packers to dispose of it as feed-grade grease. If the meat-packing plant is located conveniently near a soap plant, the possibilities of an improved price will provide special incentives for grease recovery. Variations in economics in disposing of the solids and concentrates such as paunch manure, blood, hair, casing slimes, and concentrated stick (in wet rendering) inevitably affect the diligence with which these pollutional solids are kept out of the sewer.

The limitations and surcharge regulations for wastes discharged to city sewers, however, or the cost of complete treatment if the plant discharges to a watercourse, must be evaluated carefully to establish the level of waste conservation appropriate to the packing plant (14). For example, a plant discharging to its own anaerobic-aerobic pond system may find that some floatable inert solids, such as stockpen bedding, can improve the insulating scum blanket on the anaerobic lagoon. In this case, neglect in recovery of such materials would not be important. On the other hand, a packing plant in Springfield, MO, faced with a municipal waste-treatment charge of US$ 1,400 a month, modified its production processes (including solids recovery) so that the monthly payment dropped to US$ 225.

In processing and in quality control, the meat industry finds water an essential tool to help cleanse the product and to convey and remove unwanted materials. But in wastewater handling, water becomes a problem diluter that flushes and dissolves organic matter and carries it to the sewer. Wastewater treatment is basically nothing more than a processing system to separate the organic and inorganic matter from the water that collected it.

The goal of every wastewater engineer is to remove organic solids “dry,” without discharging to the sewer, and then use an absolute minimum of water for the essentials of sanitation. The nearer this goal, the simpler becomes the wastewater problem. This goal provides the pattern in waste conservation in the plant. According to the World Bank Handbook (15), in-plant measures that can be used to reduce the odor nuisance and the generation of solid and liquid wastes from the meat production processes include the following:

1. Recover and process blood into useful byproducts. Allow enough time for blood draining (at least 7 min).
2. Process paunches and intestines and utilize fat and slime.
3. Minimize water consumed in production by, for example, using taps with automatic shutoff and improving the process layout.
4. Keep waste solids in bulk whenever possible, for disposal as a solid or as a concentrated sludge, without discharging to the sewer. Eliminate wet transport (pumping) of wastes (e.g., intestines and feathers) to minimize water consumption.
5. Reduce the liquid waste load by preventing any solid wastes or concentrated liquids from entering the wastewater stream.
6. Cover collection channels in the production area with grids to reduce the amount of solids entering the wastewater.
7. Separate cooling water from process water and wastewaters, and recirculate cooling water.
8. Implement dry precleaning of equipment and production areas prior to wet cleaning.
9. Clean with high pressure and minimum water volume (small hoses).
10. Equip the outlets of wastewater channels with screens and fat traps to recover and reduce the concentration of coarse material and fat in the combined wastewater stream.
11. Optimize the use of detergents and disinfectants in washing water.

12. Remove manure (from the stockyard and from intestine processing) in solid form.
13. Dispose of hair and bones to the rendering plants.
14. Reduce air emissions from ham processing through some degree of air recirculation, after filtering.
15. Isolate and ventilate all sources of odorous emissions. Oxidants such as nitrates can be added to wastes to reduce odor.
16. Control volume, temperature, and pressure automatically. Manual regulation can lead to waste.
17. Use valves that shut off automatically when the water is not needed. For example, photoelectric cells are used to turn water on when the product is in a washing position.
18. Study each process independently. General rules alone will not do the job.

2.2. *Segregation of Waste Streams*

In meat packing, it has been common practice to provide separate sewer systems for grease wastes, nongrease (variously termed "manure" sewer or "red" sewer), clear waters from chilling, condensing, and cooling operations, surface and roof water (surface drainage), stockpen wastes, and sanitary wastes. For new plants, however, further segregation often is desirable in order to permit removal of pollutional ingredients before the wastewaters mingle with other plant waters. Screening equipment can be smaller and can be designed for the special solids present. In some cases, such segregated waters may be sufficiently dilute to use for recycling.

In the interests of dry or semidry manure separation, a separate manure sewer should be provided in new plants for all sources of manure. This waste can be pretreated by screening (16), followed by DAF (17–20). The floated solids can be analyzed for fats and wet-rendered if warranted.

The grease sewer should receive only those wastes that contain grease. If the color of the rendered tallow is a factor, special diligence must be exercised that all manure-bearing wastes are kept out of the sewer. The settled solids should be discharged over a screen, dried, and used in feeds, if possible. These solids contain a significant amount of grease. Basically, the grease sewer should receive wastes from boning, cutting, edible and inedible rendering, casing washing (after manure and slime have been removed), canning, sausage manufacturing, slicing, prepackaging, smoking and smoked meats hanging, cooking, tank car loading and washing, carcass coolers, lard and grease storage areas, equipment washrooms, pickling areas, and the like.

The conventional nongrease sewer receives wastes from hog scalding, dehairing, tripe washing, chitterling washing, and kill drains up to and including the polisher. It also receives the flow from manure recovery systems when a separate manure screen is not provided.

Hide-processing waters commonly are recirculated with or without screening for solids reduction. If these waters must be dumped, they should be screened separately and then discharged to the nongrease sewer.

Vapors from cooking and rendering operations can be cooled and condensed through heat exchangers and recycled to driers or sent to the grease sewer.

All clear water (jacket-cooling water, air conditioner water, steam condensate, and chill water) should be separated carefully for reuse.

Curing pickle (undiluted) has a very high BOD and should be reused whenever possible. Runoff pickle from processing should be caught in recycling pan systems as part of the injection equipment. In a study, it was found that only 25% of the pickle produced was retained in the product, and the rest was lost by general leakage and spilled from the injection machines. The BOD of pickle varies, but the dextrose alone has a BOD of about 660,000 mg/L (5).

Sanitary wastes are, of course, discharged directly to the city sewer or to a separate treatment system and should not enter any pretreatment elements.

2.3. *Plant Waste Conservation Survey*

The first step in waste conservation is a well-organized and well-executed waste-conservation survey, backed by management. The following elements would be part of the basic survey (14).

First the engineer should collect data on the volume, nature, and general facilities of the business. If he/she is a company employee, this information should already be available. All plans for future construction should be known. An attempt should be made to develop a 10-year forecast of business. If the wastewaters discharge to a city sewer, he/she should know something about population trends in the area, the possibilities of industrial growth, and whether such growth will add load to the municipal plant. Whether the wastewaters discharge to a public sewer system or to the packer's private treatment plant, the engineer should be familiar with the system, the wastewater treatment plant, and the requirements for the receiving stream.

The approach to wastewater control need not be complicated or expensive. The principal effort should be applied toward preventing product (and contaminants) from entering the waste stream and reducing water use to a minimum. High waste-load areas should be probed first. Accurate sampling, chemical analysis, and flow measurements need not be performed initially, but can be deferred until after the gross problems have been solved.

Since most suspended solids in meat wastewaters are organic, their removal results in a reduction of BOD. Suspended solids concentrations (after screening) are a rough measure of BOD and can be measured easily and quickly. Dissolved solids can be measured with a conductivity meter. Red color indicates the presence of blood, a very large contributor of BOD. During the initial phase of in-plant waste control, approximate figures are sufficient. Flows must be measured at the time of sampling. Flows can be estimated, or it is simple to catch the flow in a pail or 50-gal drum for a period of time. The gpm can be calculated. In some instances, it may be necessary to break into a sewer line or disconnect a pipe to obtain a sample or flow measurement.

Solids per unit volume, with associated water consumption, will give a measure of the pounds of organic wastes generated. Problem areas then can be studied for methods of

Table 16.1
Typical waste generated by a meat-processing plant, all species

Parameter	Waste/1,000 LWK
BOD_5	4–18 lb
Suspended solids	3–17 lb
Grease	1.5–12 lb
Flow	600–2,000 gal

control. In many cases, a small outlay of money will effect substantial waste control. Records should be kept to follow progress.

Table 16.1 lists waste-load ranges to provide a rough guideline (5). These ranges are broad because they include small and large operations – some small plants with no inedible rendering and no blood recovery and others with a broad line of meat processing, with inedible rendering and blood recovery.

The following equation can be used to convert laboratory analyses (mg/L/1,000 lb LWK) and flow to lb/1,000 lb LWK:

$$\text{lb pollutant}/1,000\,\text{lb LWK} = \text{flow in gal} \times 8.34\,(\text{mg/L}/1,000\,\text{lb LWK}) \times 10^6 \qquad (2)$$

Anyone interested in typical flow, BOD, suspended solids, and grease from various processing operations will find useful data in *Industrial Wastewater Control* (21). These values vary widely from plant to plant; thus, it will be most useful to cite methods of correction without attaching specific values to each process or process change. The order of priorities for in-plant waste conservation will vary depending on the results of the waste-conservation survey in each individual plant.

2.4. *Recovery of Solids and Byproducts*

2.4.1. *Blood*

Blood has the highest BOD of any liquid material emanating from meat processing with an ultimate BOD (approximately 20-day) of 405,000 mg/L. Customary analytical methods for 5-day BOD (BOD_5) are not sufficiently accurate in these high ranges, but are estimated to average from 150,000 to 200,000 mg/L. Considering that one head of cattle contains approximately 49 lb of blood, the BOD_5 of blood from a single animal is about 10 lb, as against about 0.2 lb BOD_5 discharged per person per day (5).

Thus, if the blood from a single animal killed in a day is discharged to the sewer, its pollutional load would be equivalent to that of 50 people. Clotted blood (about 70% of the total) has a BOD (ultimate) of about 470,000 mg/L, while the liquid portion is about 200,000 mg/L (22). Comparing these figures with the ultimate BOD of domestic wastewater, about 200–300 mg/L (23), it is evident that blood conservation pays.

The curbed bleeding area that discharges to the blood tank should be as long as possible, and the blood should be squeegeed to the blood tank before the valves are switched to drain to the sewer for the cleanup operation. The floor and walls then should be cleaned with a minimum of water by use of small-diameter hoses. If the water used in the first rinse is held down to 30–50 gal, it can be discharged to the blood tank as an added conservation measure. The additional cost of evaporating this quantity of water will, in most cases, be far less than the cost of treating it as wastewater.

Water is sometimes mixed with blood to facilitate transportation in pipes. The evaporation of this added water in the drier adds expense and often can be eliminated if the drain from the bleeding area to the blood tank is large enough and the blood tank is located to permit a straight drop into it. If the blood is pumped to the tank, the piping layout should be checked. If sewer alignment cannot be improved to prevent drains from clogging, decoagulating electrodes can be installed to prevent coagulation. Troughs to catch and convey blood should be pitched and curved to facilitate squeegeeing before washing.

Blood-processing methods are important in waste conservation. For lowest losses to the sewer, continuous driers are most common, using a jacketed vessel with rotating blades to prevent burn-on. Continuous ring driers are also popular. They produce a relatively small amount of bloodwater that, in small plants, usually is discharged to the sewers. The bloodwater can be clarified further by discharging it through a small settling tank. This waste conservation problem warrants further study. The older steam coagulation systems are more serious problems in waste conservation, because a substantial amount of fines can be lost when the coagulated blood is screened. A combination of paunch manure solids and bloodwater can be cooked to produce a hydrolyzed hair stick, but the process economics should be explored before a packer embarks on such a project (24). Casing slimes can be added to the blood drier if desired or can be dried with other products in conventional inedible dry rendering.

2.4.2. *Paunch Manure*

Paunch manure is either wet or dry dumped for recovery of tripe. Wet dumping consists of cutting the paunch open in a water flow, discharging to a mechanical screen, and thence to the manure sewer. This washing action carries a large fraction of the BOD from the paunch waste solids into the water phase. Paunch solids are about 75% water, weigh about 50–60 lb/animal, and have a “dry dump” first-stage BOD of over 100,000 mg/L (BOD_5 slightly less). Eighty percent of this BOD is soluble (5).

Dry dumping consists of dry discharge of the manure solids down a chute to an inedible area for ultimate disposal as a waste solid or for blending to produce a marketable solid. After dry dumping, fines are removed by washing and are discharged into the manure sewer.

Stomach and peck contents may contain undigested grains that contain proteins and fats. An investigation may disclose that these materials can be routed directly to a drier, unopened, if the resulting product is acceptable as an ingredient in the end product.

2.4.3. *Casing Saving*

Casing-saving operations contribute substantially to pollution. Waste from the deslimer should be passed directly to cookers in inedible rendering or dried with the blood. A small catch basin in the immediate casing area will recover sizable amounts of good-quality fats. Water should be kept at a minimum. Sprays should be checked for efficiency in volume of water used, proper design, proper direction, and maximum spacing.

2.4.4. Stockpen Wastes

Stockpen wastes are high in nutrients and should be segregated in a manner to allow alternative methods of disposal. Pens should be dry cleaned, and the waste should be hauled away for land disposal.

Usually runways and pens are hosed down periodically. Consideration should be given to segregation of this strong liquid waste for disposal by trucking or piping for disposal directly on farmland, within the limits of regulations regarding land disposal (25–27).

2.4.5. Scraps and Bone Dust

Plant operations in cutting and trimming should be examined carefully for opportunities to intercept waste solids before they enter the sewer. Scraps and liquids from the hog-neck washer should be caught in a container directly beneath the washer. Some form of grease trap can suffice. Collected contents should be routed directly to rendering. Bone dust from sawing operations is an important source of pollution and contains a high concentration of phosphorus. Bone dust is of fine texture, and when diluted with water it is difficult to recover. It should be recovered intact by catching directly in containers, or by sweeping up and hauling to the inedible rendering department.

2.4.6. Hide Curing

Hide-curing operations are becoming increasingly involved as segments of tanning operations are transferred from tanneries to beef-slaughtering plants. During winter months, a single hide can contain 60 lb of attached lumps of manure, mud, and ice. In addition, salt, caustic, acids, and fleshing waste enter the wastewater stream. The wash water should be recycled or retained for separate treatment (usually screening) if considerable volumes are involved.

2.4.7. Disposal of Tank Water

If lard is wet rendered, or if any inedible wet rendering is in service at the plant, the disposal of tank water may be a problem (BOD_5 about 22,000 mg/L). In processing lard by low- or medium-temperature continuous rendering, one process uses about 150 lb of water (as steam) per 230 lb wet-rendered product. There is, however, a market in some areas for 50–60% edible stickwater produced by evaporating this tank water (5). In another process, less water is used and it goes out with the cracklings. In contrast, inedible tank water is evaporated and is commonly blended with animal feed as inedible stickwater. Under no circumstances can this high-BOD waste be discharged to the sewer. In some cases, the tank water can be trucked to a central processing plant for evaporation. It can also be dried with inedible solids.

2.5. *Water and Product Conservation*

Water conservation is an essential part of an in-plant wastewater-control program. It has been shown that packing plants using the most water per animal generate the most waste per animal. Excessive washing, especially with hot water, removes juices and tissues from product and flushes them into the sewers. Water use can be reduced at many locations.

The viscera-pan sterilizer and the final carcass washer are large water users. These washing operations should be modified so that when the carcass chain stops the water automatically shuts off. This modification can be made using solenoid-operated valves under control of the conveyor chain motor starter. The viscera-pan sterilizer uses large amounts of 180°F water. The sterilizer often runs continuously during the workday (and during the cleanup period). Thought should be given to engaging the services of those skilled in spraying techniques – not only to design the sterilizer for economy in water use but also to design cleaned-in-place (CIP) cleaning systems for the viscera pans. The sprays on the final carcass washer should be checked for proper spacing, direction, shape of spray, pressure, and water consumption.

2.6. *Selection and Modification of Process Equipment for Waste Conservation*

2.6.1. *Chitterling Washers*

Chitterling washers can be improved by fitting them with limiting orifices and spray nozzles rather than drilled pipes. Water consumption can be reduced from 130 to 70 gpm by proper design of sprays and control of water and pressure on these units (21).

2.6.2. *Hog-Casing Cleaning Machines*

These machines can be modified to recover the slime from the stripper, which amounts to 0.2 lb of dry solids per hog (21).

2.6.3. *Scalding Tub*

A means of slow drainage of the scalding tub and separate removal of the sludge will reduce the waste concentration materially. It is reported that 100 hogs, at maximum slaughter rate, produce 11.2 lb of BOD and 23.5 lb of suspended solids (21). It may be expected that as much as 30% of the BOD and 80% of the suspended solids will settle in the tub. The scalding tub can be fitted with a perforated riser pipe in the drain, extending about 0.5 ft above the floor of the tub. The residual sludge can then be squeegeed through a 1-ft^2 sluice gate at tank floor level and discharged to a truck for disposal as waste solids.

2.6.4. *Edible Rendering*

Low- or medium-temperature continuous edible rendering can be accomplished with a limited amount of water discharged to the sewers. This factor should enter the cost analysis when a new system is purchased.

2.6.5. *Hasher-Washer Screen*

It is not uncommon to eliminate the hasher-washer screen. The entire product can be dry rendered if the quality of the rendered product is not a sensitive consideration. The added bulk in dry rendering is small when balanced against increased yield and the elimination of the hasher-washer screen drainage.

2.6.6. *Automated CIP Cleaning*

For daily cleaning, consideration should be given to automated cleaning of viscera pans, tank trucks, continuous rendering systems, conveyor tables, piping, cookers, and driers. Systems that will conserve water and labor are available from detergent manufacturers.

2.6.7. *Heart Washers*

A considerable amount of raw water is used to chill hearts in modern heart washers. A study of this operation may prove that the use of refrigerated chill water will conserve water and result in a better shelf-life product.

2.6.8. *Offal Areas*

In the offal areas, continuous streams of water sometimes are used to aid in moving product down chutes. Special sprays or redesign of chutes will reduce water use at these points. Any sprays made up of a pipe with drilled orifices are usually inefficient and should be replaced with engineered sprays, designed for minimum water consumption, proper pressure, and maximum effective coverage. Master shutoff valves can be used to shut groups of sprays during rest periods. Ball-type valves are effective for this service.

2.6.9. *Knife and Sterilizing Boxes*

Knife and sterilizing boxes often are operated with excessive amounts of water and temperature. The use of electric temperature-controlled knife boxes should be considered – particularly in coolers where steam causes condensation problems and refrigeration losses.

2.6.10. *Sanitary Facilities for Personnel*

Press-to-open valves (foot or knee operated) should be used on all lavatories. Drinking fountains should not run continuously. Refrigerated water fountains will conserve water.

2.6.11. *Animal Drinking Water*

Animal drinking water should be minimal, but consistent with satisfactory yields. In the past, it was believed that abundant drinking water was necessary for good yields; consequently, drinking troughs flowed continuously. Later research indicated that animals can go 1 or 2 days without water and show negligible yield reduction. Time clock control of the master valve for drinking water supply, programmed for 1 min on and 4 min off, will reduce water use by 80% (5).

2.6.12. *Raw Water Recycle and Blowdown Water*

Once-through raw water in refrigeration condensers and compressor cooling jacket water are expensive. Such water should be either reused in plant processes or recycled through heat exchanging devices – cooling towers or evaporative condensers. Evaporative condensers are usually the most feasible.

If possible, blowdown water should be returned to the soil because of its high mineral content. Generally, regulated quantities can be discharged to the city sewer directly without violating limiting regulations. Boiler blowdown water is “soft water” and can be reused in cleanup operations or in fabric wash machines. Some experimentation is required to develop a proper blend of plant water supply with the blowdown water, particularly relating to temperature.

2.6.13. Manual Washing

Manual washing of meat and offal products can be improved. Washing operations requiring under-the-spray time of less than 50% should have press-to-open sprays. On-site observations have disclosed many hand-washing operations (particularly offal) with time under the spray of not more than 10% (5). Sprays should not flow unattended at work tables. In addition to press-to-open spray valves, efficient redesign of spray heads will improve product cleaning and conserve water. Pressures and volume of flow should be controlled with pipe restrictions or locked valves to establish a minimum consistent with quality results. Photoelectric cells could serve well as automatic control.

2.6.14. Dry Rendering

In dry-rendering systems, many plants mix raw cold water with cooking vapors from rendering driers to condense vapors and reduce odors. This mixture is discharged to the sewer.

A study of a typical operation disclosed that each drier used 120–130 gpm of water, and the mixture contained 118 mg/L of BOD_5 and 27 mg/L of grease (5). It is likely that the BOD and grease were carried over from overloaded driers. The water consumption represented 40% of the entire plant water. A heat exchanger was recommended for direct water condensing to eliminate the cooling-water loss. Heat extracted from the vapors can be removed by means of a cooling tower or returned to the plant’s hot water system. Commonly, cooking operations closely follow killing operations; thus the recovered heat can be reused.

In some instances, a portion of DAF cell effluent is routed to the condensers of inedible cooker vapor. Details on DAF are given in Sect. 3.

Condensed cooking vapors from dry-rendering operations should be routed to the fat-bearing stream if they contain a significant amount of recoverable solids.

2.7. Water and Waste Conservation in Cleanup Operations

Old-fashioned cleanup operations usually use excessive amounts of water, hot and cold. Many cleanup hoses discharge 10–20 gpm of high-velocity, 140°–180°F hot water (5). Some operators believe that a flood of hot water for cleaning floors and equipment is necessary. Not only is indiscriminate use of hot water undesirable from a wastewater-control standpoint, but such practice erodes floors and walls, removes lubrication from equipment, and can cause electrical failures.

It is altogether too common for cleanup workers to remove floor-drain grates and flush meat scraps down the drain, believing that a screen or catch basin will trap all solids. By the time the scraps are recovered, they have been broken up in the flow, and much of the organic matter has been dissolved or suspended in the wastewater to the extent that it cannot be removed without complete treatment – by the packer or by the city. What started as a removable scrap has become a part of a wastewater treatment load.

Floors and equipment should be dry-cleaned before hosing, and scraps should be taken to the inedible rendering. This first step in cleanup requires rigid surveillance.

Smaller nozzles on smaller hoses and application of modern cleaning methods will reduce water. For example, a kink-type valve, which is inserted in the hose and opens only when the hose is bent, will automatically stop the water when the operator drops the hose. Water should be controlled automatically to maintain the lowest temperature, lowest volume, and highest pressure consistent with each cleaning job. Effective detergents to emulsify fats and lift proteins and soil will reduce the quantity of rinse water required. Well-qualified cleaning consultants are available for guidance. As discussed earlier, the use of automated CIP systems will reduce and control water use.

3. PRETREATMENT OF WASTEWATER

3.1. *Introduction*

3.1.1. Advantages and Disadvantages of Pretreatment

Although compliance with regulations regarding the quality of a meat packer's wastewater for discharge to the city's sewer usually will determine the degree of pretreatment, there are some factors that may encourage pretreatment beyond the levels required by applicable regulations (5):

1. A higher quality of pretreatment may be justified economically if the charges and surcharges are at a level where some additional pretreatment becomes economically advantageous.
2. The meat packer may prefer to assume treatment responsibilities to avoid complaints from the authority.
3. There may be indications that the future will bring increases in the applicable rate structure.
4. Grease and solids may have a good market in the area. Proximity of a soap plant or similar grease market may produce economic advantages for grease recovery or may warrant some expense in improving quality of the finished inedible grease or tallow. Such improvements will also improve the wastewater effluent.

Following are some disadvantages in pretreatment:

1. The pretreatment will be placed on the property tax rolls, unless State regulations permit tax-free waste treatment for industry.
2. The maintenance, operation, and record keeping may be expensive or burdensome.
3. The burden of good operation increases as the treatment becomes more complex and extensive.

3.1.2. Evaluating Needs

After the plant has been surveyed completely, and all possible waste conservation and water reuse systems have been cataloged, the necessary pretreatment system must be designed and the cost estimated. Those parts of the treatment attributable to flow (such as grease basins and DAF) should be totaled and reduced to a cost per 1,000 gal. Similar breakouts in costs per lb can be carried out for grease, suspended solids, and BOD.

Then each major in-plant expense for waste conservation and water recycle and reuse can be evaluated, based on the estimated reduction in flow, BOD, suspended solids, and grease. From such data, priorities can be established for each in-plant waste-conservation measure suggested in the survey.

Planning for piping arrangements, location, and size should consider future projected plant facilities.

3.1.3. Costs

Waste-saving and treatment costs should be charged back to the department from which the flow, BOD, suspended solids, and grease emanated. Selected costs of some of the equipment common to pretreatment will be discussed later (14).

3.2. Flow Equalization

Equalization facilities consist of a holding tank and pumping equipment designed to reduce the fluctuations of waste streams (28). These facilities can be economically advantageous whether the industry is treating its own wastes or discharging into a city sewer after some pretreatment. An equalizing tank can store wastewater for recycle or reuse, can provide for feeding the flow uniformly to treatment facilities, or allow discharge during low nighttime or weekend flows. The tank is characterized by a varying flow into the tank and a constant or designed flow out. Lagoons may serve as equalizing tanks, or the tank may be a simple steel or concrete tank, often without a cover. It is recommended to provide aeration facilities in the tank to be able to control odor that results from having anaerobic conditions.

Advantages of equalization for the meat packer discharging to a city sewer are as follows:

1. In-plant pretreatment can be smaller, since it can be designed for the 24-h average, rather than the peak flows.
2. The city may have penalties for high peaks that can be avoided by equalization.

The disadvantages are few:

1. More equipment to maintain and operate.
2. Additional fixed costs.

3.3. Screening and Centrifuging

3.3.1. Introduction

Because so much of the pollutional matter in meat wastes is originally solid (meat particles and fat) or sludge (manure solids), interception of the waste material by various types of screens (16) and centrifuges (30) is a natural step.

Unfortunately, when these pollutional materials enter the wastewater flow and are subjected to turbulence, pumping, and mechanical screening, they break down and release soluble BOD to the flow, along with colloidal and suspended and grease solids. Waste treatment – that is, the removal of soluble, colloidal, and suspended organic matter – is expensive. It is far simpler and less expensive to keep the solids out of the sewer entirely.

But, because in-plant conservation is at best imperfect and people are fallible, final organic solids separation in the main effluent sewer generally is employed. Various combinations of facilities for pretreatment may be selected, including screening (16), gravity grease and solids separation (15), DAF (17–20), and biological treatment of various types (30–32).

The information in this discussion of screening and centrifuging can be applied both for in-plant waste conservation and waste treatment.

Figure 16.2 shows where screens might be used throughout the plant (5). While vibrating screens are shown, other types of screens could be suitable for service in the locations cited. Whenever feasible, pilot-scale studies are warranted before selecting a screen, unless specific operating data are available for the specific use intended, in the same solids-concentration range and under the same operating conditions.

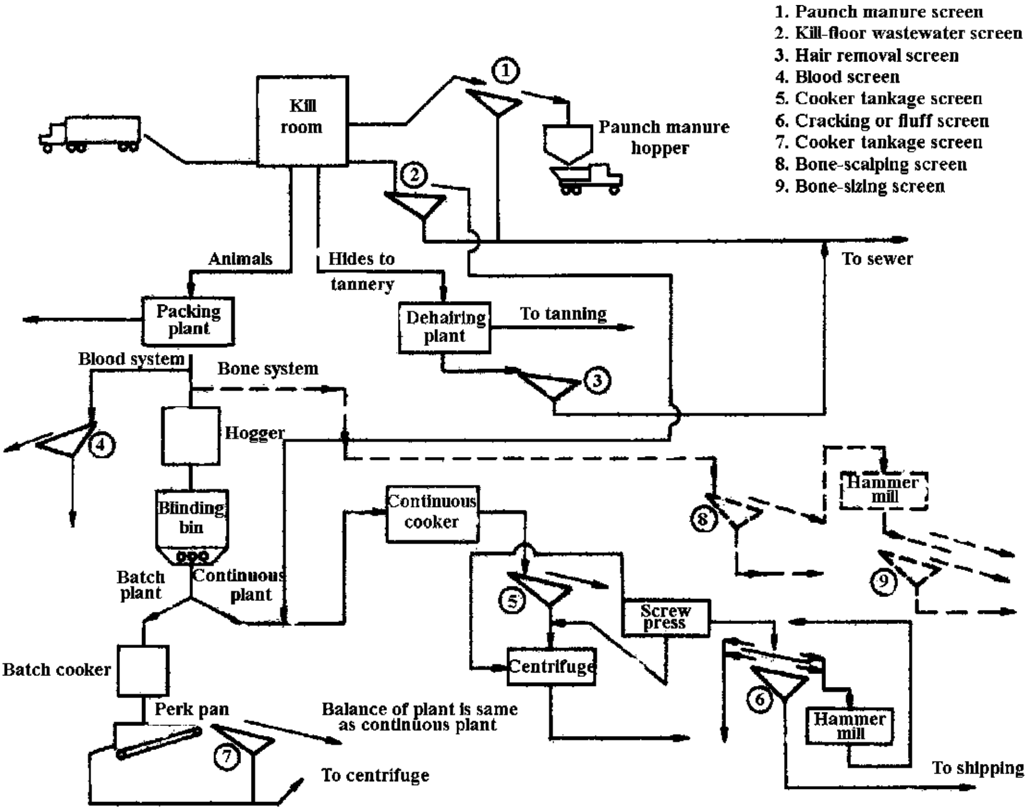


Fig. 16.2. Complete meat-processing plant.

3.3.2. Static Screens

Many so-called static screens have been installed in numerous industries to recover suspended matter from plant effluents or liquid flows within a plant. Highly successful screening operations have been achieved in the meat packing, tanning, canning, textile, and paper and board products industries, as well as in domestic wastewater treatment operations (33). Interesting new developments are underway, such as the treatment of wastes from animal-producing farms and poultry-processing plants.

In most instances, the installed equipment represents new functions or concepts in recovery and generally involves recycling or some other use of the recovered solids. In many cases, stationary screens are installed as replacements for screens that require moving parts to make a suitable separation of solids from a process stream.

Basic Design Concepts. The primary function of a static screen is to remove "free" or transporting fluids. These fluids can be removed by several means and, in older concepts, only gravity drainage is involved. A concave screen design using high-velocity pressure feeding was developed and patented in the 1950s for mineral classification, and it has been adapted to other uses in the process industries. This design employs bar interference to the slurry, which knifes off thin layers of the flow over the curved surface.

Beginning in 1969, US and foreign patents were allowed on a three-slope static screen made of specially coined curved wires. This concept used the Coanda or wall attachment phenomenon to withdraw the fluid from the under layer of a slurry stratified by controlled velocity over the screen. This method of operation has been found to be highly effective in handling slurries containing fatty or sticky fibrous suspended matter.

Since the field tests were conducted on the later design of stationary screen, details of this unit are presented here. The device is known commercially as a Hydrasieve.

Method of Operation. The slurry to be screened or thickened is pumped or may flow by gravity into the headbox of the machine. As shown in Fig. 16.3a, the incoming fluid overflows the weir above the screen area and is accelerated in velocity and thinned in depth as it approaches the screen. A lightweight hinged baffle is incorporated into the assembly in such a position that it reduces turbulence in the flow. Turbulence is reduced by the shape of the foil, which causes the fluid to respond to Bernoulli's theorem through the wedge-shaped entrance. The increasing velocity of fluid draws the baffle toward the surface of the screen.

Suspended solids tend to stratify in the thin stream, and fibrous materials align themselves lengthwise with the direction of flow. Figure 16.3b shows a segmental section of the screen wires and the slurry as it comes in contact with the upper end of the Hydrasieve screen. Note that the wall attachment of the fluid to the metal bars or wires draws or bends an under portion of the flow through the openings. Part of the underflow also moves along the arcuate surfaces of the wires and is concentrated primarily at the apex of the downward curve. Here this flow falls by gravity from the screen back or flows in streams attached to the underside of the wire assembly in a central path between the supports. The screen pattern permits a maximum of fluid extraction based on the limit of flow rate and screen area. Figure 16.3c illustrates the screen design that is registered under the trademark Marvel (5).

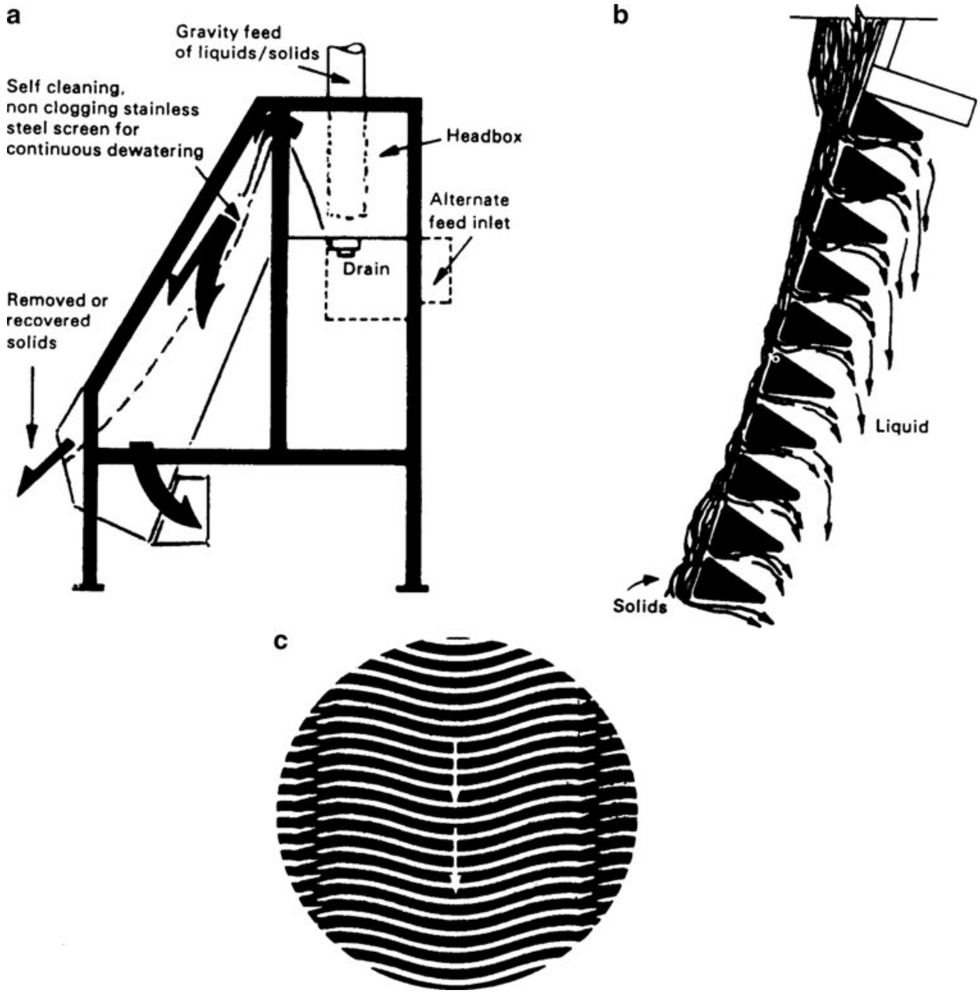


Fig. 16.3. (**a**) Path of slurry screened by Hydrasieve. (**b**) Segmented section of screen wires with slurry. (**c**) Screen design of Marvel Hydrasieve.

On the first (top) slope of the screen, most of the fluid is extracted from the bottom of the stream traveling at 25° from the vertical. When the angle of the screen changes to 35°, some additional fluid is withdrawn, and usually the massing solids begin to roll on the surface owing to the residual kinetic energy. This action compacts the solids very slightly. On the final slope of the screen, the solids tend to hesitate for simple drainage action, but are always moved off the flat surface by displacement with oncoming material. The effluent is aerated as it passes through the screen in ultrathin ribbons completely exposed to a natural or controlled atmosphere.

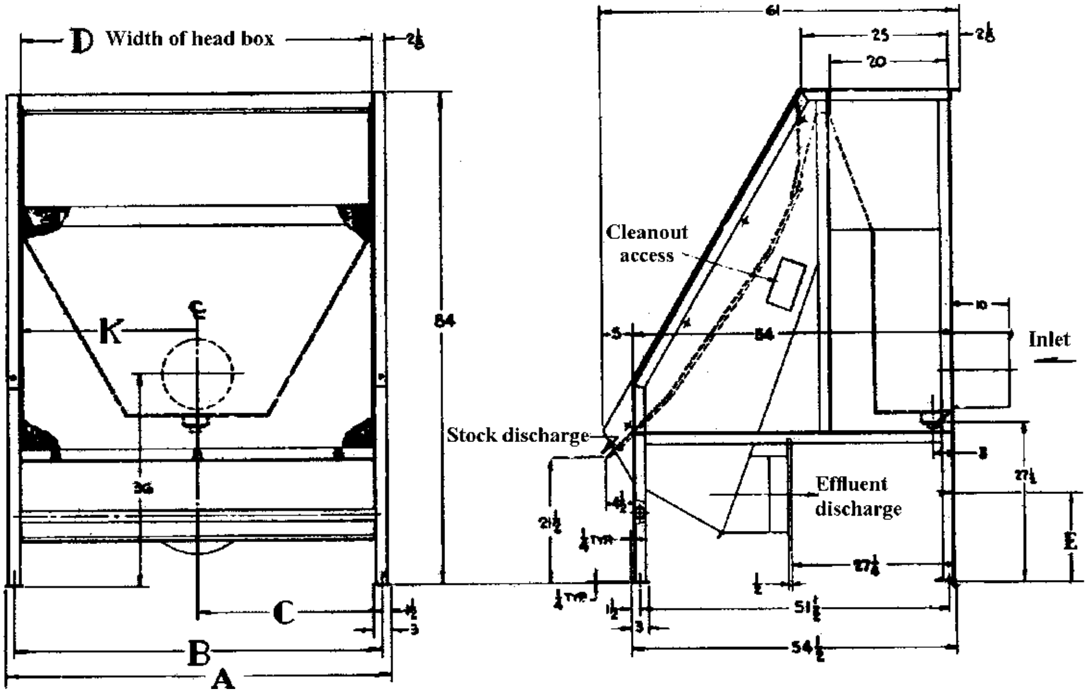


Fig. 16.4. Diagram for screen model 552-36 (see Table 16.2).

Unique Features. The arrangement of transverse wires with unique singular curves in the sense of flow provides a relatively nonclogging surface for dewatering or screening. The screens are made precisely in stainless steel and are extremely rugged. Harder, wear-resisting stainless alloys also may be used for special purposes.

Openings of 0.010–0.060 in. meet normal screening needs. The essential features of the Hydrasieve are covered in US and foreign patents. Figure 16.4 shows a diagram of a Hydrasieve model (5).

Use in Meat-Processing Industry Installations. A broad range of uses for Hydrasieve screens has been developed for meat processors and related operations, including the feed lots and stockyards as well as the tanning and hide-processing industries. In these fields of service, the Hydrasieve may be modified to provide a "waterfall" feed concept that can cope more effectively with high loadings of fat or grease. This development resulted from research work done on commercial equipment by the Institute of Leather Technology, Milwaukee, WI, and has been used widely in processing of animal hides.

Paunch manure – the residue from cattle stomachs – consists of fluids plus straw, corn, and minor miscellaneous solids. The Hydrasieve is an excellent device for screening this slurry, and usually a 0.040-in. opening screen is used. The solids are separated readily from the carrying stream, and a 72-in. Hydrasieve normally will handle a flow of 600 gpm. Solids are usually above 5%.

Hog stomach contents consist essentially of whole and split corn, with some hair and the possibility of fat. Usually, a 0.040-in. opening screen is employed, and flow rates of about 500 gpm are obtained on a 72-in.-wide unit.

Hog-hair recovery is the operation in hog processing in which the animals are scalded and dehaired in a beater-scraper type of machine. Material coming from this operation is hair and scurf, a dandruff-type flake. Also present in this operation is foam, which is self-generating because of the gelatin that is cooked out of the skins.

Seventy-two-in. units with 0.020-in. openings are in use on the hog-hair recovery application. Flow is 400–500 gpm, with loads to 1,000 gpm when the scalding tub is dumped. Some problems existed in the operation due to foaming, but these are solved with proper cold water sprays over the screen and/or antifoam at 10–20-gpm concentration ahead of the screen.

Hair screening is improved with the stockyard, paunch manure, or stomach contents added to the flow.

Ash from smokemakers results when, in smoking sausage and other meat products, sawdust is burned to produce smoke. The ash is washed from the smokemakers and should be removed before going into grease recovery systems, as this product is unwanted in the rendering. Hydrasieves offer a satisfactory means of screening the wash water.

The normal total waste flow from a packing plant is quite heavy with respect to flow, solids, and fat. Normally, when a packer screens his total flow it is a safety measure used as primary settling, ahead of additional treatment, such as pressurized air flotation. The material from the screen may be rendered.

A 72-in. unit with 0.040-in. screen operates on total waste flow of 500–700 gal/min. Sprays are used and the application is quite successful.

A typical operation on a waste stream from an operation where cattle, hogs, and sheep were processed is indicated by the test data for a 72-in. by 54-in. Hydrasieve with 0.04 Marvel screen, as follows (5):

1. Flow rate, 550 gpm
2. Solids removed, 10,000 lb/day (dry)
3. Solids passed, 6,076 lb/day (dry)
4. Effluent solids (80 minus 30 mesh), 920 mg/L
5. Solids removal, 62.5%

Solids are removed from stickwater, which is product water and condensation water evolved in the process of wet or steam rendering of lard and tallow. Normally, stickwater is evaporated to produce a high-protein feed additive. Solids in stickwater are coarse and fibrous in inedible rendering and soft and stringy in edible renderings. Normally, stickwater is hot (130°–160°F) as it goes over the screen, eliminating grease blinding.

Expelled grease solids removal is performed after meat scraps are rendered in melters. Grease is drained from the solids. The solids then are pressed in screw presses and the additional grease is expelled. This grease contains solids that normally are settled out before the grease is filtered. The grease is sent over a 0.020-in. test screen, and solids are removed to the extent that settling can be eliminated. Flow is low, but separation is also slow. About 5–10 gpm can be sent over an 18-in. unit with 0.020-in. screen, with adequate results. Modifications need to be made so that the flow will start at the overflow weir, rather than in a headbox.

Table 16.2
Hydrasieve design information for stockyard effluent based on use of 0.040 in. slot opening

Hydrasieve	Overall dimensions (ft)			Weight (lb)	Capacity (gal/min)	Price for estimating, 2006 Dollars
	Width	Depth	Height			
No. 552-18″	2	3.5	5	350	75	9,300
No. 552-36″	3.5	4	5	550	150	11,500
No. 552-48″	4.5	5	7	650	300	14,300
No. 552–60″	5.5	5	7	800	400	17,900
No. 552-72″	6.5	5	7	1,000	500	21,500
No. 552-72-2	7	9.5	7.3	1,800	1,000	35,800
No. 552-72-4	14	9.5	7.3	3,600	2,000	71,600
No. 552-72-6	21	9.5	7.3	6,400	3,000	107,400
No. 552-72-8	28	9.5	7.3	7,200	4,000	143,200
No. 552-72-10	35	9.5	7.3	9,000	5,000	179,000

In hide processing, green (untreated) hides are delivered from the meat packer and are either processed immediately or cured in brine. The first process is to wash the hide in a drum washer, where manure and dirt are removed. Some hair and manure balls are also removed and sent to the sewer. The Hydrasieve is used here to permit recycling of the wash water and for preliminary solid removal. A 72-in. unit with 0.060-in. screen permitted one processor to reduce his flow from this operation by at least half. The 72-in. units are handling 700 gpm effectively.

A fleshing machine is then used to remove tissue particles and tails. Handling this flow, due to its high fat content (5–14%), may be done using a Hydrasieve with the waterfall adapter and periodic cleaning.

The hides are cured by saturation in brine solution. The brine is regenerated continuously. Brine should be screened on a Hydrasieve to insure proper operation by removing the hair and manure that accumulate in the brine raceway, or merry-go-round. A 0.030-in. screen in a 72-in. unit will handle 450 gpm of this solution.

Summary. Almost every static screen application problem has its own, slightly different, design parameters to be met, and in-plant evaluations are sometimes required. As a guide, Table 16.2 gives brief specifications suitable for preliminary planning of an installation of effluent screen (5).

3.3.3. Vibrating Screens

Vibrating screens have many uses in a meat-packing plant. Figure 16.2 illustrates the various areas where they can be used in waste conservation (5).

Vibrating screens are designed to

1. Convey material retained on the screen surface to uncover the opening, so that the cloth can pass the undersize material or liquid.

2. Agitate the bed of material on the screen surface. Agitation and stratification are required to open the bed so that the fine particles or liquids can work their way down through the large particles and pass the openings.
3. Dislodge particles that stick or wedge in the opening. Particles of nearly the same dimension as the opening will clog. Motion of the screen must dislodge the particles.
4. Distribute the material in order to make most efficient use of the entire screening area. The motion of the deck should distribute the material over the deck evenly.
5. Retain material before discharge. For high efficiency, sizing, or removing water from the solids, it is desirable to retain the oversize as long as possible. The material must be moved faster at the feed end to obtain quick distribution and a shallow bed where the volume is greatest. At the discharge end where the volume is least, the rate of travel should be slowed to allow the remaining fines or liquids to be removed.

Vibrating screens are economical. They vary in size from 2 ft by 4 ft to 8 ft by 20 ft and are made up of three major parts:

1. The vibrating frame – or, as some may call it, the box – which is either the welded structure or the bolted assembly that supports the vibrating mechanism and the screening medium, mounted horizontally or declined on isolation springs.
2. The screening medium – cloth, perforated plate, or panels.
3. The vibrating mechanism – the heart of the vibrating screen, which imparts the motion into the vibrating frame.

The effectiveness of a vibrating screen depends on a rapid motion. Vibrating screens operate between 900 and 1,800 rpm; the motion can either be circular or straight line, varying from 1/32- to 1/2-in. total travel. The speed and motion are selected by the screen manufacturer for the particular application.

The vibrating screen is driven by a shaft turning in a pair of bearings. The shaft carries unbalanced weights, either machined into or keyed to the shaft. This assembly is normally driven by a V-belt drive.

When the unbalanced weights are rotated the screen follows the weights through a path. When a vibrator is placed on the top of the box, a slight rocking action will take place, resulting in elliptical motion with the ellipse leaning toward the vibrator. This motion tends to move the material away from the feed and retard it at the discharge end. The screen box is mounted on springs to keep vibration from being transmitted to the supports.

On most vibrating screens the cloth is pulled tightly across longitudinal steel members equipped with rubber caps. The cloth may be changed easily by loosening the tension bolts and sliding the screen cloth out at either end.

Of prime importance in the selection of a proper vibrating screen is the application of the proper cloth. The capacities on liquid vibrating screens are based on the percent open area of the cloth. With this factor in mind, cloth should be selected with the proper combination of strength of wire and percent of open area. If the waste solids to be handled are heavy and abrasive, wire of a greater thickness and diameter should be used to insure long life. If the material is light or sticky in nature, however, the durability of the screening surface may be the smallest consideration. In such a case, a light wire may be necessary to provide an increased percent of open area.

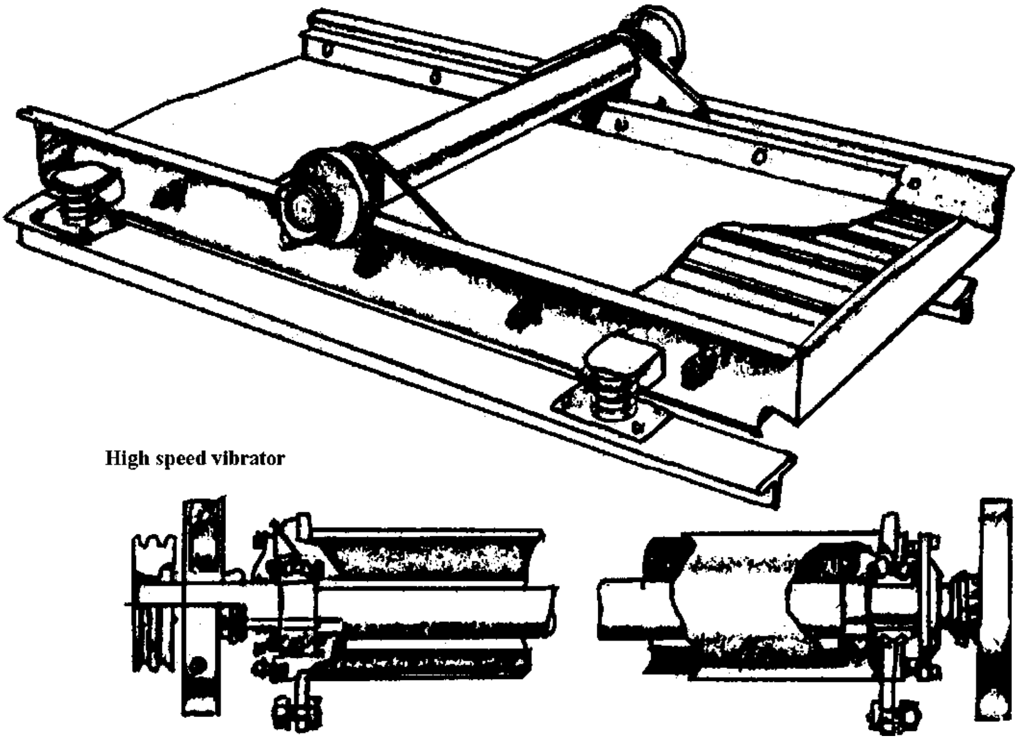


Fig. 16.5. Liquid dewatering screen (NRM-148).

Screen cloth is woven in a variety of materials, such as black steel, spring steel, all types of stainless steel, and brass wire. Normally, on liquid waste applications, a stainless steel wire is used. When conditions require other types of metal, however, special wire cloths can be supplied.

In the discussion of various installations, the term "mesh" will be used frequently to designate the opening. Where mesh is referred to as a number, the reference is to the number of openings to the linear inch. The mesh is counted by starting from the center of one wire and counting the number of openings to a 1-in. distance. If the count does not work out to an even number, the fractional part of the opening should be specified.

The NRM (Fig. 16.5) is used in liquid separation extensively; the 4-ft by 8-ft unit costs (in 2006 US$) slightly more than US$ 10,000, with feed flume and tank in black steel (5). Prices vary with feeding arrangements, surface sprays (if any), and other details, such as special metals and coatings.

3.3.4. Rotary Screens

One type of barrel or rotary screen (Fig. 16.6a), driven by external rollers, receives the wastewater at one open end and discharges the solids at the other open end. The liquid passes outward through the screen, usually stainless steel screen cloth or perforated metal, to a receiving box and effluent sewer mounted below the screen. Usually the screen is sprayed

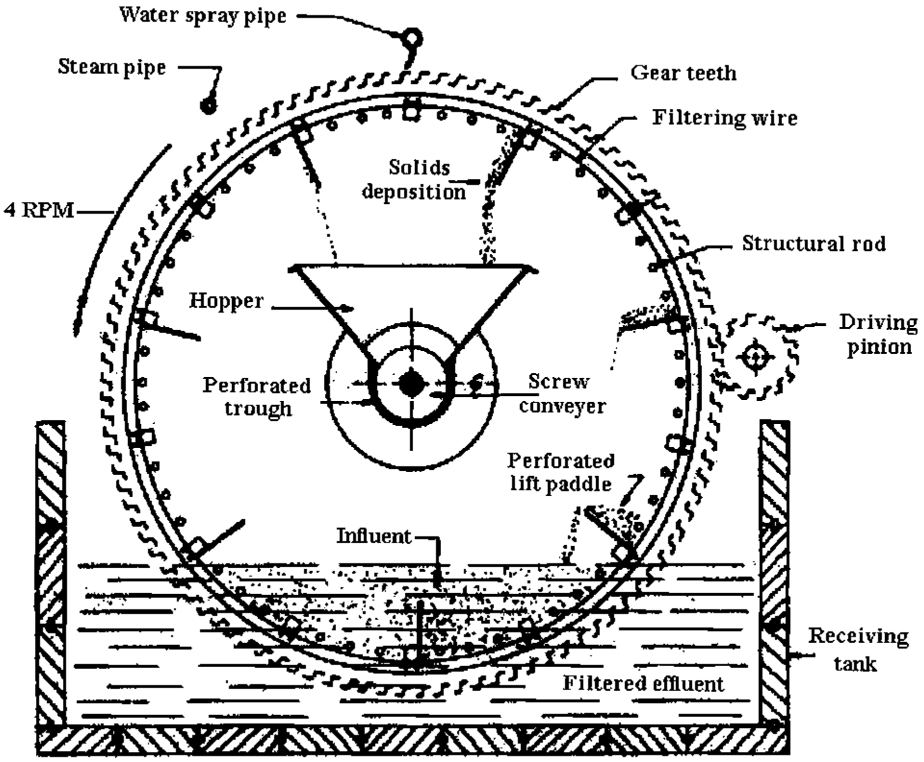


Fig. 16.6. Cross-section of rotary screen driven by pinion and gear.

continuously by means of a line of external spray nozzles, and it is inclined toward the solids exit end. This type is popular as an offal screen but has not been used to any great extent in secondary polishing – that is, in removing solids from waste streams containing low solids concentrations. A screen of this type has been developed for recycle of hide-brining waters.

Another rotary screen commonly used in the meat industry (Fig. 16.6) is driven by an external pinion gear. The raw flow is discharged into the interior of the screen below center, and solids are removed in a trough and screw conveyor mounted lengthwise at the centerline of the barrel. The liquid exits outward through the screen into a box in which the screen is partially submerged. The screen is usually 40 × 40 mesh, with 1/64-in. openings. Perforated lift paddles mounted lengthwise on the inside surface of the screen assist in lifting the solids to the conveyor trough. This type is also generally sprayed externally to reduce blinding. Grease clogging can be reduced by coating the wire cloth with Teflon. Solids removals up to 82% are reported (5).

Several other types of mechanical screens have had some application in this field (34). One is a rotating disk that is submerged partially in the wastewater flow. As it rotates, particles partially adhere and are scalped off above the flow. The screen disk is placed vertically or at a slight angle. Some problems arise in maintaining the seal between the rotating disk and the flow through box or sewer.

Another type is a circular spring-mounted horizontal screen, driven by a motor located under the screen and equipped with variable eccentric weights. As the motor rotates, the eccentric weights impart multiplaned vibrations to the spring-mounted screen. These units are normally centrally fed at the top, with the liquid discharging through the screen to a pan above the motor and the sludge discharging from a port at the periphery. Pilot units (18 in. diameter) are available on loan. These screens are used in a number of meat-packing plants, principally for paunch manure removal, for removing solids from the entire manure sewer flow and for removing solids from the main sewer leaving the plant. Mesh sizes range from 10 mesh for paunch manure to 80 mesh for the main plant sewer. One plant uses three 48-in.-diameter separators with 80-mesh screening to handle a total main plant flow of 800–1,100 gpm (5).

A horizontal rotary slowly revolving screen has been developed using wedge bars and the Coanda effect (as in the static screen described earlier), but with the wastewater flowing vertically downward through the screen. Some advantages claimed for rotary design are that the screen is cleaned in its rotation by means of a doctor blade, that it can be rinsed with a stationary spray system, and that the vertical downward flow helps backwash the screen as it flows through into the receiving box under the screen drum.

3.3.5. Centrifuges

Centrifuges have found use in processing meat-packing wastewater, principally in improving the quality and concentration of grease from grease recovery catch basins and DAF.

At one plant, tallow recovery from a catch basin was enhanced by running the skimmings through two centrifuges. At this plant, each centrifuge is of the three-stage type (having separate streams of oil, liquid, and solids), has a capacity of 55 gpm, is driven by a 25-hp motor, and costs (in 2006 US$) US$ 129,000 plus about US$ 14,000 for installation. The yield amounts to 80% of the recoverable tallow, with 0.92% moisture and a color of 13–15. The temperature is raised to 180°F and is discharged through an 80-mesh, eccentric-weighted-type 60-in. circular vibrating screen, and then heated to 195°F and centrifuged. The fat is classified as inedible fancy bleachable tallow and brings top market prices. Flow rate is about 30,000–40,000 gpd and recovered fats run about 5,000 lb/day (5).

One system of blood concentration incorporates a centrifuge to separate the water after coagulation, using a chemical aid. The centrifuge is reported to remove about 80% of the water. The coagulated blood is then dried. This system, however, still produces BOD in the effluent. Drying of whole blood is better for waste conservation.

First cost and power requirements tend to limit the use of centrifuges for waste solids recovery. As requirements for effluent quality become more stringent, however, the centrifuge may be used more frequently to remove residual grease and fine solids from waste streams.

3.4. Oil, Grease, and Suspended Solids Separation by Gravity

The catch basin for the separation of grease and solids from meat-packing wastewaters was developed originally to recover marketable grease. Because the primary object was grease recovery, all improvements were centered on skimming. Many catch basins were not equipped with automatic bottom-sludge-removal equipment. These basins could often be drained completely to the sewer and were sludged out weekly or at frequencies such that septic conditions would not cause the sludge to rise. Rising sludge was undesirable because it could affect the color and reduce the market value of the grease.

With waste treatment gradually becoming an economic incentive, catch basin design has been improved in the solids removal area as well. The low market value of inedible grease and tallow has reduced concern about quality of the skimmings, and now the concern is shifting toward overall effluent quality improvement.

The combinations of screens, catch basins, and DAF in pretreatment vary widely. For example, the Beardstown, IL, plant of Oscar Mayer & Co. discharges the grease sewer to a flotation tank with 30-min detention at 30% recycle (no chemicals), and the manure-carrying (nongrease) sewer to a 3-ft by 8-ft, 4-mesh vibrating screen followed by a gravity basin with 50-min detention prior to lagoon treatment. Overall operating results show 49% BOD removal, 66% suspended solids removal, and 76% grease removal (35).

Other pretreatment systems start with screening the individual waste streams followed by a gravity catch basin, and then may be followed by a DAF unit.

Gravity grease recovery systems will remove 20–30% of the BOD, 40–50% of the suspended solids, and 50–60% of the grease.

General removals for DAF systems without chemical treatment are about 30–35% in BOD, about 60% in suspended solids, and 80% (some as high as 90%) in grease. Combinations of gravity catch basins (about 25–30 min detention) followed by DAF produce somewhat better results, because the catch basin removes the larger solids and thereby reduces the requirements imposed upon the flotation unit (see discussion of DAF).

Chemical treatment will improve recovery when installed directly ahead of DAF systems. Chemical treatment also can improve gravity separation of greases and solids, but as much as 20 min of flocculation may be necessary to effect significant improvements.

The use of chemicals to enhance coagulation and flotation (36) varies widely. Generally, flotation is accomplished without chemicals, unless effluent quality must be improved. Alum, as a coagulant with or without a polymer, is used but tends to cause an emulsion problem in the cook tank. Ferric chloride, with or without a polymer, is also used; however, US Department of Agriculture limitations on iron content in feeds should be checked before selecting this coagulant if significant amounts are to be used and if the end product will be a feed ingredient. As knowledge of polymers improved and their use became more general, proper polymers at proper pH and under controlled mixing conditions have become more effective alone, and thus it became possible to eliminate the problems incident to iron and alum treatment. Zinc chloride (5) has had some success as a coagulant and may be effective in combination with a polymer. The proper pH – an important factor – should be determined by coagulation tests (36).

Manure-carrying sewers commonly are pretreated by means of screens, gravity basins, and sometimes DAF before discharge to the public sewers. If the wastewaters are treated in a separate system for discharge to a watercourse, the type of biological waste treatment may not require the degree of solids removal necessary for discharge to the public sewer.

Simple settling tanks are useful for stockpen flows. They generally consist of shallow concrete trenches, about 3 ft deep, designed for cleaning with a bulldozer (37). A simple baffle at the outlet end prevents escape of floatables. One head of cattle in a feed lot will discharge 10–15 times as much BOD as one person in the same period of time.

3.4.1. Design Elements

Engineers are divided as to the merits of rectangular vs. circular separators for various purposes. Many prefer rectangular to circular gravity grease recovery tanks because they believe that, in the circular tank, the grease loses its cohesiveness as the flow proceeds outward in a radial direction, with the scum covering an ever-increasing surface area, and thereby becoming thinner as it approaches the scum-removal device at the outer periphery (5). Others claim that the gradually reducing velocity of the flow as it moves radially outward improves grease separation as well as solids separation (a majority of engineers prefer circular tanks for settling flocculent solids). It is safe to say, however, that the majority favor rectangular basins for gravity recovery of grease. Accordingly, this section will concentrate on this type. In DAF systems (discussed later) the two factions are about even. In clarification following biological treatment systems, the circular clarifiers have a decided majority.

Following are size criteria based largely on experience. If individual State standards normally applied to clarifier design are imposed on the meat packer for catch basin design, the regulations, of course, must be followed.

Rate of flow is the most important criterion for design of a gravity unit. About 30–40-min detention time at 1-h peak flow is a common sizing factor. A shallow basin, 5–6 ft liquid depth, generally is preferred. This depth produces a surface hydraulic loading of about 1 gpm/ft^2. The daily flow has little relationship to the design of grease recovery systems.

Length-to-width ratio should be at least 3 to 1. Maximum widths are about 20 ft, but heavy sludges may cause an excessive stress on the scrapers at that width. Widths to 12 ft are safe. Beyond this width stresses should be checked, particularly if the system is operated intermittently.

Temperature variations can develop nonuniform density currents, reducing the efficiency of grease and solids separation. Overnight icing can occur in northern climates. Accordingly, protection against wide variations in temperature should be considered.

The design of inlet and outlet arrangements, as well as scum removal, will materially affect the basin efficiency. The bottom (invert) of the influent sewer should be above the liquid level in the basin. The inlet, however, can enter the basin below the liquid surface. Properly baffled, multiple inlets will reduce inlet velocities but can cause backup in the influent sewer or in an upstream receiving box where scum can collect. Design of such a receiving box to overflow at high-flow periods could prevent scum accumulation in the box. Surface discharge into the basin, on the other hand, can develop velocity currents in the basin. However, multiple surface inlet openings with adjustable baffles will reduce entrance velocities, permit manual adjustments of distribution of the flow across the basin width, and prevent upstream scum accumulations.

The effluent should be conducted over a weir extending the full width of the basin. Weir overflow rates should not exceed 1,500 gal/ft/h of maximum flow. A weir trough at the outlet will provide double weir length if necessary.

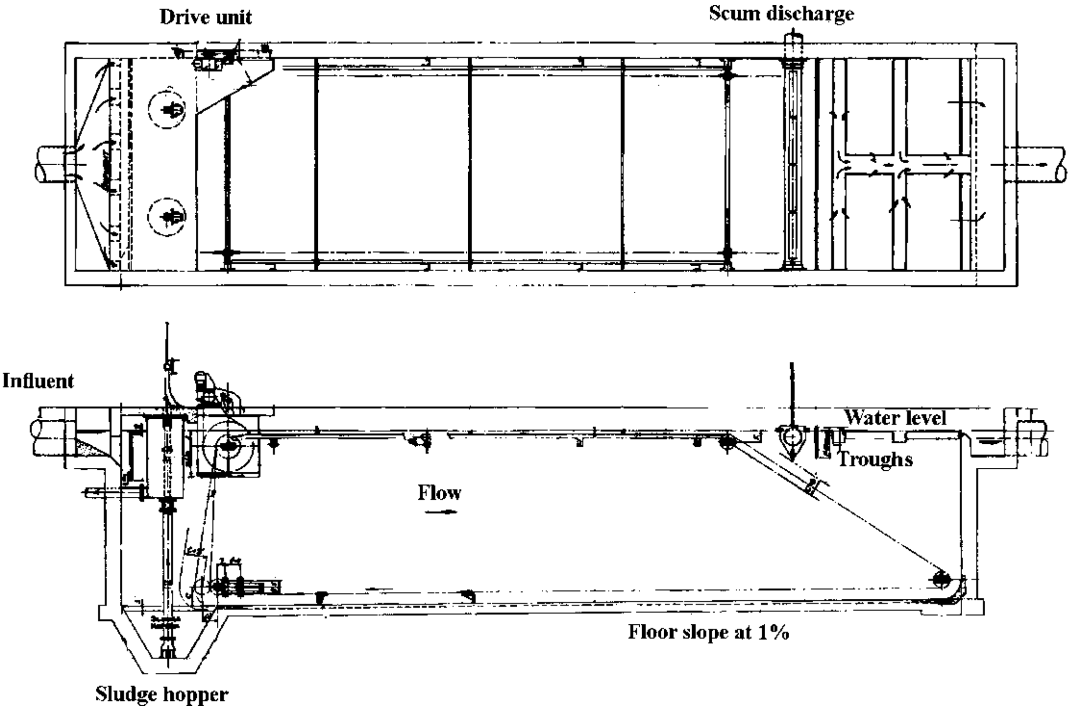


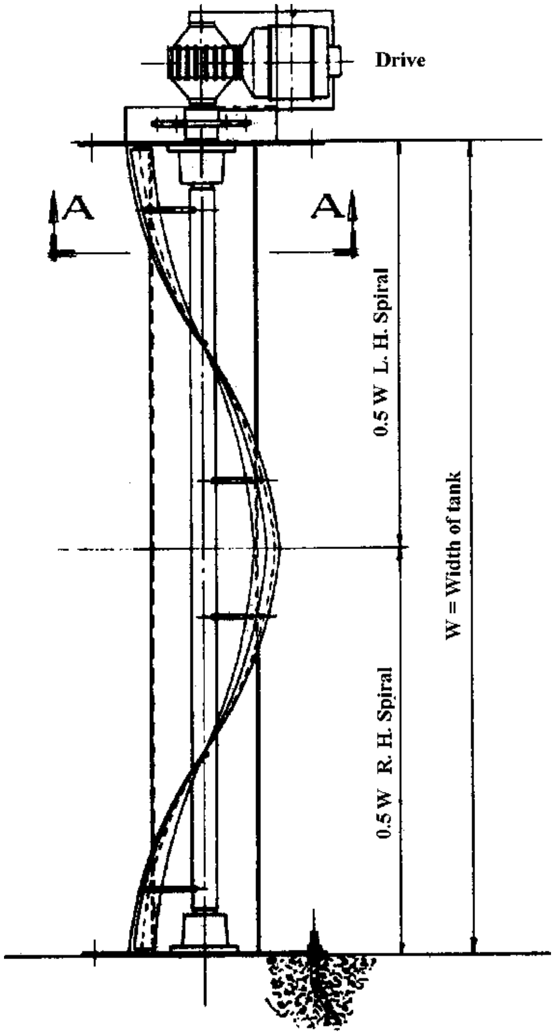
Fig. 16.7. Four-sprocket collector with scum pipe for grease recovery.

Scum removal equipment is available in several styles. The slotted "swing-pipe" scum trough (see Fig. 16.7) is popular in rectangular municipal clarifiers. In operation, it is periodically rotated manually to a point where the slot meets the liquid level, allowing scum to enter the pipe and flow out of one end to a receiving box. It is inadequate generally for the quantities of scum encountered in treating meat-packing wastewaters (5).

A powered helical scum collector (Fig. 16.8) that mechanizes scum pickup is also available. Its dewatering efficiency and its capacity do not usually satisfy the requirements for scum removal in meat-packing wastewater systems, but it is a slight improvement over the swing pipe.

A more positive pickup, but using the same four-sprocket sludge and scum scraper system, consists of a scum trough and "beach" with a short flight-type skimmer. The skimmings trough extends the full width of the basin and should be sloped to discharge to a receiving box where the grease can be decanted from the residual water. In large installations, a screw conveyor in the trough will be useful. In cold climates, the shaft of the screw can be hollow and can be connected to a steam line to keep the scum from freezing in the trough. The scum trough should be several inches above the liquid level. The metal beach provided on the upstream side for scum pickup permits some dewatering of the scum on that part of the beach above the water level. A short baffle fastened to the underside of the trough and extending

Fig. 16.8. Helical scum skimmer.



downward will reduce scum loss caused by effluent flow moving toward the effluent weir downstream from the trough.

All of the foregoing skimming arrangements permit some grease to escape to the effluent because the grease adheres to the flights as they pass downward under the skimming device. To eliminate this defect, two sets of scraper flights can be provided, as shown in Fig. 16.9. In this system, the sludge is moved independently of scum removal by a three-sprocket collector. A separate two-sprocket scraper system, operating above the liquid level, moves the scum toward the scum trough and up the beach into the trough. In this arrangement, septic action can be prevented by operating the bottom scrapers continuously. The scum scrapers also can be operated separately on a timer to hold the scum and develop a cohesive dense layer, thereby reducing the liquid content of the skimmings. Normally, about 70% of

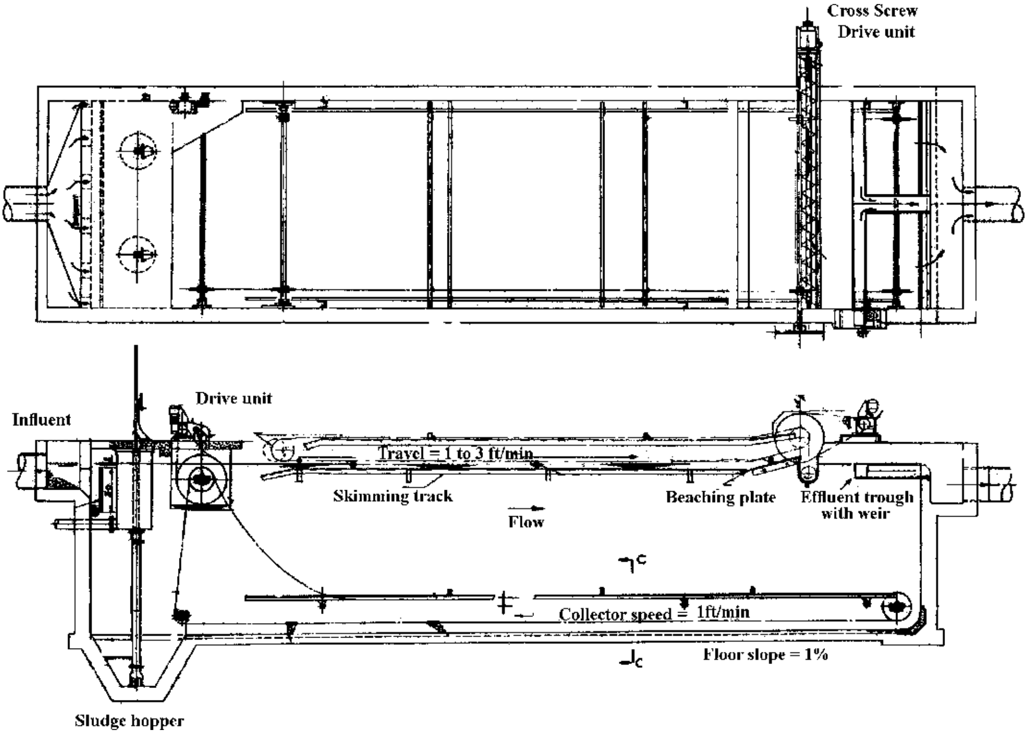


Fig. 16.9. Three-sprocket collector with flight skimmer full length and cross screw conveyor.

the scum picked up is water. The two-flight system can reduce the water content about 15–20% (5).

A pork plant using this type of arrangement has a daily production flow of 620,000 gal/day and 860 gpm in a maximum hour. This plant is large and has complete smoking and sausage manufacturing. Pretreatment consists of a gravity basin (equipped for adding DAF when necessary) designed for 28-min detention (12 ft wide, 45 ft long, and 6 ft side-water depth). Estimated raw waste concentrations are 450 mg/L BOD, 400 mg/L suspended solids, and 350 mg/L grease (5).

Scraper mechanisms for sludge removal may scrap move the sludge to one or several submerged hoppers, generally at the inlet end of the basin. The need for several hoppers arises from two design limitations. First, the side slopes for the sludge hoppers should be at least 60° with the horizontal. Second, the flat bottom of the hopper should be no greater than 2 ft by 2 ft in size.

In one innovation that eliminates the hoppers and sludge pumps, the effluent end of the basin is built in an incline and the sludge is scraped up the incline into a receiving trough at the top. The sludge is partially dewatered on that portion of the incline that extends above the liquid level. The incline can be as long as necessary to accomplish the desired dewatering before the sludge discharges into the trough. A screw conveyor in the sludge trough is an added convenience to carry the sludge to a truck or receiving box alongside the basin. The effluent weirs and scum removal trough are, of course, upstream from the incline.

3.4.2. Basin Arrangement and Materials of Construction

Usually two identical catch basins, with a common wall, are desirable to permit one to operate whenever the other is down for maintenance or repair.

Concrete tanks have the inherent advantages of lower overall maintenance and more permanence of structure. Some owners, however, prefer to be able to modify their operation for future expansion or alterations or even for relocation.

All-steel tanks have the advantage of being semiportable – more easily field erected and more easily modified than concrete tanks. The all-steel tanks, however, require additional maintenance as a result of wear in areas of abrasion.

A tank equipped with all-steel walls and concrete bottom is probably the best compromise between the all-steel tank and the all-concrete tank. The advantages are the same as for steel. The all-steel tank, however, requires a footing underneath the supporting members; with the steel-wall tank the concrete bottom forms the floor and supporting footings for the tank.

3.4.3. Design Example

Given a peak-hour flow of 1,300 gpm, design a rectangular catch basin and estimate its cost.

Solution:

1. At a selected 40-min detention, the volume = 52,000 gal (6,950 ft^3)
2. Select 6 ft average water depth; area = 1,160 ft^2
3. Select two basins, with a common wall, each 10 ft wide, 58 ft long, and 6 ft average water depth

All costs are for the two basins, with a common wall between them. Table 16.3 gives cost estimates that are order-of-magnitude prices, and thus should not be used for other than rough approximations. In each particular application, equipment prices and construction costs should be developed for the area where the plant is located and for the specific situation. All costs have been converted in terms of 2006 US Dollars from the original 1973 prices using the US Army Corps of Engineers Civil Works Construction Yearly Average cost Index for Utilities (38).

3.4.4. Maintenance and Operation

Most gravity grease recovery units use no chemicals, flocculants, or polymers to achieve the grease separation. There is no requirement, therefore, for design or maintenance of a chemical-feeding system. The gravity grease recovery unit is quite simple in construction and operation, alleviating the need for sophisticated or highly trained operators.

In gravity grease recovery and separation, as with any system of wastewater treatment, the overall system must be considered in addition to the individual elements. Particular attention should be given to maintaining low turbulence in the flow and minimizing frequency of pumping.

Table 16.3
Cost estimate for design example, two rectangular catch basins, in 2006 US$

Basin	Cost installed	Equipment			Total
		Type[a]	Base cost	Installation cost	
Concrete	89,500	I	44,800	10,700	145,000
		II	82,300	12,500	184,300
		III	116,000	20,000	225,500
Steel	104,000	I	44,800	10,700	159,500
		II	82,300	12,500	198,800
		III	116,000	20,000	240,000
Steel with concrete floor	114,600	I	44,800	10,700	170,100
		II	82,300	12,500	209,400
		III	116,000	20,000	250,600

[a] Type I, four-sprocket collector with rotatable scum pipe; type II, four-sprocket collector with short flight skimmer *without* screw conveyor in trough (slightly less with helical scum skimmer); type III, three-sprocket sludge collector with full-length, separate, two-sprocket scum-scraper system, and *with* screw conveyor in trough.

Each gravity grease recovery system requires a certain amount of housekeeping. After being in operation for a few months, the equipment becomes coated with grease. It is difficult, if not impossible, to maintain the equipment when the parts are not visible. Hence, there is a need for scraping, scrubbing, steam cleaning, and in some cases high-pressure hosing, to assist maintenance personnel in keeping the units operational. Cleanliness also helps in the control of odors and elimination of odor-producing bacteria.

Day-to-day observation and periodic checking of alignment, grease levels in speed reducers, and greasing of bearings are natural requirements for mechanical maintenance of any wastewater equipment. Eventually the chains will wear and require replacement. This equipment has a wear life proportional to the hours of use; hence, operation on timers is recommended. A high percentage of grit in the wastewater may accelerate the wearing of the components, because the grease will tend to hold the grit into the wearing parts of the unit, acting as a lapping compound and accelerating the wear.

3.5. *Oil, Grease, and Suspended Solids Separation by DAF*

DAF is a waste-treatment process in which oil, grease, and other suspended matter are removed from a waste stream. This treatment process has been most successful in removing oil from waste streams. Its principal early use was, as it still is, the removal of oil from petroleum refinery wastewaters (refer to a previous chapter). Another natural area for application of this treatment system has been the removal of contaminants from food processing plant waste streams. One of the very first applications of this treatment system was for meat processing.

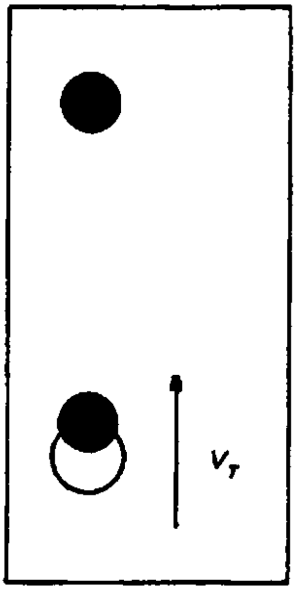


Fig. 16.10. Separation of a particle from wastewater by DAF.

Basically, DAF is a process for removing suspended matter from wastewater that uses minute air bubbles, which upon attachment to a discrete particle reduces the effective specific gravity of the aggregate particle to less than that of water. Reduction of the specific gravity for the aggregate particle causes separation from the carrying liquid in an upward direction (17–20). As Fig. 16.10 suggests, the particle to be removed may have a natural tendency either to rise or to settle. Attachment of the air bubble to the particle induces a vertical rate of rise noted as V_T. Since the waste flow must pass through a treatment unit, the particle to be removed will have a horizontal velocity. Certain criteria have been established for limits of the parameter V_H, which sets the width and depth of the treatment unit.

3.5.1. Rectangular DAF Cells

As Fig. 16.11 suggests, the effective length of the treatment unit is directly proportional to the horizontal velocity and depth and inversely proportional to the vertical rate of rise of the particle to be removed. The mechanics of operation for a DAF unit are illustrated in Fig. 16.12. It can be noted that a portion of the clarified effluent is pressurized by a recycle pump. This recycled flow is pumped to a pressure tank into which air is injected. In the pressure tank at approximately 40 psig, the recycle flow is almost completely saturated with air. The pressurized recycle flow, containing the dissolved air, leaves the air saturation tank and flows through a pressure reduction valve.

A 40-psig pressure drop occurs at the pressure reduction valve and causes the pressurized flow stream to relinquish its dissolved air in the form of tiny air bubbles. This air-charged recycle flow is then blended with the raw process flow to effect attachment of the air bubbles to the oil and other suspended solids to be removed. The combined flow stream (raw flow plus

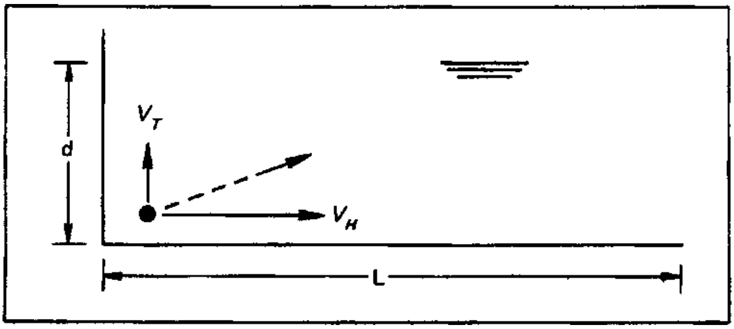


Fig. 16.11. Basic design concept of flotation unit.

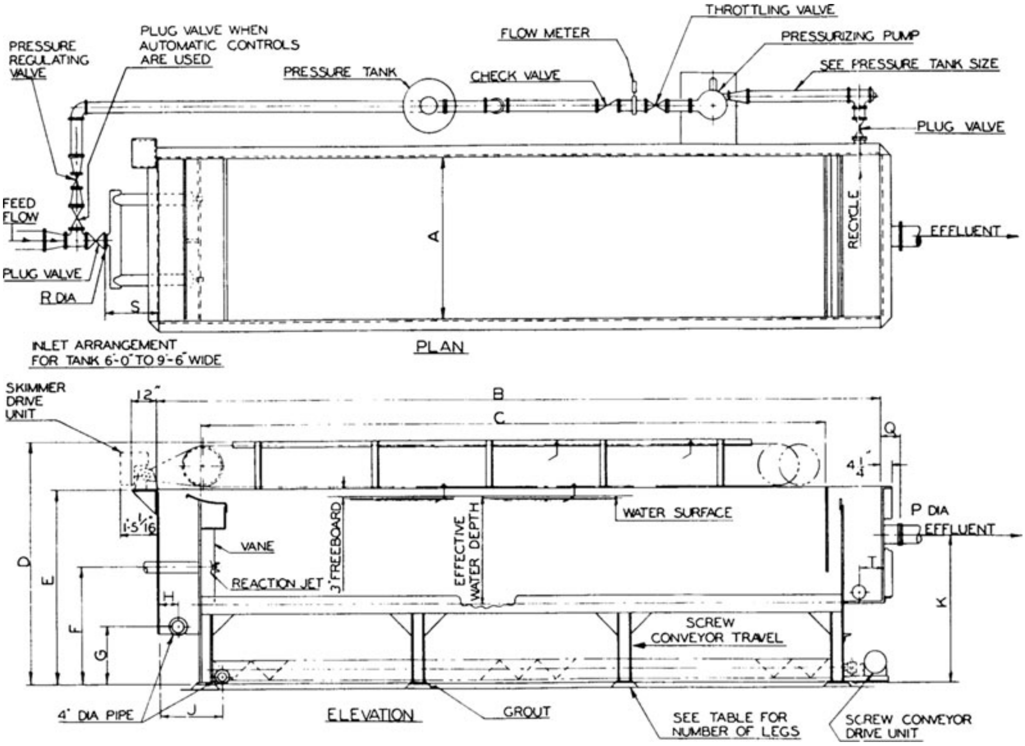


Fig. 16.12. DAF with steel flotation unit, skimmer, and sludge removal facilities.

recycle flow containing the air bubbles) is mixed and uniformly distributed over the cross section of the basin.

As the incoming flow travels to the effluent end of the basin, separation of the oil and solids from the associated liquid occurs. Solids accumulate at the water surface and form an oily sludge blanket. Clarified liquid flows over the effluent weir and into a wet well. From the effluent wet well, a portion of the effluent is recirculated. The remainder of the effluent is removed from the basin for subsequent treatment or discharge. The floated scum blanket of separated solids can be removed from the basin by skimmer flights traveling between two endless strands of chain. Since the influent stream may also contain small amounts of heavy solids, such as grit, which are not amenable to flotation, provision must also be made for solids removal from the bottom of the unit.

The foregoing discussion illustrates the recycle method of injecting the air bubbles into the waste stream. Figure 1.11 of Flotation Technology (59) shows all three methods of dissolved air injection currently used (17–20). Total pressurization, as the name implies, occurs where the total waste flow is pressurized before entering the treatment unit. Partial pressurization is a method whereby a portion of the waste flow is pressurized and mixed with the remaining raw flow before entering the treatment unit. Figure 16.13 shows typical air dissolving tubes for the intended air injection.

To obtain optimum treatment with some wastes, it has been necessary to use chemical pretreatment before DAF (15, 34). The necessity for use of chemical conditioning is normally associated with a high degree of emulsification of the oil or grease matter in waste stream flow. It is, therefore, a requirement to break the emulsion and form a floc to absorb the oil or grease. It has been shown (Fig. 16.14) that increasing the particle size increases the rate of separation. Flocculation as a means of promoting particle growth preceding flotation contributes to the effectiveness of the flotation process where chemical conditioning is used. The points of chemical injection and the possible use of flocculation associated with the three methods of air injection are shown in Fig. 1.11 of this book (59).

The use of steel-package DAF units lends itself to application in the meat-processing industry. This arrangement provides an economical, flexible design that requires minimal construction cost and area investment. Most manufacturers of DAF units have a complete line of steel tank units to meet a wide variety of flow conditions (17–20). Rex Nord Models (Fig. 16.12) would handle a raw waste flow of approximately 800, 300, and 200 gpm. These

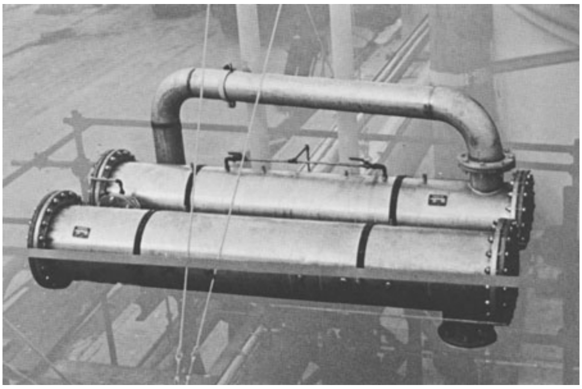


Fig. 16.13. Air bubbles injection using air dissolving tubes.

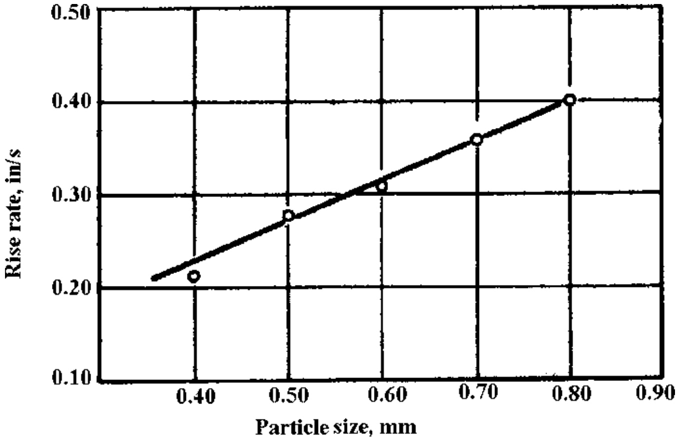


Fig. 16.14. Effect of particle size on rise rate.

raw flow figures were based on a vertical particle rise rate of 0.5 ft/min and a recycle rate of 33% (5). The use of steel-package units lends itself equally well to those applications requiring flash mixing and flocculation as a part of chemical pretreatment. Figure 16.15 shows that a steel package DAF unit is an effective primary clarifier (prior to biological treatment, such as aeration basin of activated sludge) as well as an effective secondary clarifier (after aeration basin) for a beef-processing plant.

In the following discussion, a steel-package with flash mix and flocculation compartments has been used to illustrate the costs associated with this type of unit. The capital cost of this unit (in 2006 US$) would be approximately US$ 134,000, which would include the following equipment:

1. Flash mixer and drive
2. Flocculator and drive
3. Two-shaft surface skimmer and drive
4. Screw conveyor, sludge collector, and drive
5. Complete steel tank
6. Pressure tank and associated air control system
7. Recycle pump
8. Compressor
9. Recycle piping

Table 16.4 lists the operating horsepower included in the unit described (5). Based on a 10-h-day, 5-day-week operation, costs of running for 52 weeks are shown in Table 16.5 for electrical costs at 1–1.5 cents/kW h.

To give a full range of capital costs involved with steel-package flotation units, the largest unit (flow = 800 gpm) would cost approximately US$ 204,000 with the above-listed equipment. The smallest unit would cost approximately US$ 79,000 with the same components (all costs are in 2006 US$).

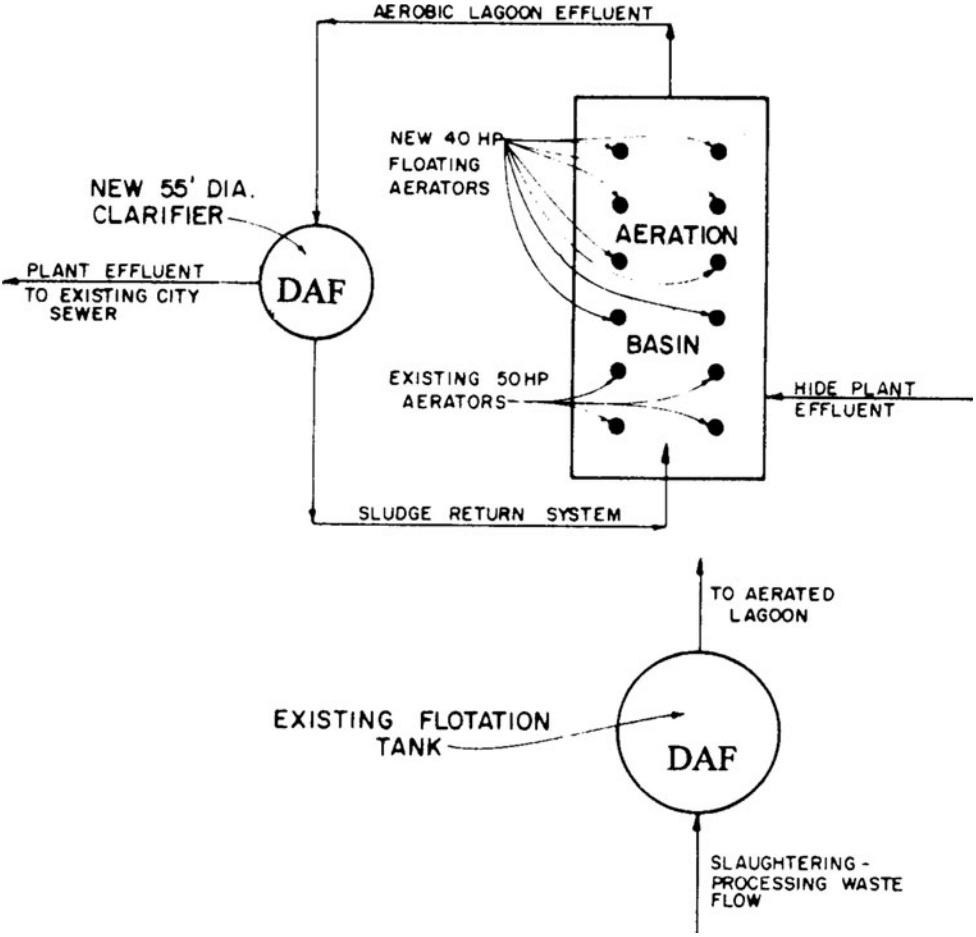


Fig. 16.15. Applications of flotation.

Table 16.4
Operating horse power for a typical DAF unit (Rex Nord Model 6020)

Item	Horsepower
Flash mixer	0.5
Flocculator	0.5
Skimmer	0.5
Bottom screw	0.5
Recycle pump	7.5
Compressor	1.5
Total	11.0

Table 16.5
Operating cost for a typical DAF unit (Rex Nord Model 6020)

Item	Yearly operation cost at indicated unit cost[a]		
	0.04 $/kW h	0.07 $/kW h	0.10 $/kW h
Flash mixer	39	68	98
Flocculator	39	68	98
Skimmer	39	68	98
Bottom screw	39	68	98
Recycle pump	583	1,020	1,456
Compressor	117	205	292
Total	856	1,497	2,140

[a] Cost is based on a 10-h-day, 5-day-week operation.

Table 16.6
Plant A operating results, hogs and cattle killing (flow = 1,600 gpm)

Sample	Hexane-soluble grease remaining (mg/L)	Removal[a] (%)
Untreated	3,000	–
After gravity settling (25 min approximately)	1,200	60
After gravity settling followed by dissolved air flotation with chemical treatment, 33% pressurized flow		
Type chemical, cationic polyelectrolyte A, dosage 0.75 mg/L	230	[1]80
Type chemical, cationic polyelectrolyte B, dosage 0.75 mg/L	80	[1]93

[a] Percent removal beyond that obtained by gravity settling alone.

Tables 16.6 and 16.7 list operating results from units treating wastes of a mixed kill of hogs and cattle and from a ham-packing operation. Tables 16.8 and 16.9 show results from bench scale testing of different types of meat-processing waste and indicate degrees of treatment obtained in different methods of treatment.

In several of the results, the use of chemicals was necessary to meet treatment objectives. Table 16.6 indicates the use of a cationic polyelectrolyte at a dosage of 0.75 mg/L. Based on a flow of 1,600 gpm and a chemical cost of 1.40 US$/lb, the cost for the chemical for a 12-h operation would be a little more than US$ 10/day. The cost of a simple polyelectrolyte feed system would be around US$ 21,000.

As is the case with most industrial waste, treatability studies should be conducted to determine not only the design parameters for a flotation unit, but also to determine whether chemical treatment is a necessity to meet treatment objectives.

Pilot DAF units are available from most manufacturers for treatability studies. The rental cost varies, but the normal rate is approximately US$ 1,800/month.

Table 16.7
Plant B operating results, ham packing, no killing (design flow = 200 gpm; actual flow = 385 gpm)

Sample	Constituent remaining (mg/L)	Removal (%)
Untreated		
Suspended solids	350	–
BOD$_5$	1,100	–
Hexane-soluble grease	600+	–
After dissolved air flotation, without chemicals, 33% pressurized flow		
Suspended solids	300	17
BOD$_5$	400	64
Hexane-soluble grease	80	87

Table 16.8
Plant C bench scale testing results, hog killing

Sample	Constituent remaining (mg/L)	Removal[a] (%)
Untreated		
Suspended solids	3,700	–
BOD$_5$	2,800	–
Hexane-soluble grease	3,300	–
After gravity settling (laboratory time to simulate 30 min full scale)		
Suspended solids	800	78
BOD$_5$	600	79
Hexane-soluble grease	500	85
After gravity settling followed by dissolved air flotation, without chemicals, 33% pressurized recycle flow		
Suspended solids	440	[1]45
BOD$_5$	380	[1]36
Hexane-soluble grease	190	[1]62
After gravity settling followed by dissolved air flotation, with chemical treatment, dosage 200 mg/L alum and 1 mg/L anionic polyelectrolyte		
Suspended solids	230	[1]71
BOD$_5$	210	[1]65
Hexane-soluble grease	55	[1]88

[a] Percent removal beyond that obtained by gravity settling alone.

Table 16.9
Plant D bench scale testing results, lamb killing

Sample	Hexane-soluble grease remaining (mg/L)	Removal (%)
Untreated (grab sample)	2,600	–
After dissolved air flotation, without chemicals, 33% pressurized flow	104	96
After dissolved air flotation, with chemicals, 33% pressurized flow, dosage 0.75 mg/L cationic polyelectrolyte	76	97

A laboratory bench scale test procedure developed to simulate the DAF process has been used most successfully in the determination of design parameters for an air flotation unit. This flotation test (see a later section) is used to determine the suspended particle rise rate (V_T), which is the most critical design parameter in the design of the flotation unit. The rate is determined by filling the pressure cell with liquid to simulate closely the recirculation of the unit effluent of pressurization in a full size unit; this recycle water should be developed by several previous flotation runs. This liquid is then injected with air until a pressure of over 40 psi is obtained; the cell then is shaken vigorously to insure that the air is put into the solution. The pressurized liquid then is introduced into the waste. The exact amount of pressurized liquid is determined by trial and error for best results. As the minute bubbles are released from solution, they attach to the suspended particle and oil and rise to the surface. After flotation is complete, a sample of the effluent is taken and analyzed. During the test, observation of the rise rate of the major portion of the solid material with respect to time is recorded. From a graphic plot of these data a rise rate can be calculated. This rise rate, along with factors for turbulence and short circuiting, is used in the selection of the basin size necessary to accomplish treatment required.

3.5.2. Circular DAF Cells

Whereas the preceding discussion was limited to rectangular DAF systems, it should be noted that the same principles are applied to circular-shaped tanks by a number of equipment manufacturers (17–20). These tanks are similar to conventional clarifiers with center baffled inlet, peripheral weir, bottom sludge removal scrapers, and surface skimmer arms discharging to a surface scum trough. The pressurized air recycle arrangements are the same as those used in rectangular tank systems. These circular systems average approximately US$ 4,300/ft of diameter to 20 ft in diameter, and US$ 3,600/ft diameter above 20 ft. These costs include steel tank side sheets, sludge and scum removal mechanism, pressurizing pump, air saturation tank, and air compressor. Installation costs can be estimated at 40% of the equipment costs (5). Variations among manufacturers lie in proprietary details such as baffling of the influent, design of the skimming system, design of the effluent trough, and design of the scraper mechanism.

Figure 16.16 shows suggested systems that are applicable to either circular or rectangular flotation units. The primary skim tank is a gravity catch basin and the DAF clarifier is a

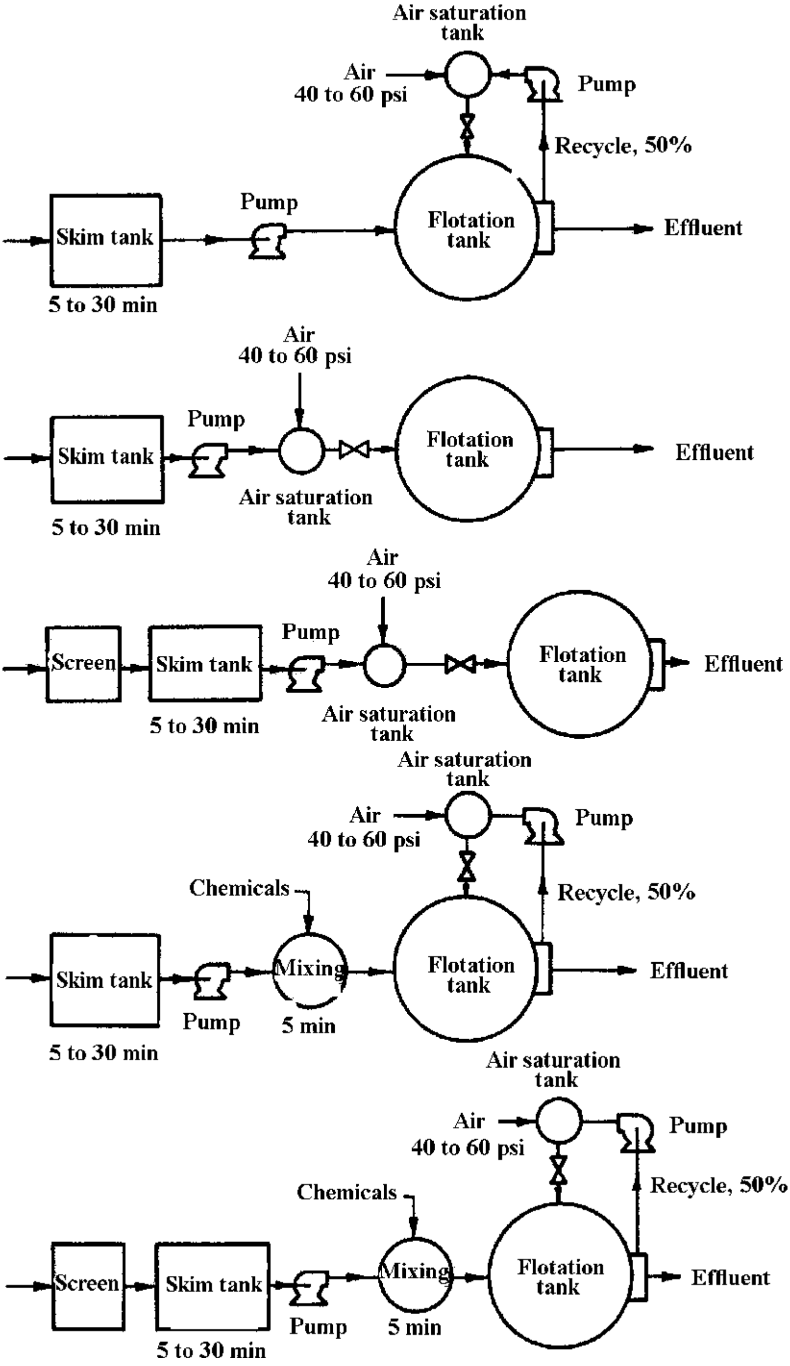


Fig. 16.16. Flow sheets for treatment of wastewater from meat-processing industry.

Table 16.10
Operating data, primary skimming followed by DAF

Plant	Product	Head/day	Figure no.	System capacity (gal/min)	Diameter flotation unit
I	Beef	1,100	16a	1,000	35 ft 9 in.
II	Beef	1,000	16a	1,500	50 ft 0 in.
III	Pork	300	16e	100	17 ft 6 in.
Operating results reported					
Plant	Chemicals added	Pollutant	Influent (mg/L)	Effluent (mg/L)	Removal (%)
I	None	Grease	1,150	150	87
II	None	Grease	2,150	213	90
III					
I					
II	None	BOD	1,710	760	55
III	$Fe_2(SO_4)_3$	BOD	1,306	200	85
I					
II	None	Suspended solids	6,200	410	93
III	$Fe_2(SO_4)_3$	Suspended solids	1,380	60	95

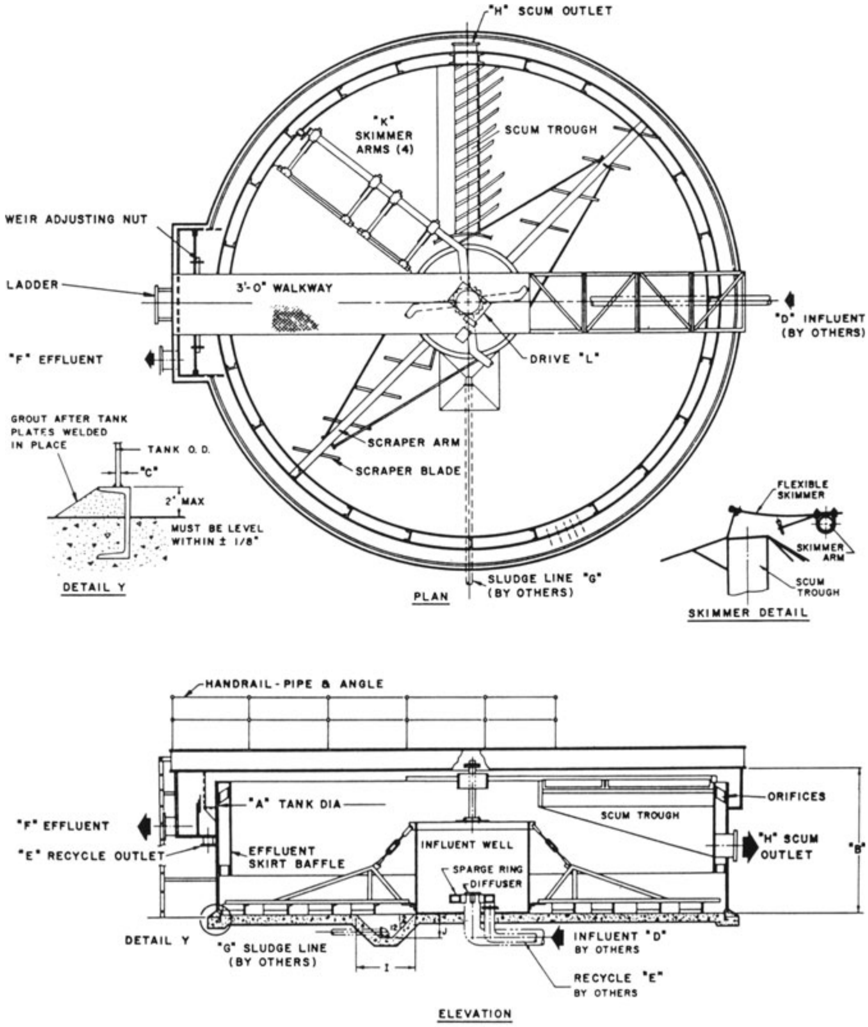
proprietary circular DAF system. The systems shown in Fig. 16.16d, e, with proper chemical treatment, are claimed to produce 90% grease removal and 55–95% BOD and suspended solids removal (see Table 16.10). Figure 16.17 illustrates the circular type of flotation system (5).

There are many other proprietary devices, processes, and mechanical details that, it is claimed, enhance the efficiency of DAF – too many to recount here (39–41). It must be stressed again that the system must operate, in pilot scale, on the wastewaters from the packing plant in question for several months before its value can be established for that particular plant.

3.5.3. The Flotation Test

Assume that a recirculation ratio of 0.33/1 (33%) is to be tried (5).

1. Place 750 mL of a representative sample of the waste in a 1-L graduated glass cylinder.
2. Fill the Float-Treat Pressure Cell approximately three-fourths full with liquid. (It is desirable that the operation of the Float-Treat Pressure Cell closely simulates the recirculation of effluent as used in the Float-Treat Flotation System. The returned effluent, recycle water, may be developed by repeated flotation of several different portions of raw waste. After the recycle water has been developed and used in the flotation tests, samples may then be withdrawn for chemical analyses.)
3. Secure the cover gasket and cover of the Float-Treat Cell, making certain that all the valves are closed.
4. Inject air into the cell until a pressure of 40 psi is attained and maintained during testing.
5. Shake the cell vigorously for 30 s.



A	TANK DIAMETER	G	SLUDGE BLOWOFF
B	SIDESHEET HEIGHT	H	SCUM OUTLET
C	SIDESHEET THICKNESS	I	SLUDGE SUMP, WIDTH
D	INFLUENT	J	SLUDGE SUMP, DEPTH
E	RECYCLE	K	NUMBER OF SKIMMERS
F	EFFLUENT	L	DRIVE HORSEPOWER

Fig. 16.17. Circular DAF clarifier for wastewater treatment from meat-processing industry.

6. Release 250 mL of the liquid, which has been pressurized, into the graduated cylinder. The volume of liquid in the graduated cylinder then totals 1,000 mL (750 mL raw and 250 mL pressurized). The ratio of volumes of recycle water to the raw waste is termed the recycle ratio. This ratio is expressed in percent and is termed the recycle rate. Thus, the recycle rate used in this

test is 33%. The most suitable recycle rate can be determined by repeated tests at varying rates of recycle and usually is not less than 20% and no more than 50%. To facilitate the introduction of the air-charged recycle water to the graduated cylinder, a rubber tube may be connected to the petcock on the pressure cell. After clearing the rubber tube of air (Allow some liquid to escape through the tube by opening the petcock. Sufficient liquid should be removed until it has a milky appearance.), the air-charged recycle water is introduced through the rubber tube into the graduated cylinder. The end of tube should be placed near the bottom of the cylinder. The air bubbles rise through the liquid in a manner similar to that in the Float-Treat flotation system.

7. Allow the contents of the graduated cylinder to come to rest, and observe the flotation. Allow sufficient time for the rising solids to come to the surface of the liquid. Usually 10 min will be sufficient time for the flotation to be completed.
8. After the flotation is completed, a sample of the raw waste and treated waste should be taken for analysis. The treated waste should be carefully withdrawn from the graduated cylinder either through the use of a petcock installed in the side and near the bottom of the cylinder or through the use of a siphon inserted into the cylinder. Sufficient liquid should be withdrawn to complete the desired analysis; however, care should be taken to avoid the break up of the scum blanket or float.
9. Should chemical flocculation with flotation be desired, the chemical may be added into the raw waste after step 1 is completed; flocculation may be carried out, for convenience, in another vessel.
10. Care should be taken not to break up the floc when transferring the waste to the cylinder. Enough time for flocculation should be allowed before introducing the air-charged recycle water. Under appropriate conditions, a floc may be formed by gentle agitation of the waste after the chemical is added.

Because of the peculiarities of some floc formations, they will break up readily upon any excessive agitation after being formed. This is most readily noticed when a liquid with a preformed floc is transferred from the cylinder used in the jar mixing test to the cylinder used in flocculation test. If the floc breaks up and does not reform immediately, it is suggested that flotation be accomplished in the same vessel where the floc was formed. The procedure for running this test is the same. However, withdrawing of the clarified liquid, as described in step 8, will probably be through a siphon.

In studying the flotation of a particular waste, it is quite possible that the test using the suggested recirculation ratio of 0.33/1 may not yield the best results. Therefore, the tests may be repeated with other recirculation ratios to obtain the optimum ratio. In these tests the values shown in steps 1 and 6 will be changed accordingly.

The observed rate of rise of the major portion of the solid material should be recorded. This value can be recorded in terms of inch per min and will be used in determining the full-scale plant requirements.

In order to insure the validity of the results obtained, care should be taken that representative samples of the waste are obtained before running tests.

3.5.4. Pilot Plants

The use of pilot plants for grease recovery and other wastewater treatment design cannot be overemphasized. The most important information obtained from pilot plant studies is that the plant can be operated with a relative flow rate and waste characteristics representative of those for which the ultimate plant will be designed. One of the most frequent errors in the use of pilot plants for design purposes is the application of pilot plant data from one meat-packing plant to another with different flow pattern, production processes, and production equipment. Most major manufacturers have pilot plant equipment available on rental terms (17–20).

4. INVESTIGATION OF THE DAF PROCESS AND ITS EFFECTIVE PARAMETERS

As explained earlier, the discharge of meat-processing wastewater into an urban sewer system, which is the more common option, requires pretreatment of the wastewater within the plant using physicochemical treatment processes (2, 18, 42, 43). Discharging directly into surface waters requires at least secondary biological treatment (30, 31, 44–48). Whatever the discharge choice, DAF constitutes the backbone process for the treatment of wastewaters from the meat-processing industry.

Publications concerning the use of DAF in treatment of wastewater from the meat-processing industry (43, 49–52) limit themselves to practical uses of this method. However, there is a lack of fundamental theory for carrying out the process. Therefore, the practice is based on empirical observations. In technology one often settles for readily available solutions offered by manufacturers of the equipment.

4.1. *Aim of the Investigation*

This investigation was aimed at studying the DAF process in the treatment of wastewaters from the meat-processing industry. The study, in particular, was aimed at finding and determining the role of relevant parameters such as the type and dose of chemicals, pH of the reaction environment, and how the flotation process proceeds in order to improve the floatability of pollutants from wastewaters and the adoption of a rational basis for design and application of the flotation process.

4.2. *Methodology*

The DAF process was investigated using the bench scale equipment layout shown in Fig. 16.18. The wastewater characteristics of the mixed wastewaters generated from the meat plant, producing 2,000–2,500 m^3/day, are shown in Table 16.11. Flotation was carried out under the following three conditions (53):

1. Without recycling and without chemical addition
2. Without recycling and with chemical addition
3. With recycling and chemicals addition

The chemicals in Case 2 were directly introduced into the saturation chamber; however, in Case 3 with recycling the chemicals were dosed into the wastewater during coagulation (rapid and slow mixing), which is followed by the flotation process. The clarified wastewater was used for recycling at ratios of 33, 100, and 300%. The corresponding volumes of clarified

Table 16.11
Wastewater characteristics of meat-processing plant

Parameter	Unit	Range of values	Average value
Turbidity	NTU	200–1,200	532
pH	–	7.1–9.9	8.3
COD	mg/L	827–3,079	1,684
BOD_5	mg/L	408–1,800	1,148
Total nitrogen	mg/L	62.6–196	118.2
Organic nitrogen	mg/L	42.6–136	66.6
Chlorides	mg/L	206–1,694	566
Sulfates	mg/L	22.6–70.4	45.7
Total solids	mg/L	2,842–4,864	3,674
Suspended solids	mg/L	693–1,987	1,213
Grease	mg/L	251–1,203	426

water added to wastewater in the 1 L flotation cylinder (Fig. 16.18) were 250 mL/750 mL, 500 mL/500 mL, and 750 mL/250 mL, respectively.

The following three types of chemicals were chosen from a large group tested during the preliminary studies:

1. Mineral coagulants: aluminum sulfate representing the group of hydrolyzing coagulants and magnesium chloride representing electrolyte coagulants.
2. Organic coagulant: lignosulfonate (waste product during the production of cellulose using the sulfite method).
3. Chemicals influencing the reaction environment: calcium hydroxide and sulfuric acid.

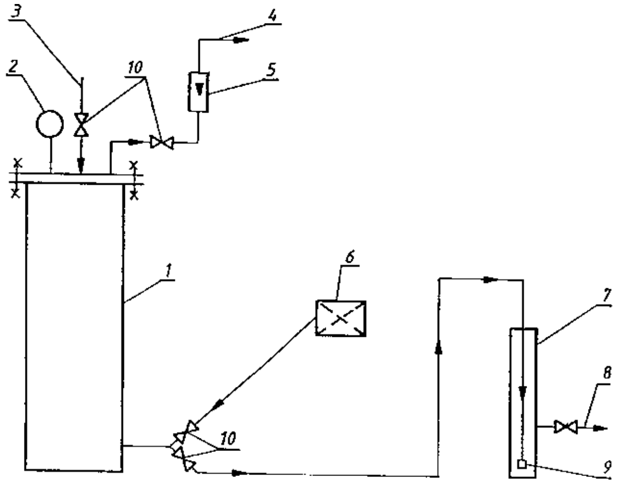
The optimum chemical doses were determined in coagulation tests (53). The characteristics of wastewater as used in the tests are shown in Table 16.12. The results of those tests in regard to wastewater turbidity are shown in Fig. 16.19.

The studies were conducted to assess DAF performance in the treatment of meat-processing wastewater (mainly removal of suspended solids). They were also used to assess the influence of the basic physical parameters of the flotation process on removal of pollutants. These factors included the amount of released air, A, dependence on saturation pressure, p, recycling, R, initial suspended solids concentration, S_i, and the average rise rate, V_t (the ratio of chamber height, h, to the flotation time in the chamber, t_s).

The obtained data were then used for the determination of the correlation between the physical variables of the process in the form of the following relationships:

1. The relationship between suspended solids content (S_e, mg/L) in the effluent and the air/solids ratio (A/S_i, L/mg) at a given rise rate ($V_T = 2.7$ m/h):

$$S_e = f(A/S_i) \tag{3}$$



1. Pressurised saturation chamber (V=5 L, $t_s=5$ min, p=0.2–0.5 MPa)
2. Manometer
3. Sewage inflow
4. Air outflow
5. Rotameter
6. Compressor
7. Flotation chamber (V=1 L, h=45 cm, d=5 cm)
8. Point of the sewage sampling
9. Nozzle (d=0.5 mm)
10. Valves

Fig. 16.18. Bench-scale DAF treatment plant.

Table 16.12
Wastewater characteristics of meat-processing plant as used in coagulation tests

Parameter	Unit	Sample		
		1	2	3
Turbidity	NTU	900	1,000	1,200
COD	mg/L	1,096	2,125	3,079
Suspended solids	mg/L	693	1,287	1,526
Grease	mg/L	336	429	1,203
Total nitrogen	mg/L	179	114	196
Chlorides	mg/L	887	746	1,065
Sulfates	mg/L	45	54	58

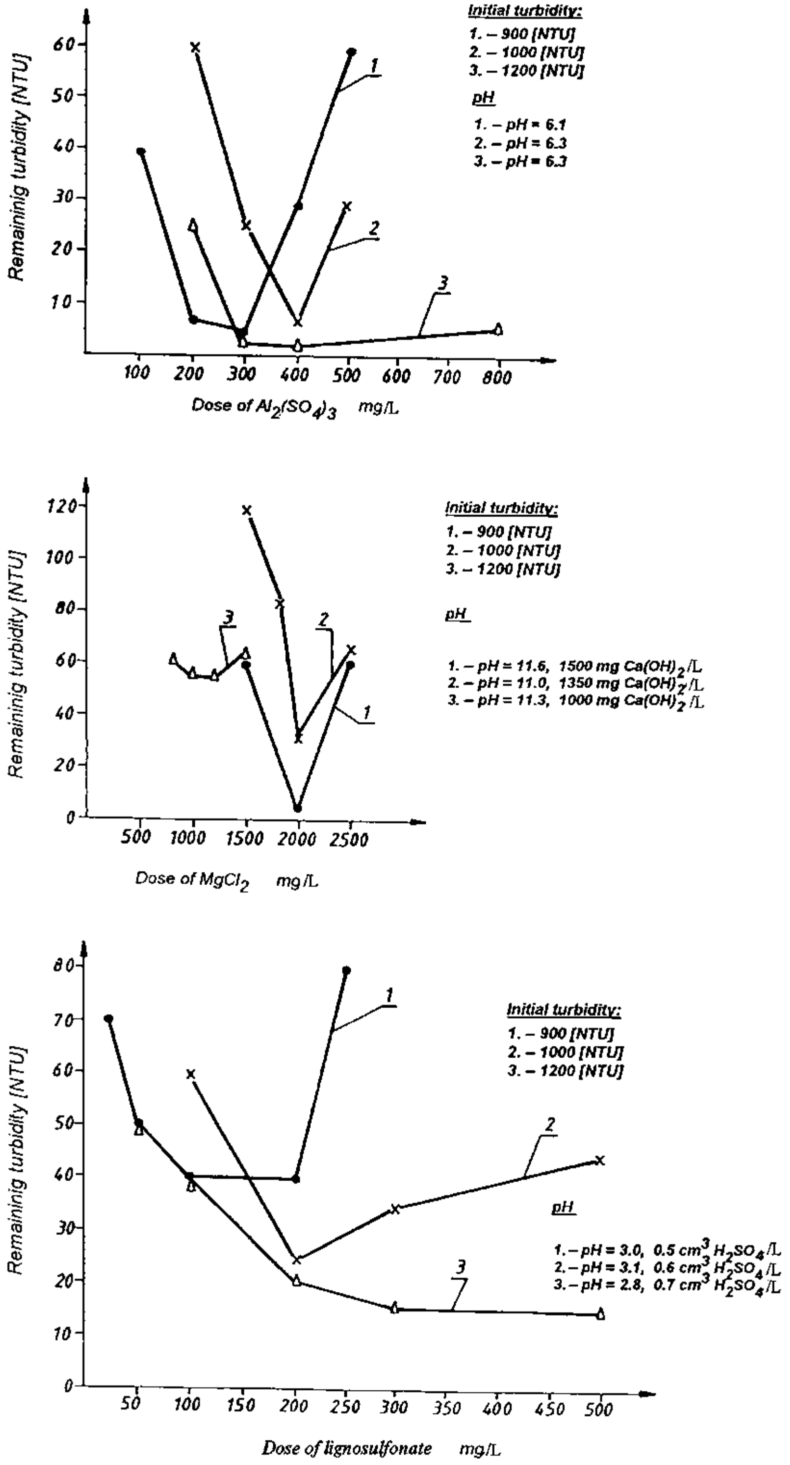


Fig. 16.19. Relationship between effluent turbidity and coagulants dose.

2. The boundary curve (for flotation area) for which the value of flotation degree is equal to zero:

$$A/S_{\mathrm{i}} = f(S_{\mathrm{i}}) \tag{4}$$

3. The relationship between the rate of suspended solids removal (r, mg/L/s) and the initial suspended solids concentration (S_{i})

$$r = f(S_{\mathrm{i}}) \tag{5}$$

These relationships take into account the parameters that serve as indicators of the formation and flotation of solid–gas bubble agglomerates (54–58). The analysis of these parameters therefore can serve to estimate the course of DAF.

4.3. *Analysis and Discussion*

From the conducted studies it was clear that the effectiveness and course of DAF as applied to the treatment of wastewater from the meat-processing industry is greatly influenced by the chemical addition. Flotation alone without chemical addition produced poor treatment results. The cause of this lies in the lack of adhesion of air bubbles on the surface of solids (including free fats) that is required to induce flotation. DAF aided by chemicals, in both cases with and without recycling, produced good coagulation of pollutants, their transformation into well-flocculated solids that are more hydrophobic, which on contact with air bubbles, forms lighter agglomerates that rise quickly and are removed from the liquid phase resulting in wastewater clarification.

During initial studies on coagulation, it was found that the efficiency of the chemicals on DAF is to a large extent dependant on the type and dose of the coagulants and the pH of the reaction environment. The results did not, however, allow for defining close quantitative relationship between the coagulant dose and the parameters that define the wastewater characteristics. The effectiveness of flocculation was more a function of the general properties of wastewater than of concentration of suspended solids, COD, or oil concentration.

The optimal pH values for the coagulants were 6.1–6.3 for $Al_2(SO_4)_3$, 11.5 for $MgCl_2$, and 2.8–3.1 for lignosulfonate. The effect of the pH on destabilization when using the mineral coagulants is attributed to hydroxide formation, whereas the effect using the organic coagulant is attributed to the reaction of the lignin component of the coagulant with the protein substances in the wastewater. The mineral coagulants were more effective than the lignosulfonate.

Mathematical analysis was used to assess the effectiveness of DAF aided by coagulants and to establish the course of the flotation process (see Fig. 16.20). The relationship between content of suspended solids, S_{e}, in the treated DAF effluent and the value of A/S_{i} ratio for different reagents and flotation layouts, according to the general formula $y = ax^{-b}$, is as follows:

1. No reagents and no recycling $S_{\mathrm{e}} = 120\ (A/S_{\mathrm{i}})^{-0.47}\ (R^2 = 0.91)$
2. $Al_2(SO_4)_3$ without recycling $S_{\mathrm{e}} = 2 \times 10^{-14}\ (A/S_{\mathrm{i}})^{-8.27}\ (R^2 = 0.90)$
3. $Al_2(SO_4)_3$ with recycling $S_{\mathrm{e}} = 4.6\ (A/S_{\mathrm{i}})^{-0.74}\ (R^2 = 0.93)$
4. $MgCl_2$ without recycling $S_{\mathrm{e}} = 3 \times 10^{-4}\ (A/S_{\mathrm{i}})^{-2.62}\ (R^2 = 0.83)$
5. $MgCl_2$ with recycling $S_{\mathrm{e}} = 3 \times 10^{-4}\ (A/S_{\mathrm{i}})^{-2.59}\ (R^2 = 0.96)$
6. Lignosulfonate without recycling $S_{\mathrm{e}} = 3 \times 10^{-13}\ (A/S_{\mathrm{i}})^{-8.12}\ (R^2 = 0.94)$
7. Lignosulfonate with recycling $S_{\mathrm{e}} = 30\ (A/S_{\mathrm{i}})^{-0.58}\ (R^2 = 0.90)$

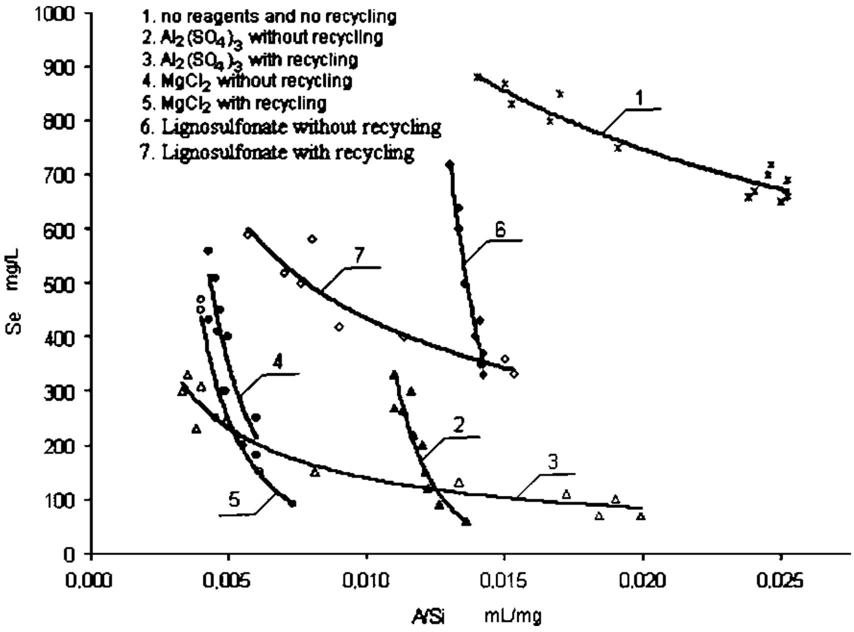


Fig. 16.20. Relationship of A/S_i ratio as a function of S_e for different chemical additions with/without recycle.

The relationships obtained from this analysis indicate that for each of the studied chemicals and flotation schemes the suspended solids content in the treated wastewater decreases exponentially with the increase in A/S_i, air to solids ratio. The curves presented in Fig. 16.20 describe the changes in suspended solids content in the treated wastewater for each of the studied chemicals. The curve for the flotation case with recycling is lower than the curve for the flotation case without recycling. This indicates that in the case with recycling the flotation takes place more readily giving better treatment results; however, it requires an increase in amount of released air per unit weight of removed pollutant than in the flotation case without recycling.

At similar A/S_i values, all chemicals exhibited greater suspended solids removal with recycling (Fig. 16.20). To obtain the same suspended solids reduction without recycling (in which formation of flocculated suspension takes place simultaneously with the release of air bubbles), the A/S_i ratio has to be greater and, hence, the amount of air released per unit weight of suspended solids removed has to be greater to ensure adequate adsorption of air bubbles by the suspended solids. Thus, without recycling there is poorer adhesion of the air bubbles to the suspended solids, and a significant amount of the released air is wasted. Consequently, in recycling, the released air bubbles apparently adhere more readily and with greater probability to the suspended flocs formed in the coagulation process. Therefore, with recycle less air is sufficient for flotation and hence, removal.

However, there is a limit to increased suspended solids removal with increased A/S_i as shown in the crossover of the curves in Fig. 16.20 (Curves 2 and 3 and Curves 6 and 7). This is attributed to the increased turbulence that breaks up the floc as the total air is increased with the recycle. Thus, there is an optimum limit to the benefit of increasing the recycling ratio.

The shape of the curves in Fig. 16.20 (Curves 4 and 5) show that, both with and without recycling, magnesium chloride was the most effective coagulant, and that the lignosulfonate (Curves 6 and 7) was the least effective. In all cases, the coagulants used improved suspended solids removal as compared with the control using no coagulant (Curve 1).

The borderline curves defining the region of floatability of suspended solids indicated on Fig. 16.21, which show the relationship of the minimum value of the A/S_i ratio as a function of the influent solids concentration and the relationship of the rate of suspended solids removal, r, as a function of the influent suspended solids concentration, further confirm the above conclusions. With recycling, the flotation process takes place at lower values of the A/S_i ratio. The most significant difference, in favor of recycling, occurs during flotation aided by lignosulfonate and aluminum sulfate, whereas the borderline curves for magnesium chloride were very similar in shape.

It was also found that the rate of suspended solids flotation, r, describing the changes occurring in the suspended solids concentration during the flotation process, is a linear function of the initial suspended solids concentration, S_i:

$$r = k\, S_i \tag{6}$$

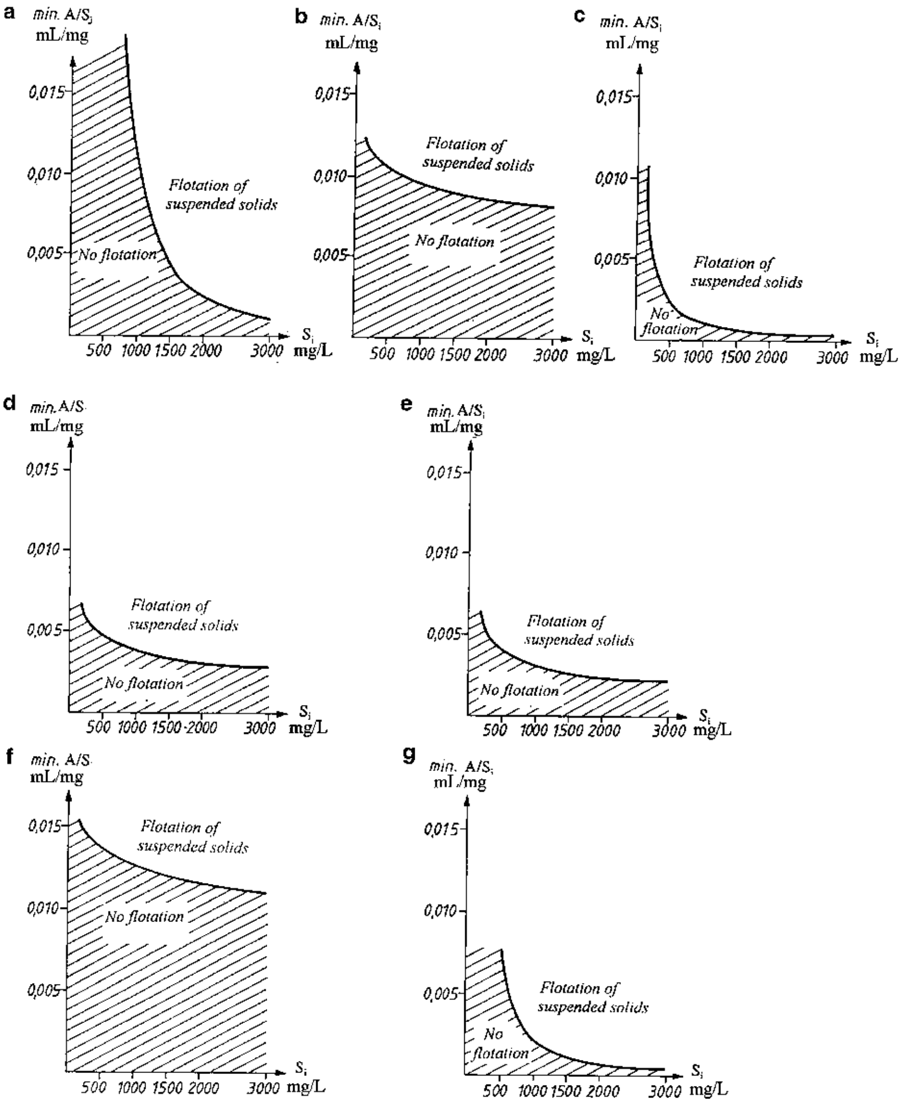
The value of the rate constant, k, of the function determined for each of the studied chemicals and flotation patterns represents the measure of the ability of suspended solids to float. In general, it can be concluded that coagulants significantly increase the actual flotation rate of suspended solids. Magnesium chloride and aluminum sulfate increase the k value by a factor of 1.4 in comparison to the case without chemicals, but lignosulfonate increases the k value only by a factor of 0.6. This confirms that suspended solids are removed from wastewater more effectively aided by chemicals, especially magnesium chloride and aluminum sulfate. The k value for flotation without the use of chemicals was very low, 0.00062 s^{-1}.

In view of the presented investigation, it can be concluded that DAF can be best carried out in a flotation scheme consisting of recycling aided by coagulation chemicals. During a DAF design stage it is recommended to use, as a guide, the threshold values resulting from the determined relationships shown in Figs. 16.3 and 16.4.

4.4. Conclusions

1. The course of the DAF process in treating wastewaters from the meat-processing industry depends mainly on:
   (a) The air to solids ratio, A/S_i
   (b) Chemicals addition
   (c) The recycle pattern

   The content of suspended solids in treated wastewater, S_e, decreases exponentially with the increase of the A/S_i ratio. The addition of coagulation chemicals improves the flotation process due to the destabilization, flocculation, and hydrophobization of heterogenic pollutants in the wastewater. The pH of the reaction environment has significant influence on the phenomenon



a) no reagents and no recycling
b) with $Al_2(SO_4)_3$ and no recycling
c) with $Al_2(SO_4)_3$ with recycling
d) with $MgCl_2$ no recycling
e) with $MgCl_2$ with recycling
f) lignosulfonate no recycling
g) lignosulfonate with recycling

Fig. 16.21. Limiting curves for A/S_i as a function of S_i indicating regions of solids flotation.

mentioned above. Magnesium chloride and aluminum sulfate were found to be better than lignosulfonate.

2. The mechanism of DAF is related to the formation of the solids–gas bubble agglomerates, and its effectiveness is mainly dependent on the amount of air released within the wastewater bulk,

turbulence, and the probability of the contact of gas bubbles with the solids. It was found that more favorable conditions for flotation of the pollutants take place in flotation with recycling, although in this case the agglomerates are more susceptible to shearing forces caused by turbulence at high A/S_i ratio, than in the case without recycling.

3. The kinetics of the pollutants removal in DAF measured by the suspended solid flotation rate depends on the physical properties of the suspended solids, the coagulation chemicals added, and the initial suspended solids in the wastewater. The rate of suspended solids flotation increases with the increase in the suspended solids content, $r = QS_i$. The value of the gradient coefficient, Q, which is a function of the solids characteristics, increases by the addition of coagulants. Magnesium chloride and aluminum sulfate increase the flotation rate of suspended solids by 140% while lignosulfonate raises the rate by only 60%.

5. CASE HISTORIES

5.1. Case I: A Hog-Killing Plant, Iowa

A hog-killing plant of medium size in Iowa, producing fresh pork with no further processing other than edible and inedible rendering, has reduced BOD to 2.5–3 lb/1,000 lb live weight kill mainly by way of water conservation. The plant has a daily kill of about 504,000 lb live weight using only 58,000 gal of water. Peak kill reaches 544,000 lb/day and peak water use 78,000 gal/day, with a minimum of 33,000 gal on any operational day.

Yards and pens are all dry cleaned, using a manure spreader for direct disposal on farmland. The blood floor is prerinsed with a small-diameter hose equipped with a fan nozzle using water at 600 psi pressure. The small amount of rinse water, 35–50 gal/day, goes to the blood tank. All blood is dried. The extra drying cost for the prerinse water is small compared with the cost saving in BOD reduction in final cleanup.

The plant is equipped with edible and inedible dry rendering, but paunches and edible stomachs are washed, and the wastewater is discharged to the sewer. The possibilities of further improvement in waste conservation by dry dumping have not been explored.

The plant produces a substantial saving in solids and BOD by its procedure in dumping the scalding tub. The tub is fitted with a drain 6 in. above the bottom of the tub, draining through a 2-in. line. The slow drain permits the sludge to settle. Then the residual sludge is scraped and shoveled to a large sluice gate that is kept closed during drainage. The sludge is hauled to farm fields.

The dehairing operation uses only 6 gal/hog at 250 hogs/h, with five workers for shaving and trimming. The wet hair is sold.

The grease sewer discharges to a small gravity catch basin 5 ft wide and 6.5 ft long, with a sloping end. A single scraper chain mechanism serves to drag the bottom sludge up the sloping end to a trough and also pushes the scum to a scum trough. The scrapers ride up a beach at the scum trough and thence over the trough to complete the circuit. Bottom solids and skimmings go to rendering.

The effluent of this basin joins the nongrease sewer at a 12-ft-diameter holding sump, from which a 400 gpm pump discharges to a circular DAF unit also rated at 400 gpm. The ratio of recycle to raw flow is 1–4. No chemicals are used. The effluent flow then is discharged to a portion of the pump sump, walled off to carry the effluent to lagoon treatment (the wastewater could be considered ready for discharge to a city sewer at this point). The walled portion of the pump sump is arranged to recycle effluent through the flotation unit during low-flow periods, to insure uniform treatment in the flotation unit.

The plant is washed down by a contract janitorial service after plant personnel dry-clean the floors and equipment to remove scraps. The initial rinse on the blood floor is done by plant personnel. All driers are equipped with sprays for cleaning in place.

The owner gives major credit to water conservation for his overall success in reducing BOD as well as water consumption.

It should be noted that the operations at this plant are limited to slaughtering and rendering. Since individual process wastes in the meat industry have not been evaluated systematically, it is impossible to predict the effect of additional processing on the results of these wastewater conservation data.

5.2. *Case II: Large Meat-Packing Plant*

A large meat-packing plant, killing 470,000 lb/day live weight beef and 1,380,000 lb/day live weight hogs, operates a complete pork-processing system that includes smoking, sausage manufacturing, and curing, as well as sliced luncheon meat, canned meats, and lard manufacturing. The plant discharges less than 4 MGD of wastewater and recycles 1.1 MGD of wastewater for various purposes in the plant. Blood is coagulated and the bloodwater is evaporated. Hides are sold green. Three-quarters of the hog hair is sold, the remainder going to landfill. Paunches are washed and the manure is removed by screening before the wastewater joins the major wastewater stream. The plant operates a laundry for shrouds and work clothes and washing facilities for all rail cars. Tripe and stomachs are washed, but casings and chitterlings are tanked direct. Viscera are hashed and washed. Wet rendering is practiced for continuous edible rendering and for inedible rendering of skimmings. Pretreatment consists of screens, gravity catch basins, and DAF. Manure sewer wastewaters are screened separately. The raw BOD_5 is 1,600 mg/L, suspended solids 1,750 mg/L, and grease 800 mg/L. After pretreatment, these data drop to 850 mg/L (47% BOD removal), 500 mg/L (71% suspended solids removal), and 150 mg/L (81% grease removal).

6. SUMMARY

In any effort to improve the quality of the wastewaters from a meat-processing plant, the first step must be a complete evaluation of in-plant waste-conservation opportunities. These opportunities include the following:

1. Recovery of product
2. Removal of solid wastes and inedibles at the source (dry, where possible)
3. Recycling of waters, such as cooling water and can quenching
4. Reuse of wastewater for inedible purposes, such as condenser water in the tank house

In many communities, there are regulations setting forth pretreatment requirements and surcharge agreements to charge the meat packer the fair share of the costs of municipal treatment. The cost of purchased water, the cost of waste treatment (pretreatment costs plus municipal surcharges), and possibly the value of recoverable byproducts offer economic incentives for waste conservation. After all feasible steps in waste conservation have been taken, the degree of pretreatment of the various waste flows must be determined, first to satisfy regulations, and second to determine whether pretreatment beyond that required legally will produce economic advantages. The basic pretreatment is required by law; any pretreatment beyond this base is an economic decision. Thus, there is an economic breakpoint where the pretreatment can stop. Possibly the legal requirements are the stopping point, and nothing can be gained by going further.

Other variables enter the picture:

1. Possibilities for increases in municipal surcharges
2. Adequacy of the municipal plant to treat the wastewaters
3. General growth potential of the community, both in industry and in population

The meat packer also must consider future business plans, such as changes in processing, additional processing, overall expansion, or possible reduction in operations. If wastewaters are treated by the packer for direct discharge to a watercourse, consideration must be given to obsolescence of the treatment plant, possible changes in legal requirements, and the costs that are part of a wholly owned facility (taxes, maintenance, operation, amortization, etc.).

Within these elusive variables, the meat packer must determine

1. The amount of in-plant waste conservation economically feasible. It should be noted, however, that a substantial amount of waste conservation often can be accomplished at insignificant expense.
2. The degree of pretreatment (for each of the segregated plant waste streams) needed in order to arrive at an economic breakpoint. For example, a small amount of biological treatment, beyond the physical and chemical treatment, will drop the BOD and suspended solids to a level equivalent to domestic wastewater, and the surcharges levied by the city based on plant wastewater concentrations beyond the level of domestic wastewater will drop to zero.
3. Whether the long-range possibilities for increases in municipal surcharges warrant consideration of a completely independent wastewater treatment system that discharges to a watercourse, thereby eliminating all dependence on the municipal system.

Most of the biological treatment systems discussed in US EPA “Waste Treatment” (32) are also applicable to treatment before discharge to a city sewer, should such treatment become necessary to satisfy municipal regulations or become economically feasible.

There follows an outline suggesting procedures for developing a decision matrix for waste conservation and pretreatment before discharge to a public sewer.

1. Employ a waste conservation supervisor. In a small plant, this supervisor may have other duties, such as safety engineering, and he may have responsibility for compliance with the Occupational Safety and Health Act. In a large plant, a full-time waste conservation supervisor should be employed having some engineering background, preferably in environmental engineering. Responsibility includes waste conservation surveys, flow measurement, sampling surveys, cost analyses of waste conservation and treatment, and continuing surveillance of the waste conservation and treatment program, including supervision of the operation of any treatment facilities.

2. Install flow measuring and automatic sampling to collect and analyze wastewater samples at sufficient frequencies and over a sufficient length of time to develop data on flow during the maximum hour and the maximum day, as well as on averages.
3. Make an in-plant waste conservation survey as detailed in this chapter. Develop annual costs for each possible change to include
   (a) Amortized cost of improvements, installed
   (b) Power costs, such as heating, cooling, and pumping for recycling and water reuse
   (c) Chemical costs, if some in-house treatment is required in recycling a waste stream
   (d) Labor cost (maintenance and operation)
4. Make a study of possible pretreatment systems, with annual costs developed as in Point 3.
5. Determine the annual cost of municipal surcharges if wastewaters are discharged to the city sewers, and select in-plant improvements based on comparative cost. If wastewaters are discharged to a private treatment facility for disposal to a watercourse, the same type of cost analysis should be made.
6. Select the elements of Points 3 and 4 that are justified economically.
7. Design selected improvements to achieve the required results, considering such elements as
   (a) Flexibility for alteration and expansion
   (b) Operating skills required
   (c) Quantity of residual solids and grease and feasible means of disposal.

NOMENCLATURE

A = Amount of air in wastewater, mL/L

A/S_i = Air/solids ratio, mL/mg

$(A/S_i)_{min}$ = Minimum air–solids ratio, mL/mg

b_o = Average unit cost of treatment, chargeable to BOD, US$ /lb

B_i = Weight of BOD from industrial users, lb/year

C_i = Charge to industrial users, US$/year

d = Diameter, cm (mm)

h = Height, cm

k = Rate constant, 1/s

p = Pressure, MPa (psi)

r = Rate of suspended solids removal, mg/L/s

R = Recycling ratio

S_e = Suspended solids content in effluent, mg/L

S_i = Suspended solids content in influent, mg/L

t_s = Time, min

v_o = Average unit cost of transport and treatment chargeable to volume, US$/gal

V = Volume, L

V_i = Volume or wastewater from industrial users, gal/year

V_T = Particle rise rate, m/s, ft/min

w_o = Average unit cost of treatment (including sludge treatment) chargeable to suspended solids, US$/lb

W_i = Weight of suspended solids from industrial users, lb/year

CIP = Cleaned-in-place

REFERENCES

1. Shammas NK (2010) Flotation-filtration system for wastewater reuse. In: Wang LK, Shammas NK, Selke WA, Aulenbach DB (eds) Flotation technology. Humana Press, Totowa, NJ
2. Wang LK, Hung YT, Shammas NK (eds) (2005) Physicochemical treatment processes. Humana Press, Totowa, NJ, 723 pp
3. FWPCA (1967) Industrial waste profile No. 8 – meat products. In series The cost of clean water. Federal Water Pollution Control Association, Federal Water Pollution Control Administration, Washington, DC, p 53
4. California State University, Sacramento and California Water Environment Association (1996) Industrial waste treatment. US Environmental Protection Agency, Washington, DC
5. U.S. EPA (1973) In-plant modifications and pretreatment – upgrading meat packing facilities to reduce pollution. U.S. Environmental Protection Agency, Washington, DC
6. U.S. EPA (1971) Federal guidelines – equitable recovery of industrial waste treatment costs in municipal systems. U.S. Environmental Protection Agency, Washington, DC
7. U.S. EPA (1992) EPA model pretreatment ordinance. U.S. Environmental Protection Agency, Washington, DC
8. NETC (1996) Industrial pretreatment and hazardous material recognition for small communities. The National Environmental Training Center, West Virginia University, Morgantown, WV
9. U.S. EPA (2001) Environmental Management System (EMS) guide, meat processing, U.S. Environmental Protection Agency, Washington, DC
10. U.S. EPA (2004) Effluent guidelines, meat and poultry products (MPP). Fact Sheet, EPA 821-F-04–004. U.S. Environmental Protection Agency, Washington, DC, http://www.epa.gov/guide/mpp/final-fs.htm#sum
11. U.S. EPA (2004) Effluent limitations guidelines and new source performance standards for the meat and poultry products, point source category. Federal Register 69(173):54475–54555
12. ABT Associates Inc. (2002) Meat Processor Wastewater Treatment Environmental Compliance Checklist. Prepared for US Environmental Protection Agency, Washington, DC
13. Callaghan E (2010) A self-assessment guide for meat processors in Georgia, Engineering Outreach Program. University of Georgia, Biological & Agricultural Engineering Department, Athens, GA. http://www.engr.uga.edu/service/outreach/publications/foodprocessing/Meat%20Processing%20Abstract.pdf
14. Carawan RE, Pilkington DH (2010) Reduction in waste load from meat processing plant-beef. Randolph Packing Co., Asheboro, NC; North Carolina Agricultural Extension Service North Carolina State University, Raleigh, NC. http://www.owr.ehnr.state.nc.us/ref/01/00466.pdf
15. World Bank (2010) Meat processing and rendering. Pollution prevention and abatement handbook. World Bank, Washington, DC. http://www.ifc.org/ifcext/enviro.nsf/AttachmentsByTitle/gui_meat_WB/$FILE/meat_PPAH.pdf
16. Deluise FJ, Wang LK, Chang SY, Hung YT (2005) Screening and comminution. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ, pp 1–20
17. Wang LK, Fahey EM, Wu Z (2005) Dissolved air flotation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes, Humana Press, Totowa, NJ, pp 431–500
18. Wang LK (2006) Adsorptive bubble separation and dispersed air flotation. In: Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical treatment processes. Humana Press, Totowa, NJ, pp 81–122

19. Shammas NK, Wang LK, Hahn HH (2010) Fundamentals of wastewater flotation. In: Wang LK, Shammas NK, Selke WA, Aulenbach DB (eds) Flotation technology. Humana Press, Totowa, NJ
20. Krofta M, Wang LK (2000) Flotation engineering, 1st edn. Lenox Institute of Water Technology, Lenox, MA, Technical Manual No. Lenox/1–06–2000/368
21. Johnson AS (1965) Meat. In: Gumham CF (ed) Industrial waste control. Academic Press, New York, NY, p 36
22. Witherow JL (1970) Meat packing waste management research program. 65th Annual Meeting, American Meat Institute, Chicago, IL
23. Metcalf and Eddy (2003) Wastewater engineering treatment and reuse, 4th edn. McGraw Hill, New York, NY
24. Beefland International, Inc. (1971) Elimination of water pollution by packinghouse animal paunch and blood. EPA Project 12060, November
25. Shammas NK, Wang LK (2007) Land application of biosolids. In: Wang LK, Shammas NK, Hung YT (eds) Biosolids treatment processes. Humana Press, Totowa, NJ, pp 705–746
26. U.S. EPA (1993) Standards for the use or disposal of sewage sludge (40 Code of Federal Regulations Part 503). U. S. Environmental Protection Agency, Washington, DC
27. U.S. EPA (1995) Amendments to the standards for the use or disposal of sewage sludge (40 Code of Federal Regulations Part 503). U. S. Environmental Protection Agency, Washington, DC
28. Goel RK, Flora JRV, Chen JP (2005) Flow equalization and neutralization. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ
29. Wang LK, Chang SY, Yung YT, Muralidhara HS (2007) Centrifugation clarification and thickening. In: Wang LK, Shammas NK, Hung YT (eds) Biosolids treatment processes. Humana Press, Totowa, NJ, pp 101–134
30. Wang LK, Pereira NC, Yung YT, Shammas NK (eds) (2009) Biological treatment processes. Humana Press,, Totowa, NJ, 818 pp
31. Wang LK, Shammas NK, Yung YT (eds) (2009) Advanced biological treatment processes. Humana Press, Totowa, NJ, 738 pp
32. U.S. EPA (1973) Waste treatment: upgrading meat packing facilities to reduce pollution. U.S. Environmental Protection Agency, Washington, DC
33. Wang LK, Hung YT, Lo HH, Yapijakis C (eds) (2004) Handbook of industrial and hazardous wastes treatment. Marcel Dekker, New York, NY, 1345 pp
34. UNEP (2010) Food manufacturing series, meat processing. Fact Sheet 7, United Nations Environment Programme. http://www.gpa.uq.edu.au/CleanProd/Res/facts/FACT7.HTM
35. Dencker DO (1968) Some solutions to packinghouse waste problems. 15th Wastes Engineering Conference. University of Minnesota, St. Paul, MN
36. Shammas NK (2005) Coagulation and flocculation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ
37. Wells J Jr (1970) How plants can cut waste treatment expense. Nat Provisioner. July 4
38. U.S. ACE (2008) Civil works construction cost index system manual, 110–2–1304, U.S. Army Corps of Engineers, Tables, Washington, DC, pp 44. http://www.nww.usace.army.mil/cost
39. U.S. PHS (1965) An industrial waste guide to the meat industry. U.S. Public Health Service Publication No. 386, Washington, DC
40. Steffen AJ (1969) Waste disposal in the meat industry, a comprehensive review. Proceedings, meat industry research conference. American Meat Institute Foundation, University of Chicago, Washington, DC
41. UNEP (2000) Cleaner production assessment in meat processing. United Nations Environment Programme, UNEP/Earthprint, Paris, France

42. Meink F, Stoof H, Kohlschütter H (1968) Industrie-Abwässer. Stuttgart, Germany
43. Barnes D, Forster CF, Hrudey SE (1984) Food and allied industries. In: Barnes D, Forster CF, Hrudey SE (eds) Surveys in industrial wastewater treatment, vol. 1. Pitman Advanced Publication Program, London, UK
44. Willoughby E, Patton VD (1968) Design of a modern meat packing waste treatment plant. J Water Pollut Control Fed 40(1):132–137
45. Wang LK, Hung YT, Lo HH, Yapijakis C (eds) (2006) Waste treatment in the food processing industry. CRC press, Boca Raton, FL, 333 p
46. Shabi FA, Cannon MC (1975) Treatment of food industry wastes. Effluent Water Treat J 15:130–139
47. Stracey IG (1975) Treatment of abattoir and meat processing effluent at Haverhill Meat Products Ltd. Water Pollut Control 74(1):101
48. Heddle JF (1979) Activated sludge treatment of slaughterhouse wastes with protein recovery. Water Res 13:7
49. Köhler R (1969) Das Flotationswerfahen und seine Anwendung in der Abwassertechnik. Wasser, Luft u. Betrieb 13
50. Köhler R (1972) Schlachthofabwasserreinigung durch Entspannungs-Flotation. Wasser, Luft u. Betrieb 1
51. Rudischer R (1977) Neue technishe Moglichkeiten der Abwasserreinigung in Betrieben der Fleischwirtschaft. Fleisch 1
52. Wasowski J, Szejner B (1984) Waste water treatment from meat processing industry (in Polish). Gospodarka Miesna 8
53. Wasowski J (1995) Application of dissolved air flotation for treatment of wastewater from meat processing industry. Water Sci Technol 31(3–4):341–344
54. Gaudin AK (1957) Flotation. Mc Graw-Hill, New York, NY
55. Bartoszewski K (1975) Highly effective methods of sewage treatment (in Polish), Budow. Wodne i Inz. Sanit. vol. 23. Krakow University of Technology, Kraków, Poland
56. Reed SW, Woodward FE (1976) Dissolved air flotation of poultry processing waste. J Water Pollut Control Fed 48:1
57. Zabel R (1978) Flotation. Twelfth International Water Supply Congress. Kyoto, Japan
58. Banks CJB, Wang Z (2006) Treatment of meat wastes. In: Wang LK, Hung YT, Lo HH, Yapijakis C (eds) Waste treatment in the food processing industry. CRC Press, Boca Raton, FL, pp 67–100
59. Shammas NK, Bennett GF (2010) Principles of Air Flotation Technology. In: Flotation Technology. Wang LK, Shammas NK, Selka WA, Aulenbach DB (eds). Humana Press, Totowa, NJ

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Treatment of Seafood Processing Wastewater

Lawrence K. Wang, Donald B. Aulenbach, and Nazih K. Shammas

CONTENTS

Abstract Dissolved air flotation (DAF) has been widely used for the pre-treatment or the primary treatment of seafood processing wastes. Screening for removal of large particles (bones, shells, etc.) prior to DAF is recommended. Suspended solids are readily removed in a DAF unit that requires less space than an equivalent standard sedimentation basin. A DAF system can be started and shut down easily to accommodate fluctuations in seafood processing. Additional treatment facilities, such as, filtration, ion exchange, granular activated carbon adsorption, electrocoagulation, biological treatment processes, etc. may have to be provided to meet certain discharge standards.

Key Words Seafood processing • pretreatment • flotation • DAF • solids removal • fish meal • electrocoagulation • primary treatment • filtration • ion exchange • granular activated carbon adsorption • GAC • disinfection • odor control.

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1. INTRODUCTION

1.1. *Environmental Protection and Effluent Limitations*

Wastes from seafood processing plants may be as varied as the types of fish that are processed. In this discussion, seafood is considered to include both finfish and shellfish that reside in both fresh and salt water. In addition, the preparation process may vary from retaining the whole fish, in which the fish are usually eviscerated, to filleting, in which the skin and bones are removed, as well as the heads. In the case of shellfish, the fish may be distributed both including the shell and separated from the shell. Different means of shipment, such as refrigerated, frozen, canned, or precooked, will also produce different wastes.

Processing of seafood for food is relatively inefficient. It has been estimated (1) that only 25–30% of the usable meat from an average pollack catch is converted into product. This results in large volumes of high biochemical oxygen demand (BOD) wastes. An estimated 1.7 million metric tons of fish waste are generated per year in Alaska alone.

Unique to the fish processing industry is the ability to process the fish on board the fishing vessel on its way back to port. Here, the wastes, consisting primarily of fish parts, require only grinding to a maximum size of 0.5 in. and discharge overboard. This is considerably less costly than treatment requirements at onshore processing facilities. This chapter is limited to means of treating seafood wastes at onshore processing facilities.

Further, the degree of treatment of the processing wastes may vary with the location of the plant and discharge requirements from the state in which the plant is located (2–102). Appendices A, B, C, D, and E introduce the typical U.S. Environmental Protection Agency (US EPA) regulations in 1998–2010 for the owners and operators of shore-based seafood processing and by-product recovery facilities in Kodiak, Alaska, under a general National Pollutant Discharge Elimination System (NPDES) Permit No. AK-G52-8000.

1.2. *Main Activities of Fish Processing*

The main activities of fish processing can be divided into primary processes for direct consumption and secondary processes for processing of fish and shellfish into fish products. Also included are the subsequent packaging and canning procedures of these products.

Primary processes are

1. Fish dressing
2. Freezing
3. Glazing
4. Roe processing
5. Milt processing
6. Salting
7. Smoking

Secondary processes include

1. Sorting
2. Meal production
3. Extraction of oils
4. Packaging

1.3. Wastewater Streams

This industry is water intensive, usually requiring large quantities of high quality water for washing fish, cleaning of processing areas, cooling, and production. Consideration should be given to (a) the efficient use of this resource, (b) restricting consumption of water during periods of water shortage, and (c) the effects of discharging waste water containing pollutants and nutrients on the ecosystem of the receiving body of water, e.g., toxicity to fish and other aquatic organisms.

Waste waters in the fish processing industry are generated by the following activities: (a) fish unloading, (b) equipment sprays, (c) offal removal, (d) fish preparation, and (e) facility cleaning. Domestic and sanitary wastewaters at each facility should be discharged to a Publicly Owned Treatment Works (POTW) for treatment and disposal where available.

The wastewaters of a seafood processor that require pretreatment before being discharged to a POTW include (a) butchering waste streams, (b) surimi processing waste streams, (c) fish meal/powder waste streams, and (d) stick water. This chapter introduces the treatment requirements and best available treatment technologies for pretreatment of seafood processing liquid discharges (97–116).

Pretreatment before discharge of effluent should be considered in relation to the receiving body of water and the waterways used. Treatment of seafood processing effluents must cover the following pollutant issues: (a) level of total suspended solids (TSS), (b) high organic load leading to elevated BOD, (c) oil and greases, (d) ammonia, (e) cleaning agents (e.g., chlorine bleaches), (f) coliforms, and (g) temperature increase to a cold receiving body.

1.4. Solid and Liquid Waste Management

Recycling and reclaiming materials should be a priority where possible throughout the fish processing operation. If this is not possible, disposal should be environmentally acceptable and in compliance with the laws and regulations.

Spillage and contamination of soil and ground water can be guarded against through secondary containment. Areas to be considered are impoundment areas for storage of solids and liquids including those for (a) fuels, (b) raw and in-process materials, (c) solvents, (d) wastes, and (e) finished products.

Contamination of soil, ground, and surface waters should be prevented by the necessary measures for the proper disposal of wastes including the following: (a) hazardous materials, (b) process residues, (c) solvents, (d) oils, and (e) sludges from process waste water treatment.

Any seafood waste disposed of to a marine environment must (a) pass through a 5 mm sieve and (b) be deposited where water movement prevents long term build-ups of solid waste deposits or significant decreases in dissolved oxygen levels (100).

2. GENERAL REVIEW

2.1. US Environmental Laws

In 1973–1974, the US Environmental Protection Agency (US EPA) published a development document (3) and an economic analysis (4) on effluent limitation guidelines and new source standards for the catfish, crab, shrimp, and tuna segment of the canned and preserved seafood processing industry. Subsequently, US EPA promulgated effluent limitation guidelines and standards of performance for new sources for this segment of the industry (5).

In 1975, US EPA published a development document (6) and an economic analysis (7) on effluent limitations guidelines and new source performance standards (NSPS) for the fish meal, salmon, bottom fish, sardine, herring, clam, oyster, scallop, and abalone segment of the canned and preserved seafoods processing industry. Subsequently, US EPA promulgated effluent guidelines and standards of performance for new sources for this segment of the industry (8–10).

In 1978, US EPA published proposed rules for Best Conventional Pollution Control Technology for a variety of canned and preserved seafood subcategories (11–13).

In 1979, US EPA withdrew the BAT (Best Available Technology) effluent limitations for the canned and preserved seafoods category pending a review for promulgating BCT (Best Control Technology) limitations (14). In addition, US EPA modified the BCT effluent limitations for the tuna subprocessing subcategory to reflect the results of an extensive investigation of the performance of dissolved air flotation (DAF) systems (15).

In 1980, US EPA published a petition from a portion of the Alaskan seafood industry to modify Best Practical Treatment (BPT) effluent limitations guidelines and to change wastewater control technology from screening and solids handling to grinding, for plants in the Anchorage, Cordova, Juneau, Ketchikan, and Petersburg (Alaska) areas (16). Also, US EPA announced proposed and final rules designating an interim Pacific Ocean dumping site for fish cannery wastes produced on Tutuila (American Samoa) that could no longer be accommodated on land (17, 18).

The Food Processors Institute of the National Food Processors Association published a bibliography and a guide to food processing waste management including fish processing wastes (19, 20). Also, in 1980, bibliographies on fish processing wastes were published on the basis of the Food Science and Technology Abstracts database (21, 22). A more recent Seafood Wastewater Bibliography was compiled in 2003 by Webster at Oregon State University (23).

In 1981, US EPA proposed amendments to BPT and NSPS for Alaskan subcategories of the Canned and Preserved Seafood Processing Point Source Category (24). Reviews on fish processing wastes included a survey of studies on recovery of protein, other nutrients, and flavor materials and their conversion into food ingredients or products (25), and on the use of fish and shellfish wastes as fertilizers and feedstuffs (26).

In 1981, guidelines were published by Auburn University for the design and operation of effluent and waste disposal systems for use with small-scale catfish processing plants (27).

Recently, general NPDES discharge permits have been issued by the US EPA and specific State Pollutant Discharge Elimination System (SPDES) permits have been issued by the State governments to all seafood processors in different regions. For instance, the NPDES Permits Nos. AK-G52-P000 and AK-G52-8000 were issued for Alaska in 1995 and 1998, respectively (93, 94).

2.2. *Foreign Environmental Laws*

In Canada, the Fish Processing Operation Liquid Effluent Guidelines (95, 96) were promulgated under the Canada Fisheries Act as a stop-gap measure to provide some measure of control over the negative effects of fish plant operations along the Canadian coast. DAF is recommended by Canadian government to all seafood processors for removal of TSS, BOD, and chemical oxygen demand (COD) from the seafood processing effluents (95). In 1986, the Canadian government conducted a study to search for solutions to what was already being recognized as a growing problem for seafood waste treatment disposal. It was concluded (97) that over half of the quantity of solid seafood waste generated was a result of shellfish processing. Only 60% was utilized in the production of fish meal, the rest being either landfilled, spread on agricultural fields, or dumped at sea (97). Production of chitin and chitosan from shellfish waste and fish silage from finfish wastes was also explored and recommended. Many workshops were organized by Fisheries and Oceans Canada to search for better solutions (98). Recently, Coastal Zones Research Institute (99) published a guide to address marine products processing activities and recommend the Best Management Practices (BMP) for all seafood processing plants in Canada.

In Japan, protein losses in the effluents from the processing of frozen surimi from Alaskan pollack were determined in 1982 by sampling at various points in the process (28). Total losses in the effluent ranged from 30 to 60% of the protein contents of the frozen products. Recovery of protein from the effluent becomes an important engineering task.

In Guyana, the operational guidelines for fish processing were issued by the Environmental Protection Agency to support legislation and regulations for the protection and enhancement of the environment. Specifically, the practical options for proper environmental management of seafood processing operations are provided to the owners and operators of fish processing plants (100).

3. PRODUCTION EFFICIENCY AND BY-PRODUCT RECOVERY

3.1. Resources Recovery, Waste Disposal, and Industry Constraints

3.1.1. Resources Recovery

According to a fish processing industry roundtable report (101), the fish processing industry currently converts only 20–25% of the usable meat from an average pollock catch to a directly edible product. An estimated 1.7 million metric tons of fish waste are generated per year in Alaska alone, with over 100,000 tons of waste coming from the Bering Sea crab fisheries. These large volumes of wastes reduce the levels of dissolved oxygen in the water and generate toxic by-products during decomposition, contaminating aquatic habitats, and threatening a variety of resources.

One way to reduce seafood processing wastes is to improve the efficiency of recovery of the edible portion of the fish. Ismond (29) has described some simple, less costly methods of increasing processing efficiency. Recycling of purified waste waters frequently results in cost savings. Anderson and Jespersen (30) describe means of greater recovery, including the splitting of the heads to recover more meat from the cheeks. Realizing that this is an international concern, the United Nations Environment Program (31) published a report on cleaner production assessment in fish processing. Driscoll (32) recommended waste minimization and increased product recovery techniques in the crabmeat processing industry.

Recovery of usable materials is an indirect means of reducing a waste load, provided the recovery process does not involve the production of products or the use of materials that are even more difficult to handle. Boardman (33) has shown several uses of quahog and clam shells that have no adverse impact on the environment.

Recovery of chitosan from crawfish has been shown by No and Myers (34) to be a useful coagulant in the recovery of organic compounds from seafood processing waste streams.

Keller (35) presented several ways to profit from the by-products of seafood wastes. Valle and Aguilera (36) more specifically showed the recovery of liquid by-products from fish meal factories. Gates (37) described means of waste reduction, water conservation, and by-product recovery in the seafood processing industry.

Production of fish protein concentrates has been described by Barzana and Garcia-Garibay (38) Marti (39) and Marti et al. (92) recovered proteins from fish meal factory wastewaters. Suh (40, 41) studied the recovery and utilization of proteins and lipids from the washing wastewater of seafood processing plants. Additional studies on protein recovery were conducted by Guerrero (42).

3.1.2. *Waste Disposal*

Wastes generated during at-sea processing, consisting largely of fish parts, are currently ground to US EPA specifications (half-inch pieces) and then discharged overboard. On-shore processing facilities are regulated under state and federal water permits and are subject to air quality and solid waste management restrictions. Disposing of wastes on shore puts pressure on landfills, especially in rural Alaskan communities. The ability to discharge at sea is currently viewed by some as giving off-shore processors a competitive advantage over their on-shore counterparts, who are subject to more restrictive, and consequently more expensive, environmental control measures.

3.1.3. *Industry Constraints*

A significant challenge facing the seafood processing industry in the Pacific Northwest, as well as other regions of the United States, is determining cost-effective ways to further reduce and recover suspended and dissolved solids found in plant wastewater streams. Solutions are needed for a number of reasons, including: (a) external political and internal industry pressure to strive for full utilization of the seafood resource; (b) the need to increase the efficiency of the processing plants over time to maximize their competitiveness and profitability; (c) the need to comply with upcoming federal regulations that will impose stricter limits on the seafood processing industry's wastewater discharges since in many cases, current technology used in the industry will not meet the discharge limits proposed in these regulations, and the only allowable option is for the companies to barge the wastewater three miles out to sea and dump it; and (d) the need to minimize the negative environmental impacts of the seafood processing plants' operations on surrounding communities.

In many ways, the fish processing and harvesting industries are unique in their waste streams and in the specific constraints of their operations, including the often remote locations involved. One key factor is the seasonal nature of fishing operations. Surge periods in processing (open seasons) require full capacity operation for short periods with little opportunity for down time. The economics of the present system for fishery management, promoting race-to-the-finish fishing, offer little incentive for waste reduction. At-sea processors are also limited by space constraints, in addition to time pressure. Comprehensive waste reduction programs are difficult to implement, and to enforce, under these conditions, and little regulatory pressure is currently being exerted to do so (101–102).

3.2. Waste Reduction Opportunities

Although there has been progress in managing wastes from the fish processing industry, the huge volume of waste currently generated has led both industry and government agencies to explore further reduction and use enhancement opportunities. A memorandum of understanding between US EPA and the state of Alaska examines pollution issues in Akutan and Unalaska, and Total Maximum Daily Load (TMDL) analyses are being jointly conducted by industry and government.

3.2.1. Increased Processing Efficiency

One area of significant potential waste reduction in the fish harvesting and processing industries is increased processing efficiency, which reduces waste and increases productivity by extracting more meat per fish. A technique that increases efficiency by as little as 1/2 of 1% is sufficient to generate widespread industry interest, and both the National Food Processors Association and the National Marine Fisheries Service have been active in promoting research in this area. For example, a fish head splitter has been developed that removes meat from the cheeks, neck, and other areas previously considered too difficult to access. Other methods that enhance waste reduction during processing include mechanically recovering usable meat from frames in the mince process, using centrifuges to recover fish from the process rinse water, and recovering crab meat through brine flotation systems in processing plants.

3.2.2. Reduction of By-Catch

During fish harvesting, the primary focus of waste reduction efforts is by-catch (capture of nontarget fish species with the catch, which are subsequently thrown overboard). The Alaska Fisheries Development Foundation is attempting to fund a study examining the configuration of net codends in an effort to reduce the catch of undersized fish. Trawl net manufacturers are experimenting with new designs that would reduce or eliminate the catch of undersized specimens or unwanted species. Controlling for product size is becoming increasingly important: Some Alaskan pollock fisheries chose to shut down for 6 weeks in 1992 because stocks were not large enough to process economically.

3.2.3. Marketable By-Products

Another waste reduction target for the industry is the transformation of fish wastes into marketable by-products. Surimi and flaked fish for institutional sale are recent examples of products created from previously undervalued fish parts. Chitin and chitosan, chemicals extracted from crab and shrimp shells, produce chitinous polymers similar to cellulose. Chitosan can be used in the treatment of municipal wastes, the manufacture of animal meal products, and various medical applications.

3.2.4. Uses for Fish Residuals

Potential uses for fish residuals, or offal, are being examined closely by several organizations in Alaska. Hydrolyzed wastes can be used for fish or pig meal, as well as fertilizer components. Fish oils are being successfully used as a fuel additive in boilers in a Dutch Harbor processing plant. Some firms have sold carapaces for food presentation in restaurants. In addition, several companies are currently examining uses for stick water, the wastewater stream from fish meal production.

3.2.5. Pollution Prevention Opportunities

Waste minimization audits of plant operations have been valuable in identifying waste reduction opportunities. Reduction of packaging waste, fuel oils, cleaning chemicals, and other maintenance and operations wastes can significantly reduce material and shipping costs to remote plant locations. A roundtable participant from an Alaskan salmon enhancement facility noted that his facility is researching such options as combining its waste with that of a Juneau brewery to create marketable product. Heat produced by a Juneau incinerator would be used to convert approximately 1,000 tons of fish waste produced annually into farm-raised salmon feed (currently a $400,000 per year expense item).

4. TREATMENT PROCESSES

4.1. Treatment of Seafood Processing Wastewater by Chemical Coagulation

In a Japanese patent, Watanabe (43) described a process for treating marine processing wastes containing blood involving screening, heating to 70°C, and flocculating with 200 mg/L $Al_2(SO_4)_3$, and 10 mg/L of a polymeric flocculant. The coagulated solids were filtered out. BOD and COD reductions of 65–70% and 75–80%, respectively, were achieved.

For the treatment of pollack processing water in Japan, sodium alginate was a more effective coagulant than carboxymethyl cellulose or sodium polyacrylate according to Nishide (44). However, Fukuda (45) reported that polyacrylate or $A1_2(SO_4)_3$ when added to pollack meat waste water gave optimum coagulation at pH 4.5–5.0. Coagulation was improved, and the optimum pH was decreased by increasing the NaCl concentration from 0.05 to 0.5 M.

Takei (46–48) reported that the effectiveness of $Al_2(SO_4)_3$ as a coagulant for fish-processing wastewater treatment depended upon species of fish, pH, and amount of coagulant. Carrageenan gave similar results as $Al_2(SO_4)_3$ when used as a coagulant. A water extract from dried seaweed gave a COD removal of 97% when added to mackerel washwater having a COD of 2,000 mg/L.

Nishide (44) compared the effectiveness of sodium alginate and carboxymethyl–cellulose (CMC) when used in conjunction with $AlCl_3$ in treating fishery wastewater. Approximately 50% reductions in COD were obtained with 140 mg/L $AlCl_3$ and 20 mg/L CMC at pH 6.0 or with 120 mg/L $AlCl_3$ and 80 mg/L sodium aluminate.

According to Welsh and Zall (49), fish scales from carp and porgy were effective coagulating aids in removing colloidal materials from scallop shucking wastewater.

Optimum pH for coagulation was 5.0 for both types of scales. Greatest reductions in turbidity were observed with carp and porgy scale dosages of 15 and 25 mg/L, respectively.

Welsh and Zall (50) conducted experiments on using zeta potential as a method for monitoring the treatment of scallop shucking wastes with coagulants. Optimum coagulation with a fish scale coagulant was obtained at a concentration of 15 mg/L with an optimal zeta potential of -10 mv. COD, SS, total solids (TS), total Kjeldahl nitrogen (TKN), and ash removals at the optimum dose were 48%, 95.4%, 46%, 57%, and 44%, respectively.

Gallanger (51) used chemical coagulation both to achieve wastewater treatment and to increase by-product recovery. By-product recovery can offset the cost of the waste treatment. Along with Johnson, Gallanger (52) reported on their studies at the 39th Purdue Industrial Wastes Conference.

Genovese and Froilan-Gonzalez (53) used chemical coagulation to improve separation of solids from the waste stream.

4.2. *Treatment of Seafood Processing Wastewater by Carbon Adsorption*

Knickle (54) investigated the treatment of fish and shellfish processing wastewater by using filtration, reverse osmosis, adsorption, and chemical precipitation processes. Dilution and chemical precipitation were the most effective and economical treatment methods for wastes from an operating shellfish processing plant.

Wastewater from fish and shellfish storage can be heated with activated carbon after hypochlorite treatment. COD and ammonia removals of 95.9% and 99.8%, respectively, were obtained after passing wastewater containing 1,067 mg/L COD and 1,500 mg/L NH_3 through an activated carbon bed. Treating fishery wastewater with 80 mg/L sodium alginate in combination with 120 mg/L aluminum chloride formed large flocs and resulted in 50% removal of COD (55).

4.3. *Disinfection and Odor Control*

DeFalco (56) described the correction of an odor problem in a spray irrigation system for treating vegetable and fish processing wastes by chlorination of the effluent and raising the soil pH by applying hydrated lime to ionize H_2S. The importance of controlling the pH of the final effluent, maintaining aerobic conditions in the soil, avoiding the use of boron-containing detergents, and maintaining a uniform application of waste by using revolving sprinklers was emphasized.

Osada and Maebucki (57) found wastewaters from boiling mackerel and mackerel pike are rich in histidine and Mg^{2+}. Adding 0.05–0.25% allyl alcohol or 0.05–0.1% allyl thioglycolate to the waste followed by dialysis for 1 h removed fishy odors.

4.4. *Treatment of Seafood Processing Wastewater by DAF*

Riddle and Shikaze (58) presented a survey of the characteristics and treatment of fish processing effluents in Canada, including wastes from the processing of ground fish, salmon, herring, shellfish, and fish meal. Treatment methods reviewed included screening with tangential screens, DAF, and biological treatment.

In a survey of Gulf Coast shrimp canneries, Maudlin and Szabo (59) evaluated the physical, chemical, and biological characteristics of the wastes and the waste treatment methods used. The weight of waste discharged per unit weight of shrimp processed was similar in most canneries. Screening removal of heads and shells could be performed efficiently with few operational problems. DAF gave good treatment efficiencies on an experimental scale, but the efficiencies of pilot scale operations remained to be demonstrated.

Tashiro (60) presented a characterization of the wastes from fish canneries in Japan and described the quantities of wastewater and treatment methods used. Tanaka et al. (61) described a process for treating fish processing wastes by adding 50 mg/L or more of $Al_2(SO_4)_3$ as a coagulant, adjusting the pH to 6.5, adding 0.1% polyacrylamide, and removing the floc by air flotation. BOD, COD, and TSS were reduced by 89%, 85%, and 93%, respectively.

Several Japanese patents outlined various flotation and flocculation processes for treating fish processing wastes (62). Typical treatment methods included (a) foam flotation at an isoelectric pH of 4.9 (63), (b) precipitation of proteins with $Ca(OH)_2$ and Fe^{2+} or Fe^{3+} salts (64), (c) with $CaCl_2$ and Na_2HPO_4 or H_3PO_4 followed by sodium polyacrylate (65, 66), and (d) adjustment of the pH from 5 to 6 followed by adding sodium polyacrylate (67).

In 1976, Barnett and Nelson (68) used a system consisting of a tangential screen (Hydrasieve), a centrifugal concentrator, and a DAF and skimmer system for treatment of a tuna processing wastewater. Removals of BOD, TSS, and oil and grease were 80%, 95%, and 95%, respectively.

According to Kissam (69), solids from DAF treatment of tuna processing waste are suitable for anaerobic digestion if the salinity is below 13,000 mg/L NaCl. In a laboratory study, after a 15-day detention time, the digester gas contained 80% methane. The COD, TS, volatile solids, protein, and lipid removals were 64–70%, 47%, 57%, 47%, and 83%, respectively.

In an investigation of DAF treatment of fish-processing effluents, Graham and Yacob (70) found that protein and solids removals were low without coagulants. Protein and TS removal of 85% and 35%, respectively, were obtained with 0.002 M $Al_2(SO_4)_3$ at pH 5.5–6.0. However, with polyphosphates (Calgon), maximum protein removals from red cod and gurnard processing wastes were obtained at pH values less than 4 and 2.5, respectively.

Shrimp cannery and oyster processing wastewaters were treated effectively on a pilot-plant scale by DAF (71). Coagulants investigated included alum, lignosulfonate, and a synthetic cationic polymer. Highest removals of BOD, SS, and oil and grease were obtained with alum and a synthetic anionic polymer as a coagulant aid.

In 1979, a case study of fish processing waste treatment by pressure DAF was reported in Japan (72).

A 1981 Japanese patent describes processes for treating fish processing wastes by pressure flotation and separation of proteins at the isoelectric point (73).

Soule (74) reported that treatment of fish canning effluents by DAF and secondary treatment processes disrupted the detrital food web in the waters of San Pedro Bay, California. Total fish, anchovy, white croaker, marine bird, and California gull numbers were reduced 4-fold, 100-fold, 10-fold to 20-fold, 2.5-fold, and 23-fold, respectively. There was also approximately a fourfold decrease in benthic fauna.

High fat wastewater and solids from fish processing were dewatered in a process consisting of filtration, pressurization, $NaAlO_2$ addition, pressurization with polymer addition, and DAF (75). The top float and sediment were adjusted to pH 4.3 with H_2SO_4 and then more polymer was added. This was then centrifuged to give a concentration of 36.3% solids product, which was disposed of in a landfill.

Imamura (76) described a patented process in which fish waste was adjusted to pH 7–8 with alkali, heated to 55–60°C, and treated with proteolytic enzyme for 4 h followed by pH adjustment to 5.2 and final separation of a protein solution and oil from the solids. The protein and oil were separated by DAF and centrifugation to give recoveries of protein and oil of 80 and 82%, respectively. In a similar process, Sato and Ishida (77) adjusted the pH of the froth of pollack processing wastewater to 5.0, added sodium polyacrylate, treated the waste with pressurized water, adjusted the pH to 8.5 with NaOH, and then added a protease. After incubation at 50°C for 3 h, the waste was heated for 20 min and centrifuged to separate the oil and protein.

DAF has been widely used for the equivalent of primary treatment of seafood processing wastewater. A summary of the results of selected studies on fishing processing wastes is presented in Table 17.1 (78–87). It can be seen that DAF is an effective system for the treatment of fish processing wastewater. Solids removal is accomplished effectively and requires less space than traditional sedimentation basins. Where required, secondary treatment for BOD removal is recommended.

4.5. *Treatment of Seafood Processing Wastewater by DAF and Ion Exchange*

A pilot plant consisting of a microstrainer, a DAF clarifier, and an ion exchange column was proven to be feasible for the treatment of scallop processing wastewater (2). The strainer effluent was prepared for the DAF process using 70 mg/L alum and 70 mg/L activated sodium aluminate (both as $A1_2O_3$), 8 mg/L polymer 2PD-462, 0.5 mg/L sodium carbonate, and 0.5 mg/L phosphoric acid. The pilot plant operated at a flow of 30 gpm with 75% recycle. The DAF effluent was passed through one of three ion exchange columns designated IE-A, IE-C, and IE-M, respectively. The resins were obtained from Rohm & Haas Company, Philadelphia, with the corresponding designations of Amberlite IRA-68, Amberlite IRA-84, and an equal mixture of the two. Detention time in the ion exchange resins was 30 min (90). Description of the DAF pilot plant can be found from the literature (107).

The results of the study are summarized in Table 17.2. All three resins achieved over 95% removal of TSS, coliforms, turbidity, color, and total P, and over 54% of COD, BOD_5, ammonia nitrogen, cadmium, zinc, copper, and TKN. The resin IE-M was the most effective for trace metals removal. Additional treatment is needed to achieve the targeted effluent standards for COD, BOD_5, ammonia nitrogen, cadmium, zinc, and copper for resins IE-A and IE-C (90).

Table 17.1
Summary of studies of fish processing waste treatment processes

Product processed	Treatment system	Performance	% Reduction	References
Fish processing	Screening, emulsified waste degasified under 10 in. Hg to remove H_2S, sedimentation	BOD	90	(78)
		SS	80	
		Oil and Grease	80	
Perch and smelt combined waste	Sedimentation	BOD	20	(79)
		SS	9	
	DAF 1/3 recycle, air:solids = 1:1, no coagulant	BOD	35	
		SS	26	
	Batch aerated reactor 20 days	BOD filtered	98	
		BOD unfiltered	89	
Gulf shrimp canning	Screening (Sweco Vibro – Energy separator)	BOD	15	(80)
		SS	40	
	DAF, air:solids = 1.4, 75 mg/L alum, 2 mg/L Magnifloc 835A polymer, pH 5.2	BOD	65	
		COD	59	
		SS	65.6	
		Protein	52.5	
		Orthophosphate	27.5	
Fish and whale processing	Heating at 90° 10 min, cool, pH adjust to 5.0 with dilute HCl, 50 mg/L sodium polyacrylate added, DAF	COD	92	(81)
Sardine canning	Screening (Bauer Hydrasieve)	BOD	4–14	(82)
		SS	16–37	
	DAF plus 200 mg/L alum and 2 mg/L polymer	BOD	57–71	
		Oil and Grease	80	
Crab processing	Screening (20 mesh), sump tank chlorination	BOD	82	(83)
		SS	95	
Tuna processing	Screening, equalization, sodium aluminate flocculation, DAF with anionic polymer	BOD	42.9	(84)
		SS	74.8	
		Oil and Grease	83.5	
Fish meat	Screening, oil and grease separation, neutralization, activated sludge, sedimentation, electrolysis, sand filtration	BOD	98.6	(85)
Trout processing	Belt screen, surge tank with alum, centrifugal screen with lime, vibrating screen, DAF with polymer	BOD	84	(86)
		SS	82	
		Oil and Grease	85	
	After in-plant cleanup	BOD	90	
		SS	90	
		Oil and Grease	98.5	
Shrimp and oyster canning	Screening, coagulation, pH adjustment, surge tank, multi-model DAF			(87)
	Shrimp	BOD	56.5	
		SS	65.6	
		Oil and Grease	85.0	
	Oysters	BOD	43	
		SS	89	
		Oil and Grease	56	

Table 17.2
Treatment of seafood (crab) processing wastes by DAF and ion exchange (values in mg/L except as noted)

Wastewater parameters	Raw seafood wastewater	DAF effluent	DAF and IE-A[a] effluent	DAF and IE-C[b] effluent	DAF and IE-M[c] effluent
Flow, gpm/ft^2	NA	2	2	2	2
pH, unit	7.0	6.9	NA	NA	NA
TSS	1,325	50	NA	NA	NA
COD	2,600	820	544	781	NA
BOD	1,238	560	NA	NA	NA
NH_3-N	37.5	17.2	NA	NA	NA
Coliform, #/100 mL	14	0	ND	NA	NA
Cd	0.114	0.047	0.028	0.029	0.002
Zn	0.346	0.041	0.048	0.082	0.013
Cu	0.224	0.058	0.055	0.056	0.026
Turbidity, NTU	THTM	10	NA	NA	NA
Color, unit	THTM	80	NA	NA	NA
Total Phosphorus (P)	50	1.85	NA	NA	NA
TKN	145	52	NA	NA	NA

NA not available; *ND* none detected; *THTM* too high to measure.
[a] IE-A = Amberlite IRA-68.
[b] IE-C = Amberlite IRC-84.
[c] IE-M = equal amounts of A and C.

4.6. *Treatment of Seafood Processing Wastewater by DAF and Granular Activated Carbon (GAC)*

In view of the additional treatment that may be needed with effluents from the ion exchange treatment system above, the same pilot plant as described in Sect. 4.5 (88, 107) was used to study the additional treatment afforded by activated carbon. Following treatment consisting of a microstrainer, and DAF under the conditions previously described, the effluent was passed through a GAC column. The three GACs studied with their designations were

GAC-1 = Charcoal wood GAC, 10–30 mesh from City Chemical Corporation, NJ
GAC-2 = Darco GAC HD-4000 from Astro Chemicals, Inc., MA
GAC-2 = Darco GAC 12 × 40 from Astro Chemicals, Inc., MA

The flow through the GAC column was 2 gpm/ft^2, equivalent to 30 min detention time.

The results of the study are summarized in Table 17.3. The combined DAF–GAC treatment resulted in 97.5% COD removal and 94.6% ammonia nitrogen removal. The remaining metals were still above the targeted effluent standards (90).

Table 17.3
Treatment of seafood processing wastes by DAF and carbon adsorption (values are in mg/L except as noted)

Wastewater parameters	Raw seafood wastewater	DAF effluent	DAF and GAC-1[a] effluent	GAC-2[b] effluent	GAC-3[c] effluent
Flow, gpm/ft^2	NA	2	2	2	2
pH, unit	7.0	6.9	NA	NA	NA
TSS	1,325	50	NA	NA	NA
COD	2,600	820	182	NA	NA
BOD_5	1,238	560	NA	NA	NA
NH3-N	37.5	17.2	NA	NA	NA
Coliform, #/100 mL	14	0	NA	NA	NA
Cd	0.114	0.047	0.012	0.016	0.020
Zn	0.346	0.041	0.030	0.048	0.039
Cu	0.224	0.058	0.028	0.052	0.062
Turbidity, NTU	THTM	10	NA	NA	NA
Color, unit	THTM	80	NA	NA	NA
Total Phosphorus, (P)	50	1.85	NA	NA	NA
TKN	145	52	NA	NA	NA

70 mg/L alum, 70 mg/L Sodium Aluminate (both as $A1_2O_3$) and 8 mg/L Polymer 2PD-462, 0.5 mg/L sodium carbonate and 0.5 mg/L phosphoric acid were dosed to DAF with 75% recycle flow.
GAC detention time was 30 min.
[a]GAC-1 = Charcoal wood.
[b]GAC-2 = Darco GAC HD-4000.
[c]GAC-3 = Darco GAC 12 × 40.

4.7. *Treatment of Floats from DAF by Composting or Evaporation*

Tuna processing wastes generated on Tutuila Island, American Samoa, represent an ongoing disposal problem as well as an emerging opportunity for use in renewable energy production (105). The biological conversion of the organic fraction of this waste including co-digestion with municipal solid waste (MSW) to useful products such as methane and a fertilizer-grade residue is proposed. The tuna processing waste is concentrated by DAF with a total solids content of 8–14%. Most of the total solids are volatiles, with protein/oil and grease accounting for greater than 90% of the volatile component. Initial batch anaerobic fermentation studies conducted with an anaerobic consortium adapted to a domestic MSW feedstock revealed inhibition of the microbial population when tuna processing waste was added. However, this inhibition was quickly overcome, and with appropriate adaptation, vigorous anaerobic biodegradation of the tuna processing wastes occurred. Fermentation studies were carried out utilizing both conventional low solids and novel high solids anaerobic reactor systems operated at mesophilic temperatures. The data reveal a stable fermentation, with total anaerobic bioconversion approaching 80–90% of the theoretical values for COD loadings. The results from these studies will provide information for the design of a pilot plant facility.

Totzke (104) also reported a case history of using DAF for removal of FOG from seafood wastewater and other food industry wastes. The float from the DAF process units was then successfully disposed of by a composting process. The readers are referred to the literature for the composting process (106).

Alternatively, the float from a DAF process can also be dewatered by an evaporation process for the purpose of resource recovery (108, 109).

4.8. *Treatment of Seafood Processing Wastewater and Stick Water by Electrocoagulation (Flotation and Sedimentation)*

Electrocoagulation involves the introduction of an electrical charge in a wastewater stream, in order to coagulate and precipitate the pollutants (110–116). This electrochemical process results in a sludge that can either float by flotation or sink by sedimentation, depending on the specific gravity. Voltage, amperage, and residence time can be adjusted to increase the separation and recovery of solids. An electrocoagulator consists of an anode and cathode between which the wastewater is pumped. This process has had success in other industries in recovering suspended and dissolved solids, as well as in breaking oily emulsions (112).

Ramirez and Clemens (110) applied electrocoagulation to treatment of rendering wastewater. Otake et al. (111) used electrocoagulation for treatment of a wastewater from fish paste-manufacturing factories.

At the Dutch Harbor, Alaska processing facility, the operators processed pollock (used to produce surimi, the main ingredient in imitation crab meat), bottom fish, and crab (102). As a consequence, a large volume of inedible waste fish solids is generated. To maximize the use of the seafood resource, many of the larger seafood processors render the waste materials into fish meal, which is used for the production of aquaculture feeds and as a feed supplement for animals. Figure 17.1 is a simplified schematic of the rendering process.

As shown in Fig. 17.1, waste at the Dutch Harbor facility (102) is cooked and then pressed to squeeze out moisture. The pressed fish solids are then dried into fish meal. The press liquid is processed, in order to recover more fish solids and fish oil. The remaining liquid, called "stick water," must be disposed of. Although a considerable amount of solids and oil are recovered from the press liquid, the resulting stick water contains some unrecovered materials. In addition, the stick water contains salt that results from holding the fish and fluming the fish waste in sea water. Even though the fish waste is dewatered before rendering, some sea water is still present. The electrocoagulation system shown in Fig. 17.2 was identified as a technology having the potential to recover solids from seafood processing wastewater at the fish meal plant (102). A pilot plant study was conducted under the following conditions:

Stick water temperature to the electrocoagulator	170°F
Cell voltage	5 V
Cell amperage	90 amp
Electrocoagulator voltage	220 V
Measured electrocoagulator amperage	2 amp
Measured electrocoagulator flow rate	25 gpm

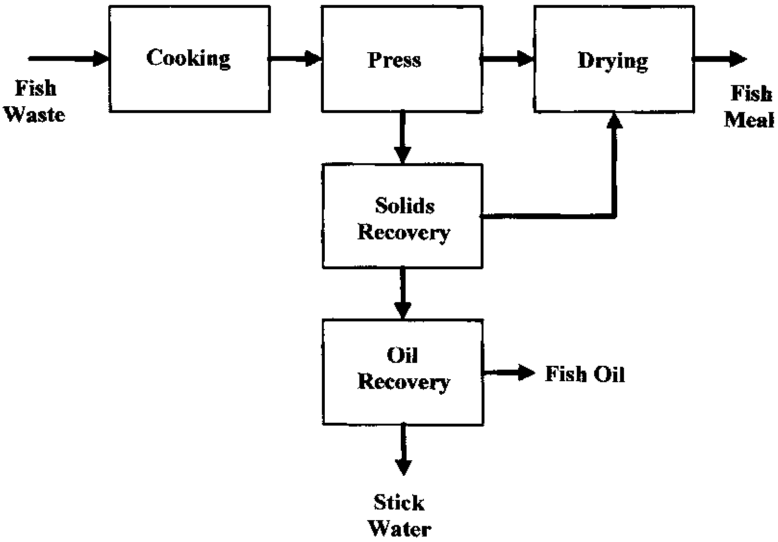

Fig. 17.1. Simplified meal plant flow schematic.

Treatment of stick water using electrocoagulation was concluded to be successful (102). The following were the researchers' conclusions: (a) TSS recovery rate was 50–90%; (b) the recovered solids could be dewatered to at least 24% solids; (c) Fats/Oil/Grease (FOG) recovery rate was almost 99+%; (d) BOD reduction was between 62 and 67%; (e) the processing cost per 10,000 gallons of wastewater was at US$32 or less; and (f) the recovered solids did not have a fat, salt, or ash content that would be detrimental if added back to the existing fish meal.

5. SUMMARY

DAF has been widely used for the equivalent of primary treatment of seafood processing wastes. Screening for removal of large particles (bones, shells, etc.) prior to DAF is recommended. Suspended solids are readily removed in a unit that requires less space than an equivalent standard sedimentation basin. A DAF system can be started and shut down easily to accommodate fluctuations in seafood processing. Soluble BOD and COD are not

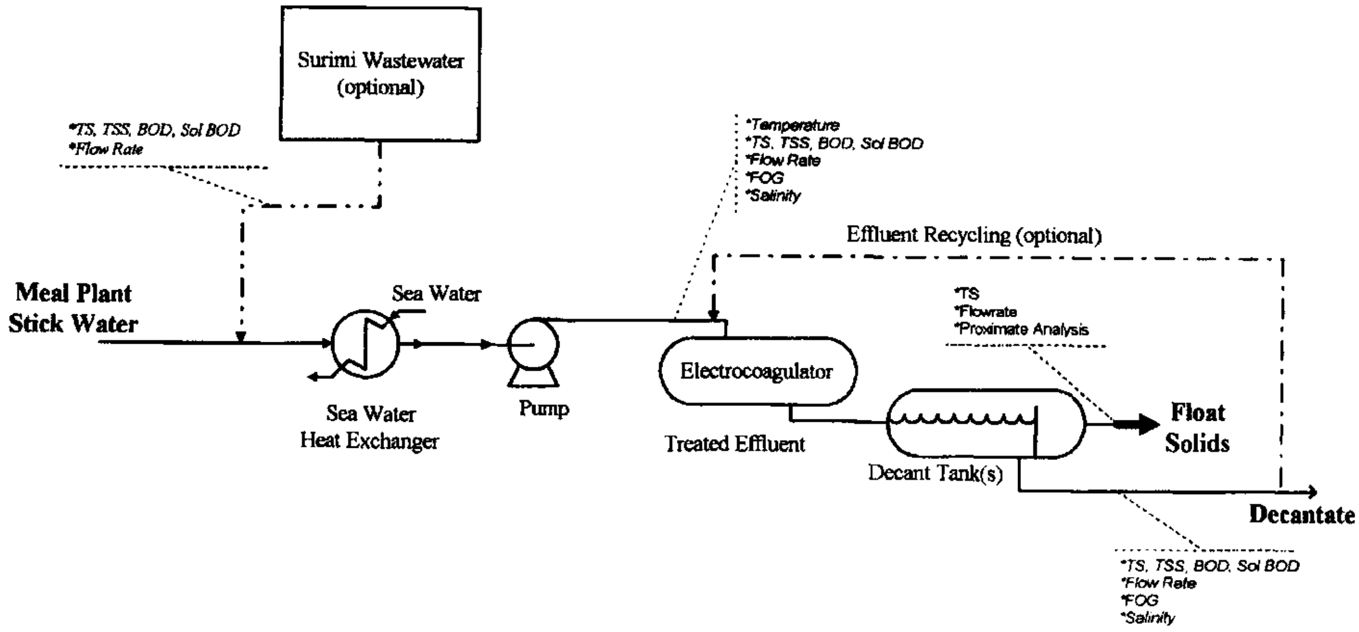

Fig. 17.2. Flow diagram of an electrocoagulation system for treating stick water.

completely removed by DAF. Additional treatment facilities may have to be provided to meet certain discharge standards for these parameters (90–91, 103, 112–116).

APPENDIX A. EFFLUENT DISCHARGE LIMITATIONS FOR BUTCHERING WASTE STREAMS

Type of seafood	Conventional/hand-butchered, lb/1,000 lb				Mechanized, lb/1,000 lb			
	Total suspended solids		Oil and grease		Total suspended solids		Oil and grease	
	Daily max	Monthly average	Daily max	Monthly average	Daily max	Monthly average	Daily max	Monthly average
Bottom fish	3.1	1.9	4.3	0.56	22	12	9.9	3.9
Salmon	2.6	1.6	0.31	0.19	44	26	29	11
Herring frozen whole	2.6	1.6	0.31	0.19				
Shrimp	320	210	51	17				
Scallops	6.6	1.4	7.7	0.24				
Crab, whole/sections	12	3.9	1.3	0.42				

Daily discharges shall be calculated as follows:
lb pollutant/1,000 lb raw product = (Flow, MGD) × (pollutant, mg/L) × (8.34) Total lb processed during the sampling day.
Bottom Fish includes Flounder (e.g., Arrowtooth), Rockfish/Red Snapper, Pacific Cod, Halibut, Pollock, Black. Cod/Sablefish, Grey Cod, Flatfish/Sole, Whitefish.
Salmon includes Pink, Chum, Sockeye, Coho, Silver, and others.
Crab includes King, Tanner (Opilio and Bairdi), Dungeness, other incidental seafood, such as sea cucumbers, snails, skates, sea urchins etc.

APPENDIX B. BUTCHERING WASTE STREAM MONITORING

Parameter	Frequency	Sample type
Flow (MGD)	Daily	24-h record[a]
TSS (lb/1,000 lb; mg/L)	Weekly	Composite/grab[b]
O&G[c] (lb/1,000 lb; mg/L)	Weekly	Grab
Settleable solids (mL/L)	Weekly	Composite/grab[b]
pH (standard unit)	Weekly	Grab
Production (raw; lb)	Weekly	Calculated
Number of processing days	Monthly	Measured
Water surface and shoreline	Daily	Visual inspection

[a] Flow may be estimated if there is no dedicated flow meter measuring the flow for the butchering waste stream. The DMR sample type should be filled in to reflect that the flow is estimated.

[b] Grab samples may be taken during intermittent processing.

[c] Analyze using the Collins/Tenny test procedure or any other US EPA approved method.

APPENDIX C. SURIMI WASTE STREAM MONITORING

Pollutant parameter (units)	Monthly average[a]	Daily maximum[a]
BOD_5 (lb/1,000 lb; mg/L)	3.8	6.7
TSS (lb/1,000 lb; mg/L)	1.5	3.7
O&G (lb/1,000 lb; mg/L)	0.76	1.4

[a] Daily of pounds of pollutants per 1,000 lb of seafood wastes input will be calculated as follows:
lb pollutant per 1,000 lb raw product
= (Flow, MGD) × (pollutant, mg/L) × (8.34)
= total pounds processed during the sampling day.

APPENDIX D. EFFLUENT DISCHARGE LIMITATIONS FOR FISH MEAL/POWDER WASTE STREAMS

Parameter (units)	Frequency	Sample type
Flow (MGD)	Daily	24-h record[a]
BOD_5 (lb/1,000 lb; mg/L)	Weekly	Composite/grab[b]
TSS (lb/1,000 lb; mg/L)	Weekly	Composite/grab[b]
O&G (lb/1,000 lb; mg/L)	Weekly	Grab[c]
pH (standards units)	Monthly	Grab
Temperature (degree F)	Weekly	Grab
Settleable solids (mL/L)	Weekly	Composite/grab[b]
Number of processing days	Monthly	Measured
Color (color units)	Monthly	Grab

[a] Flow may be estimated if there is no dedicated meter measuring the flow for fish meal/powder processing. The DMR sample type should be filled in to reflect that the flow is estimated.
[b] Grab samples may be taken during intermittent processing.
[c] Analyze using the Collins/Tenny test procedure or any other US EPA approved method.

APPENDIX E. FISH MEAL/POWDER WASTE STREAM MONITORING

Parameter	Frequency	Sample type
Flow (MGD)	Daily	24-h record[a]
TSS (mg/L)	Weekly	Composite/grab[b]
BOD_5 (mg/L)	Weekly	Composite/grab[b]
O&G[c] (mg/L)	Weekly	Grab[c]
Production (lb of fish into surimi)	Weekly	Calculated
Number of processing days	Monthly	Measured

[a] Flow may be estimated if there is no dedicated flow meter measuring the flow for surimi processing. The DMR sample type should be filled in to reflect that the flow is estimated.
[b] Grab samples may be taken during intermittent processing.
[c] Analyze using the Collins/Tenny test procedure or any other US EPA approved method.

REFERENCES

1. PNPPRC (1993) Pollution prevention opportunities in the fish processing industry. Pacific Northwest Pollution Prevention Research Center, Seattle, WA
2. Wang LK, Wu BC, Foote R, Rogalla F (1985) Treatment of scallop processing wastewater by flotation, adsorption and ion exchange. Technical Report LIR/05–85/139. Lenox Institute for Water Technology, Lenox, MA
3. U.S. EPA (1974) Development document for proposed effluent limitations guidelines and new source performance standards for the catfish, crab, shrimp, and tuna segment of the canned and preserved seafood processing point source category. Report No. EPA 440/1–74–020. U.S. Environmental Protection Agency, Washington, DC
4. U.S. EPA (1973) Economic analysis of proposed effluent guidelines, seafoods processing industry. Report No. EPA 230/1–73–025. U.S. Environmental Protection Agency, Washington, DC
5. U.S. EPA (1974) Effluent guidelines and standards, canned and preserved seafood point source category, catfish, crab, shrimp and tuna processing subcategory. Federal Register, 39, 124, 23134. U.S. Environmental Protection Agency, Washington, DC
6. U.S. EPA (1975) Development document for interim final effluent limitations guidelines and proposed new source performance standards for the fish meal, salmon, bottom fish, sardine, herring, clam, oyster, scallop and abalone segment of the canned and preserved seafood processing point source category. Report No. EPA 440/1–74–041. U.S. Environmental Protection Agency, Washington, DC
7. U.S. EPA (1975) Economic analysis in interim final effluent guidelines, seafoods processing industry, fish meal, salmon, bottom fish, clams, oysters, sardines, scallops, herring, sbalone. Report No. EPA 230/1–74–04 7. U.S. Environmental Protection Agency, Washington, DC
8. U.S. EPA (1975) Effluent guidelines and standards, and proposed guidelines and standards, canned and preserved seafood processing point source category. Federal Register, 40, 21, 4582. U.S. Environmental Protection Agency, Washington, DC
9. U.S. EPA (1975) Effluent guidelines and standards, canned and preserved seafood processing point source category, corrections. Federal Register, 40, 70, 16204. U.S. Environmental Protection Agency, Washington, DC
10. U.S. EPA (1975) Effluent guidelines and standards, canned and preserved seafood processing point source category. Federal Register, 40, 231, 55770. U.S. Environmental Protection Agency, Washington, DC
11. U.S. EPA (1978) Best conventional pollutant control technology. Federal Register, 43, 37570. U.S. Environmental Protection Agency, Washington, DC
12. U.S. EPA (1978) Best conventional pollutant control technology. Federal Register, 43, 39062. U.S. Environmental Protection Agency, Washington, DC
13. U.S. EPA (1978) Best conventional pollutant control technology. Federal Register, 43, 50227. U.S. Environmental Protection Agency, Washington, DC
14. U.S. EPA (1979) Best conventional pollutant control technology; reasonableness of existing effluent limitation guidelines. Federal Register, 44, 40732. U.S. Environmental Protection Agency, Washington, DC
15. U.S. EPA (1979) 40 CFR Part 408 Amendment to final rule and response to petition for modification for the tuna processing subcategory of the canned and preserved seafood processing point source category. Federal Register, 44, 45944. U.S. Environmental Protection Agency, Washington, DC

16. U.S. EPA (1980) Canned and preserved seafood processing point source category. Federal Register, 45, 52411. U.S. Environmental Protection Agency, Washington, DC
17. U.S. EPA (1980) Ocean dumping, proposed designation of site. Federal Register, 45, 56374. U.S. Environmental Protection Agency, Washington, DC
18. U.S. EPA (1980) Ocean dumping, final designation of site. Federal Register, 45, 77434. U.S. Environmental Protection Agency, Washington, DC
19. Katsuyama AM (1979) A guide for waste management in the food processing industry. Food Processors Institute, Washington, DC
20. Warrick LF (1979) Guide to literature on waste management for the food processing industries. Food Processors Institute, Washington, DC
21. Hippler R (1980) Waste treatment: food processing. Technical Report No. NTIS PB 80–803562. Department of Commerce, National Technical Information Service, Springfield, VA
22. Young CG (1980) Waste treatment in dairy, poultry, meat and seafood industries. Technical Report No. NTIS PB 80–805 039. Department of Commerce, National Technical Information Service, Springfield, VA
23. Webster J (2003) Seafood waste bibliography. Oregon State University, New Port, OR
24. U.S. EPA (1981) Canned and preserved seafood processing point source category. Federal Register, 46, 2544, U.S. Environmental Protection Agency, Washington, DC
25. Hood LF, Zall RR (1980) Recovery, utilization and treatment of seafood processing wastes. In: Conell JJ (ed) Advances in Fish Science and Technology. Fishing News Books, Ltd., Surrey, England, p 355
26. Swanson GR (1980) Fish and shellfish wastes. In: Bewick MWM (ed) Handbook of organic waste conversion. Van Nostrand-Reinhold, New York, NY
27. Lovell RT (1981) Design of small-scale catfish processing plants in Alabama, Circular No. 255. Agricultural Experiment Station, Auburn University, Auburn, AL
28. Watanabe T (1982) An estimation of the amount of protein lost in the effluent from frozen surimi manufacture. Nippon Suisan Gakkaishi (Jpn) 48:869; Chem Abs 97:132971e (1982)
29. Ismond A (1994) Best management practices and low-tech solutions for increasing the efficiency of seafood processing plants. Ministry of Agriculture, British Columbia
30. Anderson E, Jespersen C (1995) More food and less waste in seafood processing. United Nations Environment Program, Paris, France
31. UNEP (2000) Cleaner production assessment in fish processing. United Nations Environment Program, Paris, France
32. Driscoll TP (1990) Waste minimization and product recovery in the crabmeat processing industry. American Meat Institute, Georgia Tech Research Institute, Georgia Institute of Technology, Atlanta, GA
33. Boardman GD (1989) Characterization and utilization of waste from ocean quahog and surf clam processing plants. Virginia Sea Grant Program, Virginia Polytechnic Institute and State University, Blacksburg, VA
34. No HK, Meyers SP (1989) Crawfish chitosan as a coagulant in recovery of organic compounds from seafood processing streams. J Agric Food Chem 37(3):580
35. Keller S (1990) Making profits out of seafood wastes: International conference on fish by products. Alaska Sea Grant College Program, Fairbanks, AK
36. Valle JM, Aguilera JM (1990) Recovery of liquid by-products from fish meal factories: a review process. Biochem Int 25(4):122

37. Gates KW (1991) Waste reduction, water conservation, and recovery of seafood by-products. Mar Technol Soc J 25(1):44
38. Barzana E, Garcia-Garibay M (1994) Production of fish protein concentrates. In: Martin AM (ed) Fisheries processing: biotechnological applications. Chapman and Hall, London, UK, pp 206–222
39. Marti C (1994) Recovery of proteins from fishmeal factory wastewaters. Process Biochem 29(1):39
40. Suh JS (1994) Recovery and utilization of proteins and lipids from the washing wastewater in marine manufacture by isoelectric point shifting precipitation Method 2. Bull Korean Fish Soc 27(5):495
41. Suh JS (1995) Recovery and utilization of proteins and lipids from the washing wastewater in marine manufacture by isoelectric point shifting precipitation Method 3. Bull Korean Fish Soc 28(2):157
42. Guerrero L (1998) Protein recovery during the overall treatment of wastewater from fish-meal factories Bioresour Technol 63(3):221
43. Watanabe T (1974) Treatment of waste solutions containing animal blood. Jpn Kokai 74:79,052; Chem Abs 82:89, 839j (1975)
44. Nishide E (1978) Effect of water soluble polyanions on the removal of organic substances by a metal coagulant from fisheries waste water. Nihon Daigaku Nojuigakubu Gakujutsu Kenkyu Hokoki (Jpn) 35:335; Chem Abs 89:94600h
45. Fukuda V (1977) Coagulation treatment of waste water from the manufacture of marine products. Mizu Shori Gijutsu (Jpn) 18:453; Chem Abs 87:106458s (1977)
46. Takei M (1977) Treatment of waste water with coagulant in fish processing factory, I. Variation of effect in coagulation. Tokai-Ku Suisan Kenkyusho Kenkyu Hokoku (Jpn) 89:57; Chem Abs 88:27420r (1978)
47. Takei M (1977) Treatment of waste water with coagulant in fish processing factory, II. Coagulations obtained with seaweeds, Tokai-Ku Suisan Kenkyusho Kenkyu Hokoku (Jpn) 89:65; Chem Abs 88:4I256y (1978)
48. Takei M (1977) Coagulant from seaweeds. Jpn Kokai 77:143982; Chem Abs 89:11709b (1978)
49. Welsh IW, Zall RR (1979) Fish scales: a coagulating aid of the recovery of food processing wastewater colloids. Process Biochem, 14(8):23
50. Welsh RW, Zall RR (1981) Using zeta potential to optimize coagulating aid doses used to treat food processing wastes. Process Biochem 16(4):31
51. Gallanger SM (1983) Wastewater treatment and by-product recovery in seafood processing using coagulant addition. University of Alaska, Fairbanks, AK
52. Johnson RA, Gallanger SM (1985) Use of coagulants to treat seafood processing wastewaters. Proceedings of the 39th industrial wastes conference, Purdue University, West Lafayette, IN, pp 573–584
53. Genovese CV, Froilan-Gonzalez J (1998) Solids removal by coagulation from fisheries waste waters. Water 24(4):371
54. Knickle HN (1974) Treatment of wastewater from fish and shellfish processing plants. Technical Report No. PB 235,925. Department of Commerce, National Technical Information Service, Springfield, VA
55. Nishide E, Nisizawa K (1979) Effect of sodium alginate on the removal of organic substances by a metal coagulant from fishery waste water. Proc Natl Seaweed Symp 9:487

56. DeFalco AJ (1974) Correction of an odor problem by operational and engineering changes for a food processing wastewater treatment facility. Proceedings of the 27th Industrial Waste Conference. Purdue University, West Lafayette, IN, Ext. Ser. 141, p 534
57. Osada H, Maebucki K (1976) Utilization of waste water in fishery curing processes III. Components of the broths of mackerel and mackerel pike and the elimination of the offensive odor. Kanzume Jiho (Jpn) 55:147; Chem Abs 85(1):12300s (1976)
58. Riddle MJ, Shikaze K (1973) Characterization and treatment of fish processing plant effluents in Canada. Proceedings of the 4th national symposium on food processing wastes, Washington, DC, p 400
59. Maudlin AF, Szabo AJ (1974) Shrimp canning waste treatment study. Technical Report No. EPA 660/2–74–061. U.S. Environmental Protection Agency, Washington, DC
60. Tashiro H (1975) Treatment of waste water from canneries. PPM (Jpn) 6:3,42; Chem Abs 83:65,144h (1975)
61. Tanaka T (1974) Purification of waste water from marine product processing plant. Jpn Kokai 74:84,048; Chem Abs 82:34855r (1975)
62. Bough WA (1976) Chitosan, a polymer from seafood waste, for use in treatment of food processing waste and activated sludge. Process Biochem 11(1):13
63. Maeda M, Ogawa T (1975) Treatment of waste water containing protein. Jpn Kokai 75:159,150; Chem Abs 84:155364e (1976)
64. Ohtake S (1975) Treatment of waste water from smoked food processing. Jpn Kokai 75:117,256; Chem Abs 84:79370n (1976)
65. Matsuura R (1976) Treatment of waste water from manufacture of marine products. Jpn Kokai 76:41,257; Chem Abs 85:148571n (1976)
66. Matsuura R (1976) Marine product process waste treatment. Jpn Kokai 76:36,763; Chem Abs 85: t48587x (1976)
67. Namisa M (1975) Recovering protein from waste water containing crude protein. Jpn Kokai 75:33,142; Chem Abs 85:l006lq (1976)
68. Barnett HJ, Nelson RW (1976) A preliminary report on studies to develop alternative methods of removing pollutants from tuna (albacore) process waste waters. Proceedings of the 6th national symposium on food processing wastes, EPA 600/2–76–224, U.S. Environmental Protection Agency, Cincinnati, OH, p 407
69. Kissam A (1977) Preliminary evaluation of anaerobic-sludge digestion for the tuna processing industry, Proceedings of the 8th national symposium on food processing wastes. Technical Report No. EPA 600/2–77–184. U.S. Environmental Protection Agency, Cincinnati, OH, p 155
70. Graham EE, Yacob AW (1975) Dissolved air flotation for treatment of fish effluents. Proceedings of the 3rd national chemical engineering conference on treatment recycle disposal. Victoria, Australia, p 156
71. Szabo AJ (1979) Dissolved air flotation treatment of Gulf shrimp cannery waste cwater. Technical Report No. EPA 600/2–79–061. U.S. Environmental Protection Agency, Cincinnati, OH
72. Kawakami A (1979) Treatment of fishery and fish processing wastewater. Ebara Infiruko John (Jpn) 78:20; Chem Abs 92:98899x (1980)
73. Mitsui Miike Machinery Co. (1980) Treatment of effluent from fish processing. Jpn Kokai Tokkyo Koho 80:152599; Chem Abs 94 108789u (1981)
74. Soule DF (1981) Changes in harbor ecosystem following approved waste treatment, Elsevier Oceanogr Ser (Amsterdam), 27B. Mar Environ Pollut 2:261
75. Dunn HJ (1982) Dewatering aqueous waste sludge. Canadian Patent 1116 765

76. Imamuar K (1973) Treating waste water from processing of marine products for recovering proteins and fish oil. Japan Patent No. 73 93,158; Chem Abs 81:19482s (1974)
77. Sato T, Ishida K (1974) Removing oils, fats and proteins from waste waters from the fishery and livestock industry. Japan Patent No. 7432,4671; Chem Abs 81:12658g (1974)
78. Pavia E, Myagi AD (1974) Treatment of waste waters from the processing of fish. U.S. Patent No. 3,787,596
79. Riddle MJ, Murphy KL (1974) An effluent study of a fresh water fish processing plant. Proceedings of the 27th industrial waste conference. Purdue University, West Lafayette, IN, Ext. Ser. 141, p 777
80. Maudlin AF, Szabo AJ (1974) Gulf shrimp canning plant wastewater processing. Proceedings of the 5th national symposium food processing wastes. Washington, DC, 199
81. Ohhasi H (1974) Treating waste waters containing protein from fish and whale processing. Japan Patent No. 7434, 159; Chem Abs 81:126574f (1974)
82. Atwell JS (1973) Water pollution control problems and programs of the Maine sardine council. Proceedings of the 4th national symposium on food processing wastes. Washington, DC, p 125
83. Brinsfield RB (1978) Characterization, treatment, and disposal of wastewater from Maryland seafood plants. J Water Pollut Control Fed 50:1943
84. Ertz DB (1977) Dissolved air flotation treatment of seafood processing wastes – an assessment. Proceedings of the 8th national symposium on food processing wastes. 98, EPA 600/2–77–184. U.S. Environmental Protection Agency, Cincinnati, OH
85. Horioka M (1977) Practice for the treatment of wastewater from fish meat processing. PPM (Jpn), 8(10):18; Chem Abs 89:I1609u (1978)
86. Keith JS (1978) Treating trout processing wastewater – a successful case history. Proceedings of the 9th national symposium on food processing wastes. 110, EPA 600/2–78–188. U.S. Environmental Protection Agency, Cincinnati, OH
87. Szabo AJ (1981) Dissolved air flotation treatment for treatment of seafood wastewater. In: Otwell WS (ed) Seafood waste management in the 1980's. Department of Food Science and Human Nutrition, Florida Sea Grant College, Orlando, FL, pp 137–146
88. Wang LK (1985) Treatment of seafood processing wastewater by dissolved air flotation, carbon adsorption and free chlorination. Technical Report No. LIR/04–85/132. Lenox Institute for Research Inc., Lenox, MA
89. Claggett FG (1972) Clarification of fish processing plant effluents by chemical treatment and air flotation. Northwest Pollution Conference, Portland, OR, October 25–27 1972
90. Krofta M, Wang LK, Pollman CD (1989) Treatment of seafood processing wastewater by dissolved air flotation, carbon adsorption and free chlorination. Proceedings of the 43rd Industrial Waste Conference. Purdue University, West Lafayette, IN, pp 535–550
91. Selley PP (1981) Dissolved air flotation for treatment of shrimp waste In: Otwell WS (ed) Seafood waste management in the 1980's. Department of Food Science and Human Nutrition, Florida Sea Grant College, Orlando, FL, pp 147–152
92. Marti MC, Roeckel M, Aspe E, Novoa M (1994) Fat removal from process waters of the fish meal industry – a study of three flotation methods. Environ Technol 15(1):29–39
93. U.S. EPA (1995) General NPDES permit for seafood processors within 3 nautical miles of the Pribilof Islands, Alaska – General NPDES Permit No. AK-G52-P000. Federal Register, October 10, 1995. U.S. Environmental Protection Agency, Washington, DC

94. U.S. EPA (1998) General NPDES permit for seafood processors – general NPDES permit No. AK-G52–8000. Federal Register, March 31, 1998. U.S. Environmental Protection Agency, Washington, DC
95. FO-Canada (2010) Seafood plant effluents – turning problems into profits. Fisheries and Oceans Canada, New Brunswick, Canada. www.glf.dfo-mpo.gc.ca/sci-sci/effluents/index-e.html
96. FO-Canada (1971) Fish processing operations liquid effluent guidelines. Fisheries and Oceans Canada, New Brunswick, Canada
97. FO-Canada (1986) Fish waste disposal practices and options for eastern New Brunswick. Report No. 176. Fisheries and Oceans Canada, New Brunswick, Canada
98. FO-Canada (2003) Fish plant effluents: a workshop on sustainability. Report No. 271. Fisheries and Oceans Canada, New Brunswick, Canada
99. Costal Zones Research Institute (2010) Best management practices: marine products processing. Costal Zones Research Institute, New Brunswick, Canada. www.glf.dfo-mpo.gc.ca/sci-sci/effluents/index-e.html
100. Guyana EPA (2010) Operational guidelines for fish processing. Environmental Protection Agency, Guyana. www.sdnp.org.gy/epa/
101. Alaska DEC (2005) Pollution prevention opportunities in the fish processing industry. Alaska Department of Environmental Conservation, Pacific Northwest Pollution Research Center, Anchorage, AK
102. Alaska DEC (1996) Solids recovery from seafood processing stick water using electrocoagulation. Alaska Department of Environmental Conservation, Pacific Northwest Pollution Research Center, Uni-Sea, Anchorage, AK
103. Boardman GD, Libelc EL, Flick GL (1988) Characterization of wastes at Virginia clam processing facilities. Proceedings of the 1988 food processing waste conference. Georgia Institute of Technology, Atlanta, GA
104. Totzke DE (1991) Handling and disposal practices for dissolved air flotation float. Proceedings of the 1991 food processing waste conference. Georgia Institute of Technology, Atlanta, GA, pp 333–344
105. Rivard CJ, Nagle NJ (1992) Biological disposal of tuna processing wastes using a novel anaerobic composting system. Proceedings of the 1992 food processing waste conference. Georgia Institute of Technology, Atlanta, GA, p 119–128
106. Wang LK, Shammas NK, Hung YT (eds) (2007) Biosolids treatment processes. Humana Press, Totowa, NJ
107. Wang LK, Guss DB (1988) Pretreatment of food industry wastewater using a high rate flotation clarifier. Proceedings of the 1988 food processing waste conference. Georgia Institute of Technology, Atlanta, GA, Section 3, DAF
108. Driscoll TP (1990) Waste minimization and product recovery in the crabmeat processing industry. Proceedings of the 1990 food processing waste conference. Georgia Institute of Technology, Atlanta, GA, pp 262–266
109. Wang LK, Hung YT, Shammas NK (eds) (2006) Advanced physicochemical treatment processes. Humana Press, Totowa, NJ, p 690
110. Ramirez ER, Clemens OR (1978) Physicochemical treatment of rendering wastewater by electrocoagulation. Proceedings of the ninth national symposium on food processing wastes, p 264, EPA-600/2–78. U.S. Environmental Protection Agency, Washington DC
111. Otake S, Fukui K, Teraoka K, Yoshida H (1977) Electrocoagulating treatment of waste water from fish paste-manufacturing factories. Bull Jpn Soc Sci Fish 43(8) 975–981

112. Tay JH, Show KY, Hung YT (2004) Seafood processing wastewater treatment. In: Wang LK, Hung YT, Lo HH, Yapijakis C (eds.) Handbook of industrial and hazardous wastes treatment. Marcel Dekker, New York, NY, pp 647–684
113. Nadeeshani Nanayakkara KG, Wei Y, Zheng YM, Chen JP (2010) Food industry wastewater treatment. In: Wang LK, Shammas NK, Hung YT (eds) Handbook of advanced industrial and hazardous wastes treatment. CRC Press, Boca Raton, FL, pp 1233–1254
114. Wang LK, Guss D, Krofta M (2010) Kinetics and case histories of activated sludge secondary flotation systems. In: Wang LK, Shammas NK, Hung YT (eds) Handbook of advanced industrial and hazardous wastes treatment. CRC Press, Boca Raton, FL, pp 1155–1190
115. Wang LK, Ivanov V, Tay JH, Hung YT (2010) Environmental biotechnology. Humana Press, Totowa, NJ
116. Wang LK, Wang MHS, Suozzo T, Dixon RA, Wright TL, Sarraino S (2009) Chemical and biochemical technologies for environmental infrastructure sustainability. 2009 National Engineers Week Conference, Albany, NY

18

Laboratory Simulation and Testing of Air Flotation and Associated Processes

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CONTENTS

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Abstract Experimental procedures are developed for simulation and evaluation of various air flotation and associated treatment processes, including mixing, flocculation, sedimentation, dissolved air flotation, induced air flotation, and filtration. These experimental procedures are useful for determination of chemical types, dosages, chemical reaction time, mixing intensity, pH condition, solids concentration, biological reaction time, as well as for prediction of treatment efficiencies of numerous combinations of physical, chemical, and biological processes for water and wastewater treatment.

Key Words Dissolved air flotation • DAF • dispersed air flotation • induced air flotation • IAF • laboratory experiments • simulation • filtration • sedimentation • hydrolyzine • metallic salts • polymers • foam separation • pilot plant operation • jar test.

1. PROCEDURE AND APPARATUS FOR CHEMICAL COAGULATION SIMULATION

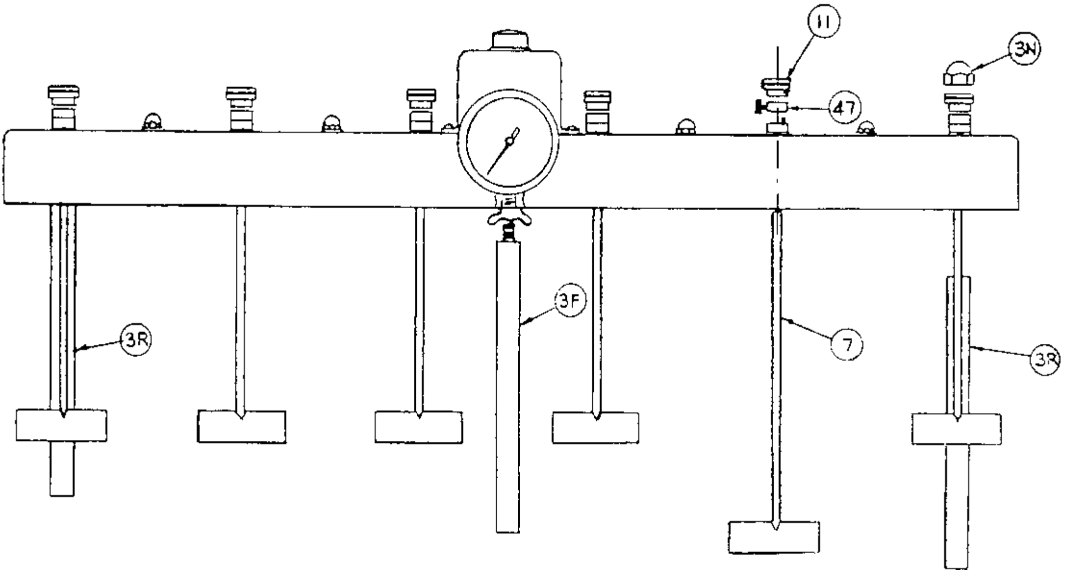
Chemical coagulation and flocculation are an important part of water and wastewater clarification. Coagulation is the destabilization of a colloidal suspension that results in the joining of minute particles by physical and chemical processes (1). Flocculation results in formation of larger, settleable flocs by bridging. These are the first processes in a water or wastewater treatment sequence to remove either suspended matter or color. Adsorption of ionic forms also occurs to varying degrees depending on the type of ion involved and the presence and amounts of other chemical constituents in the water or wastewater.

Inorganic coagulants (aluminum, iron, magnesium salts, etc.) may be used to coagulate particles and to form settleable flocs composed of the hydrous metal oxide precipitates and impurities (2). Alkalinity and pH controls are extremely important whenever the inorganic coagulants are used. Experiment (I) introduces several recommended laboratory experimental procedures involving the use of inorganic coagulants.

Polyelectrolytes are high molecular weight polymeric substances used in water purification and waste treatment to aid in the clarification of turbid suspensions or the dewatering of sludges and biosolids. These compounds consist of a long chain organic "backbone" with various types of ionic (cationic or anionic) or nonionic solubilizing groups. Because of the extremely long chain lengths, one end or segment of the polymer molecule is capable of reacting independently of the other end or segments. The individual segments are adsorbed onto the surfaces of the dispersed particles bridging between the normally stable (unsettleable) sol particles. Under proper conditions of time, temperature, concentration and mixing, this bridging leads to unstable settleable or filterable floc (3). This mechanism of destabilization by polymers is commonly known as chemical coagulation. Although electrostatic interactions between polyelectrolyte and particle are important it has been observed that anionic (negative) polymers will destabilize negative sols. Polyelectrolytes may be obtained that vary significantly in molecular weight and composition, as well as charge. These may be natural products, such as some starches and gums, or synthetically produced. Not all of these substances are acceptable for use with drinking waters. At the present time there is no analytical way to predict the behavior or applicability of a given polymer with a particular water or wastewater. Polymers are less sensitive to pH variations than metal coagulants; however, the dose required for optimum clarification varies over much wider ranges. Alkalinity control is not important when an organic polymer is used alone as the sole coagulant for floc formation or enhancement. Experiment (II) introduces a recommended laboratory experiment involving the evaluation of a polymer as a coagulant.

When both inorganic salt (such as alum) and organic polymer are used as coagulants and coagulant aids, respectively, in a treatment system, alkalinity and pH controls become important. In this case, the laboratory experiments listed in Experiment (I) should be followed for process optimization.

In general, chemical coagulation (or flocculation) experiments can be conducted in a Standard Jar Test Apparatus (Fig. 18.1) for determining the optimum chemical dosage. The apparatus has six motorized stirrers that can be turned at the same speed. Jar tests are conducted with various coagulants and coagulant aids at different dosages and pH conditions. Usually, 1 L of test sample and necessary chemicals are placed in a beaker and rapidly mixed



Assembly instructions

1. Insert front leg (Item 3F) in opening shown and screw up tight.
2. Insert 2 back legs (Item 3R) in holes in projecting arms in rear of stirrer and turn cap nuts (Item 3N) down tight
3. Insert paddle (Item 7) in opening in bottom of stirrer and push through. Slip height adjustment bushing (Item 47) over end of shaft with thumbscrew (Item 48) screwed out enough to allow entry. Place bakelite knob (Item 11) on end of shaft, push down tight and screw in set screw (Item 11A) until tight.

Instructions for Maintenance

1. Lubricate paddle shafts occasionally with vaseline and wipe off surplus.
2. Put a few drops of machine oil in the ten oil holes provided on top of stirrer.

SPECIFICATIONS.
LENGTH -- 34"
HEIGHT – 16" (OVERALL)
DEPTH – 10¾"
WEIGHT – 24 lb

Fig. 18.1. Standard jar test apparatus.

by the stirrer at 100 rpm for one min, then slowly flocculated at 15–30 rpm for 10 more min or longer, and finally settled at 0 rpm for 30 min. The supernatant liquid in the beaker is sampled for water quality analysis. Both the supernatant and the settled sludge are visually observed and recorded.

Chemical coagulation and flocculation tests serve to indicate the optimum chemical dosages for removal of turbidity and color, including pH adjustment and whether there is a necessity for the use of supplemental activated carbon (4, 5). Jar tests, furthermore, yield a wealth of qualitative information on the rate of agglomeration as a function of energy input (paddle speed), the settleability of the floc formed, the floatability of the floc formed and the clarity of the treated water (which might be related to the subsequent length of filter run) (6–20). The water quality parameters, such as, suspended solids, pH, color, surfactant, chemical residues, floatable solids, settleable solids, etc. can be tested using the Standard Methods for the Examination of Water and Wastewater (21).

2. PROCEDURE AND APPARATUS FOR DAF SIMULATION (FULL FLOW PRESSURIZATION SYSTEM)

A compressed air tank available from Sears, Roebuck and Company, Chicago, IL (e.g., Sears 2-gal Open Top Sprayer, Model 786.15371) or similar is modified by removing the nozzle on its hose extension and fitting a pressure gauge into the tank. A 1,000-mL plastic graduated cylinder is fitted with a valve on the bottom to draw off subnatants. Both the modified compressed air tank and cylinder are shown in Fig. 18.2 and are frequently used for

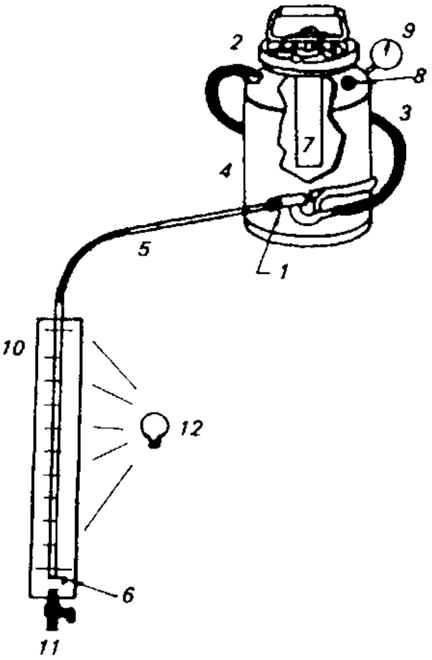


Fig. 18.2. Standard DAF test apparatus for water and wastewater clarification and sludge thickening (13, 18, 20).

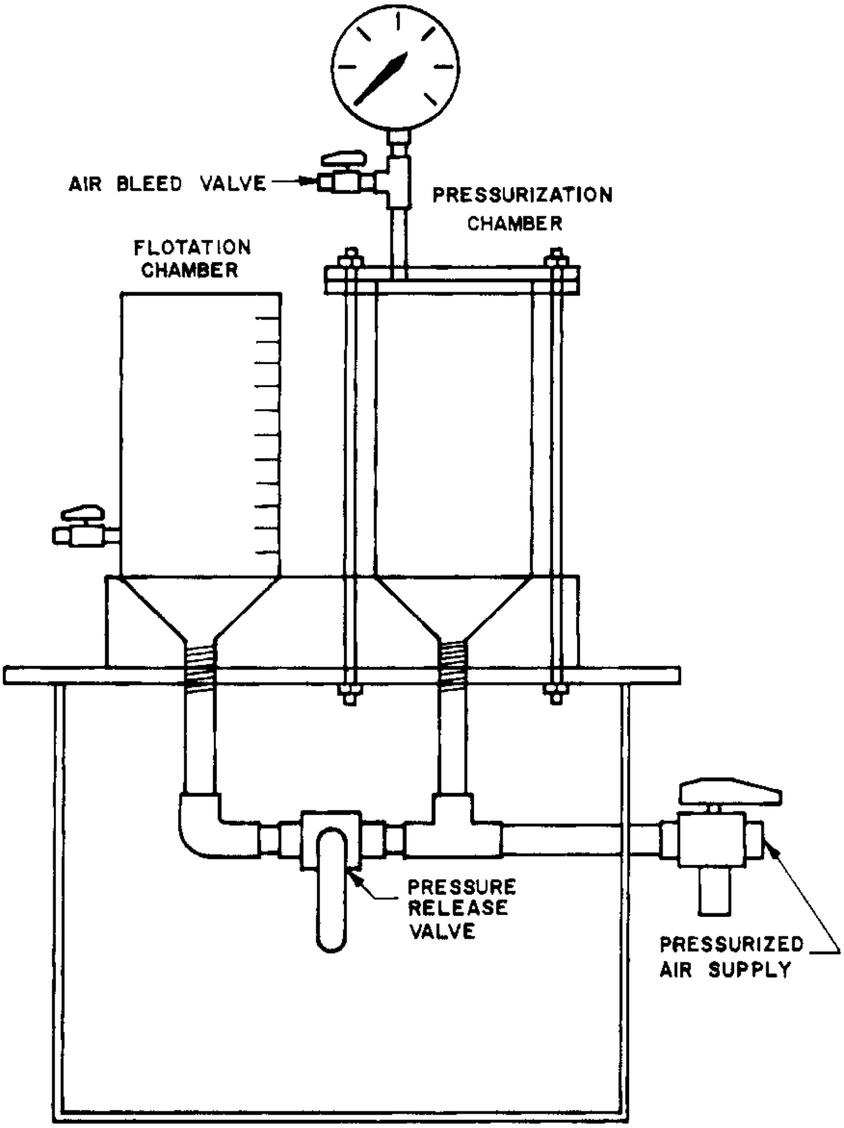


Fig. 18.3. Standard DAF test apparatus for sludge thickening.

DAF clarification testing, but occationally used for DAF sludge thickening. An alternative bench-scale apparatus for DAF sludge thickening studies is illustrated in Fig. 18.3 (17).

The dissolved air flotation (DAF) unit can be operated under the following three conditions (6, 7):

1. Full flow pressurization (Fig. 1.11a).
2. Partial flow pressurization (Fig. 1.11b).
3. Recycle flow pressurization (Fig. 1.11c).

To start a DAF full flow pressurization experiment using the standard DAF test apparatus shown in Fig. 18.2, the compressed air tank, shown in Fig. 18.2, is filled half full with raw or pretreated liquid sample (i.e., influent) that has been adjusted to process temperature. The compressed air tank is then pumped to 45–65 psig and shaken for 2 min to allow the air to dissolve in the sample. The first portion of pressurized sample (approximately 100 mL) is released into the sink to allow any bound air to escape and to clear the outlet.

The remaining pressurized sample (1,000 mL) is then carefully and slowly released into the modified 1,000-mL graduated cylinder (see Fig. 18.2) by putting the outlet shaft all the way to the bottom of the cylinder and moving the shaft upward with the upward flow of the filled sample. (If the proper dose of chemicals is added at the same time that 1,000 mL of pressurized sample is released into the 1,000-mL cylinder, it is suggested that the filled cylinder be capped and inverted once to insure proper mixing of chemicals). Note when a line of demarcation first appears between the clarified liquid at the bottom and the solids layer at the top; it is time to estimate the rising velocity of the sludge blanket by noting the level of the interface at regular time intervals. The rising velocity (in/min) of the sludge–water interface should be estimated accurately with the aid of a stop watch. A light source behind the cylinder may enhance visibility of the particles. After 2–3 min, the mL volume of floating sludge, the mL volume of settled sludge if any, and the physical characteristics of subnatant are recorded. At least 200 mL of subnatant (i.e., effluent) should be withdrawn from the cylinder bottom to test for suspended solids and other water quality parameters.

Equation (1) can be used to calculate the air-to-solids ratio for the full flow pressurization system based on the laboratory experimental results (6, 7).

$$A/S = 1.3a(FP - 1)/X, \tag{1}$$

where A is the mass flow rate of air released for flotation of suspended solids (mg/s), a the air solubility (mL/L), 1.3 the weight in mg of 1 mL of air, and 1 is the one atmosphere of air remaining in solution after depressurization.

The flotation efficiency in terms of suspended solids removal can be calculated by the following formula:

$$E = 100(1 - X_e/X), \tag{2}$$

where E is the percentage of suspended solids removal, X the suspended solids in influent (mg/L), and X_e is the suspended solids in effluent (mg/L)

3. PROCEDURE AND APPARTUS FOR DAF SIMULATION (PARTIAL FLOW PRESSURIZATION SYSTEM)

The experimental apparatus for partial flow pressurization of DAF (Fig. 1.11b) is identical to that for full flow pressurization, shown in Fig. 18.2.

To start a DAF partial flow pressurization experiment, the 1,000-mL graduated cylinder (Fig. 18.2) is initially filled with the desired volume (V_i) of raw or pretreated liquid sample (i.e., influent not to be pressurized) which is adjusted to the process temperature. The value of V_i is decided based on the desired percentage of partial flow as shown in Table 18.1. It is

Table 18.1
Values of V_i as a function of Partial Flow

Percentage of partial flow based on (V_p/V_i) (%)	Percentage of partial flow based on $V_p/(V_p+V_i)$ (%)	Unpressurized influent volume (V_i) (mL)	Pressurized influent volume (V_p) (mL)
11.11	10	900	100
25.00	20	800	200
42.86	30	700	300
66.67	40	600	400
100.00	50	500	500

important to specify how the percentage of partial flow has been calculated in the engineering report in order to avoid any misunderstanding.

The compressed air tank (Fig. 18.2) is then filled approximately half full with influent (with or without chemical addition) and adjusted to the process temperature. The compressed air tank is subsequently pumped to 45–65 psig and shaken for 2 min to allow air to dissolve in the pressurized influent. The first portion of pressurized water (approximately 100 mL) is released into the sink to allow any bound air to escape and to clear the outlet. The remaining pressurized water (V_p) is then released into the 1,000 mL graduated cylinder (which is initially filled with V_i mL of the influent) by putting the outlet shaft all the way to the cylinder bottom and moving the shaft upward with the upward flow of the sample ($V_i + V_p$).

The rising velocity (in/min) of floating sludge or flocs is timed with a stop watch. After 2–3 min, important physical characteristics of floating sludge, settled sludge, and subnatant are recorded. At least 200 mL of subnatant should be withdrawn from the cylinder bottom to test for suspended solids and other water quality parameters.

Equation (2) can be used for calculation of flotation efficiency.

4. PROCEDURE AND APPARATUS FOR DAF SIMULATION (RECYCLE FLOW PRESSURIZATION SYSTEM)

The recycle flow pressurization system and the experimental apparatus for the system are shown in Figs. 1.11c and 18.2, respectively.

To start a DAF recycle flow pressurization experiment, the 1,000-mL graduated cylinder (Fig. 18.2) is initially filled with the desired volume (V_i) of raw or pretreated liquid sample (i.e., influent) that is adjusted to the process temperature. The value of V_i is decided based on the desired percentage of recycle flow as shown in Table 18.2.

The compressed air tank (Fig. 18.2) is then filled approximately half full with the recycle water (e.g., clarified effluent or other source of clean water) adjusted to the process temperature. Suspended solids value of recycle water (X_r) is tested to provide a correction factor in the final calculation. The compressed air tank is subsequently pumped to 45–65 psig and shaken for 2 min to allow air to dissolve in the clean water. The first portion of pressurized water (approximately 100 mL) is released into the sink to allow any bound air to escape and to clear

Table 18.2
Values of V_i as a function of recycle flow

Percentage of recycle flow (%)	Influent volume (V_i) (mL)	Recycle volume (V_r) (mL)
11.11	900	100
25.00	800	200
42.86	700	300
66.67	600	400
100.00	500	500

the recycle outlet. The remaining pressurized water (V_r) is then released into the 1,000-mL graduated cylinder (which is initially filled with V_i mL of the influent) by putting the outlet shaft all the way to the cylinder bottom and moving the shaft upward with the upward flow of the sample ($V_i + V_r$).

The rising velocity (in/min) of floating sludge or flocs is timed with a stop watch. After 2–3 min, the important physical characteristics of floating sludge, settled sludge, and subnatant are recorded. At least 200 mL of subnatant should be withdrawn from the cylinder bottom to test for suspended solids and other water quality parameters.

The material balance Eq. (3) should be used for recycle flow correction:

$$X_e(V_i) + X_r(V_r) = X_c(1{,}000), \tag{3}$$

where X_e is the theoretical effluent suspended solids (mg/L), V_i the volume of influent used (mL), X_r the suspended solids of recycle water (mg/L), V_r the volume of recycle water used (mL), and X_c is the suspended solids of the clarified subnatant (mg/L).

The value of X_e calculated from Eq. (3) is then used in Eq. (2) for the determination of flotation efficiency in terms of suspended solids ($X_r = X_c$).

Equation (4) should be used for calculation of the air-to-solids ratio based on the laboratory experimental results:

$$A/S = 1.3aV_r(FP - 1)/V_iX. \tag{4}$$

The quantity of air which will theoretically be released from solution following pressure reduction can be computed from

$$a_r = a(FP_r - P_e)/14.7, \tag{5}$$

where a_r is the air released at atmospheric pressure at 100% saturation, mL/L liquid. (Air volume at standard conditions, e.g., 0°C + atm. absolute); a the air saturation at one atmosphere pressure, mL/L (standard conditions); P_r the pressure before release, psi absolute; and P_e is the pressure after release, psi absolute

Equation (5) is valid for all (DAF) systems (Fig. 1.11a–c). The actual quantity of air released will depend on how close the equilibrium solubility at P_r is attained and on the turbulent mixing conditions at the point of pressure reduction. The closeness to equilibrium solubility will depend on the time of retention under pressure, on the mass transfer contact surface between air and water, and on the degree of mixing. Conventional static holding tanks can usually yield up to 50% saturation in normal retention times.

The use of packing or mixing can produce 90% saturation in conventional retention times. This can be taken care of in the calculations by multiplying P_r by a factor, F, where F is the fraction of saturation attained in the retention tank, and is equal to one for water saturated with air.

It should be noted that the operation of the pressure cell closely simulate the recirculation of effluent as used in the full-scale flotation system. The returned effluent (recycle water) may be developed by repeated flotation of several different portions of raw waste. After the recycle water has been developed and used in the flotation tests, samples may then be withdrawn for chemical analysis.

5. PROCEDURE AND APPARATUS FOR IAF SIMULATION (BATCH SYSTEM)

Figures 18.4 and 18.5 show the tester dimensions and piping arrangements, respectively, of a bench-scale foam separation unit for use in these types of experiments.

To start the batch induced air flotation (IAF) experiments, sufficient volume of raw water is adjusted to the desired pH with 1.0N sodium hydroxide or 1.0N sulfuric acid, an appropriate amount of surfactant is added to the raw water, and the mixture is poured into the Foamer Tester (Fig. 18.4). Compressed air is then diffused through the liquid mixture by means of a plastic cloth grid (Fig. 18.5). Foam is withdrawn from the top and collected in a container. The run is allowed to proceed until no additional foam is formed. A sample of the bulk liquid near the reactor bottom is analyzed for pH, color, turbidity, and other water quality parameters. The foam is collapsed in a beaker and its volume measured.

From batch foam separation experiments, one may be able to determine the feasibility of the process and the approximate optimum chemical dosages.

6. PROCEDURE AND APPARATUS FOR IAF SIMULATION (CONTINUOUS SYSTEM)

Figure 18.6 shows an experimental set-up for continuous foam separation experiment. Continuous pilot plant operations allow the engineers to determine not only the optimum chemical dosages but also the optimum operational conditions in terms of flows, feed locations, chemical dosages, etc (8, 9).

For the continuous foam separation study, the sample solution is prepared, mixed well, and placed in the large feed tank. Four liters of initial sample are taken with the desired amount of collector added. The initial color, turbidity, optical density, surfactant concentration, streaming current reading, conductivity, and pH are determined. The collector is also uniformly prepared and placed in a smaller feed tank. The solutions of influent feed and collector are pumped into the foam separation cell at specified rates for each run. The concentrations in the feed tanks are adjusted to provide the desired concentrations of target solute and of collector. Compressed air is diffused through the solution by means of the coarse gas diffuser. After start-up, the bulk liquid is pumped through the system, and the optical density is continuously recorded. The run is continued until a steady state is reached

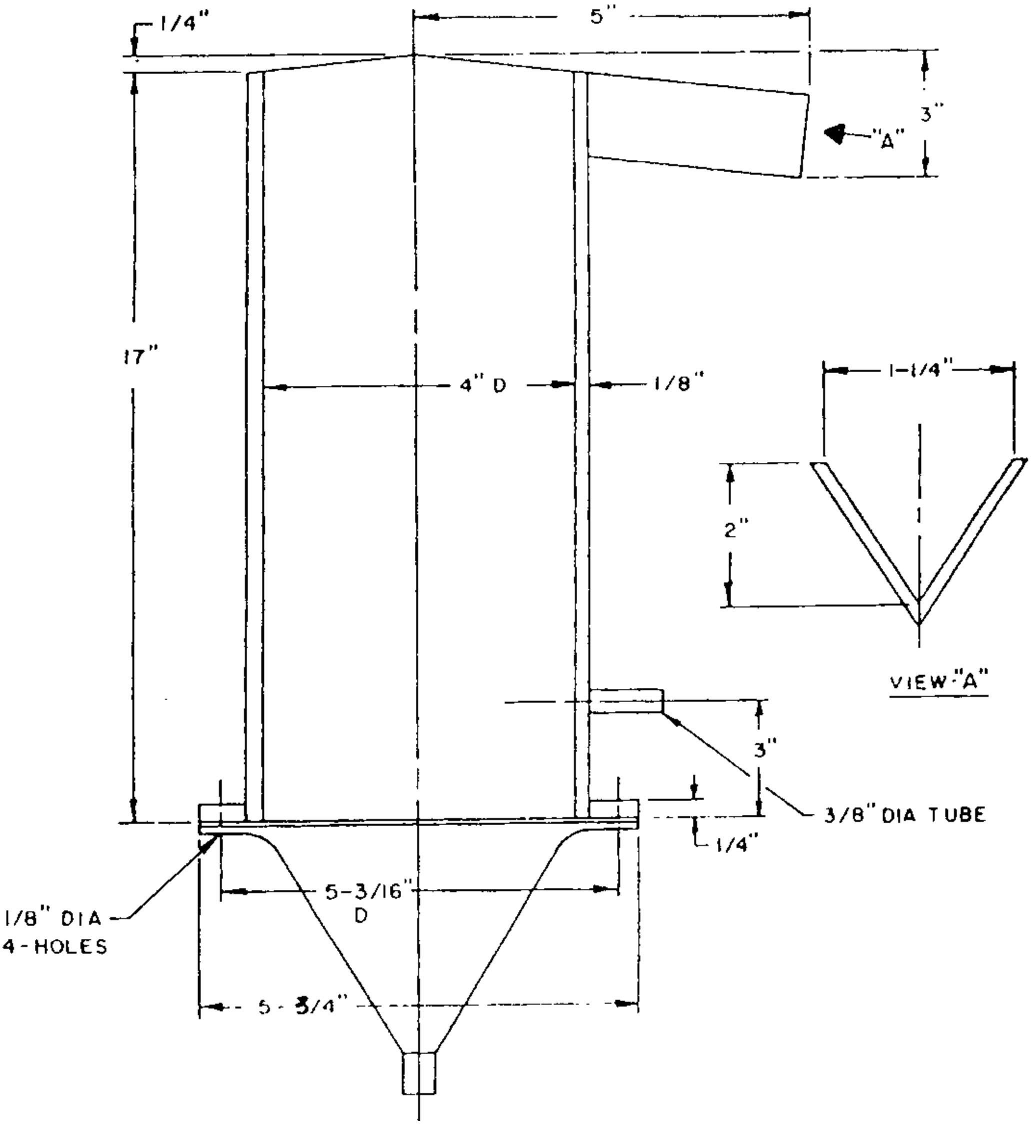


Fig. 18.4. Dimensions of bench scale IAF cell (13, 20).

(i.e., there is no change in the optical density). During the steady state, the bubble velocity and bubble size are measured. Samples of bottom effluent and collapsed foam are taken throughout the entire experiment. Samples are analyzed for color, optical density, residual solute concentration, residual surfactant concentration, turbidity, streaming current reading, conductivity, and pH.

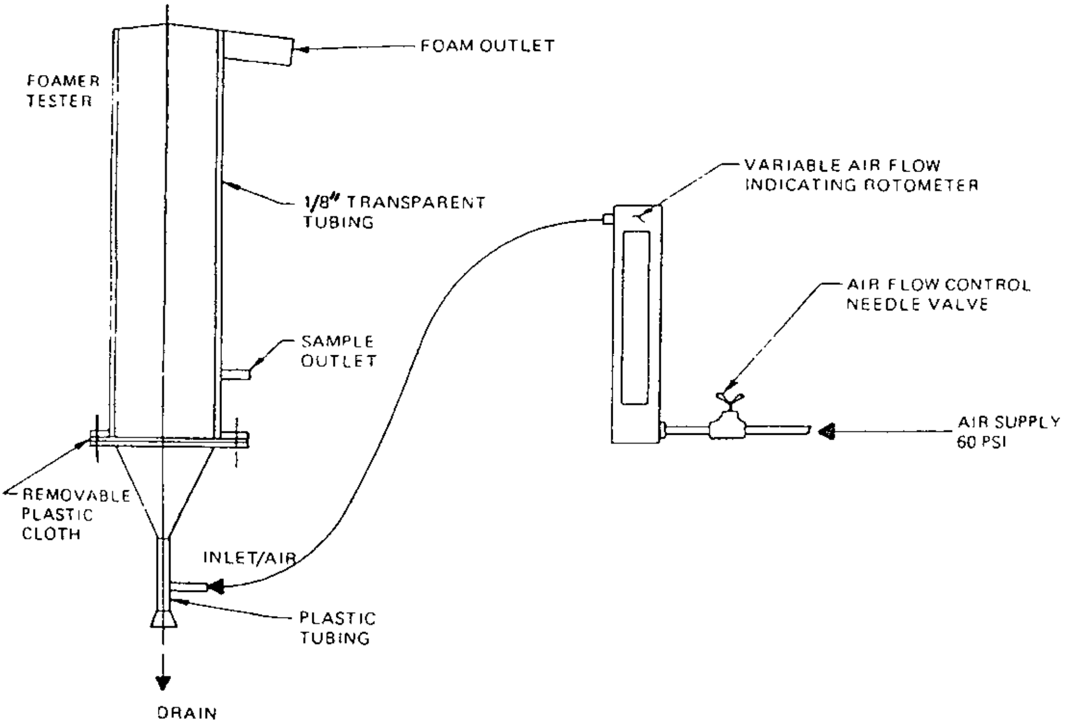


Fig. 18.5. Bench scale IAF system (13, 20).

7. PROCEDURE AND APPARATUS FOR SIMULATION OF CHEMICAL COAGULATION, SEDIMENTATION AND FILTRATION

A conventional physicochemical treatment system consisting of rapid mechanical mixing (10), slow mechanical flocculation (1), and filtration (11) (Note: Filtration also includes granular activated carbon) can be used for both water purification and wastewater treatment. The procedures and apparatus for simulation of the conventional physicochemical treatment system are partially covered by other sections (Section 8. Procedures and Apparatus for Simulation of Chemical Coagulation Flotation and Filtration), Experiment (I) (Section 9. Coagulation and Flocculation with Hydrolyzine Metallic Salts) and Experiment (II) (Section 10. Coagulation and Flocculation with Organic Polymers), with a few modifications and additions.

Since the conventional physicochemical treatment system relies upon production of heavy and dense flocs for subsequent separation by sedimentation (12), the rapid mixing speed and detention time as well as flocculation mixing speed and detention time must be either optimized in the laboratory or controlled in accordance with the design criteria recommended by the Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers (22, 23).

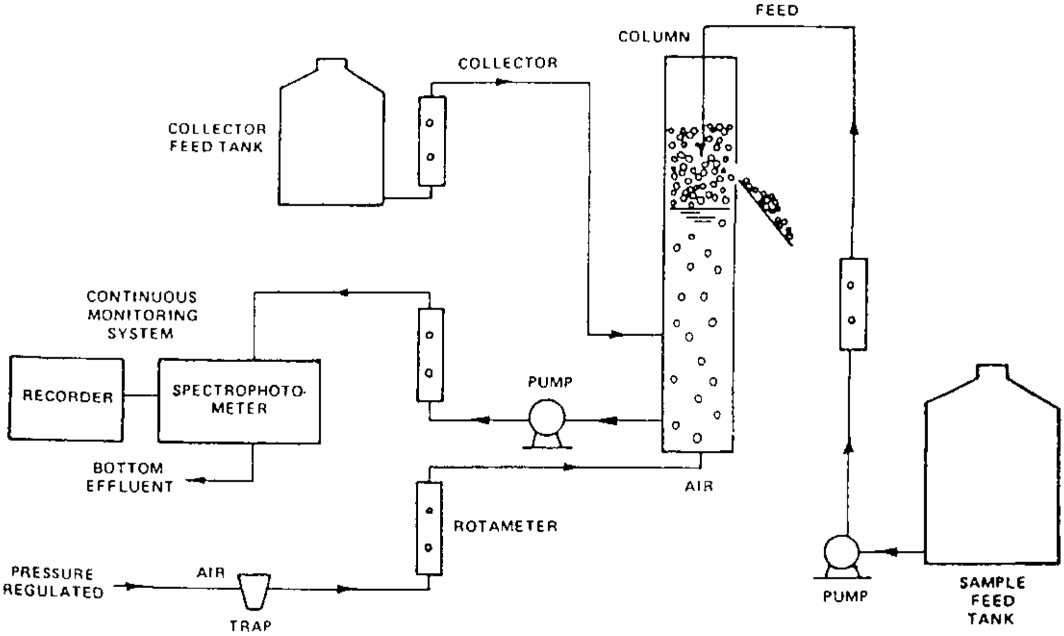


Fig. 18.6. Apparatus for continuous foam separation experiments (19).

For instance, for water purification:

1. Rapid mixing chamber should be equipped with mechanical devices and its detention time should not be more than 30 s.
2. Slow mechanical flocculators shall have a detention time of 30 min or longer and shall be driven by variable speed drives with the peripheral speed of paddles ranging from 0.5 to 3.0 ft/s; the rotational speed (rpm), of a Standard Jar Test Apparatus' paddle can then be determined accordingly.
3. Sedimentation generally shall have a minimum of 4 h of settling time. Reduced sedimentation time may be approved only when equivalent effective settling can be demonstrated.

For simulation of the filtration step, the supernatant of settled water from a Standard Jar Test Apparatus shall pass through either a Whatman filter paper No. 40 (or equivalent) or a simulated bench-scale filtration column. For quick chemical dosage determination and the conventional treatment system simulation, the Whatman filter paper is recommended. For further confirmation testing, the bench-scale filtration column shall be constructed and operated according to the design criteria recommended by the Great Lakes-Upper Mississippi River Board of State Sanitary Engineers. The filtration rate should not exceed 3 gpm/ft^2 of filter area except where testing as approved by the reviewing authority has been demonstrated. During filter backwash, a minimum rate of 15 gpm/ft^2 consistent with water temperature and specific gravity of the filter media shall be maintained. A backwash rate of 20 gpm/ft^2 or a rate necessary to provide for a 50% expansion of the filter bed is recommended. A reduced backwash rate of 10 gpm/ft^2 may be acceptable for full depth anthracite or granular activated carbon filters.

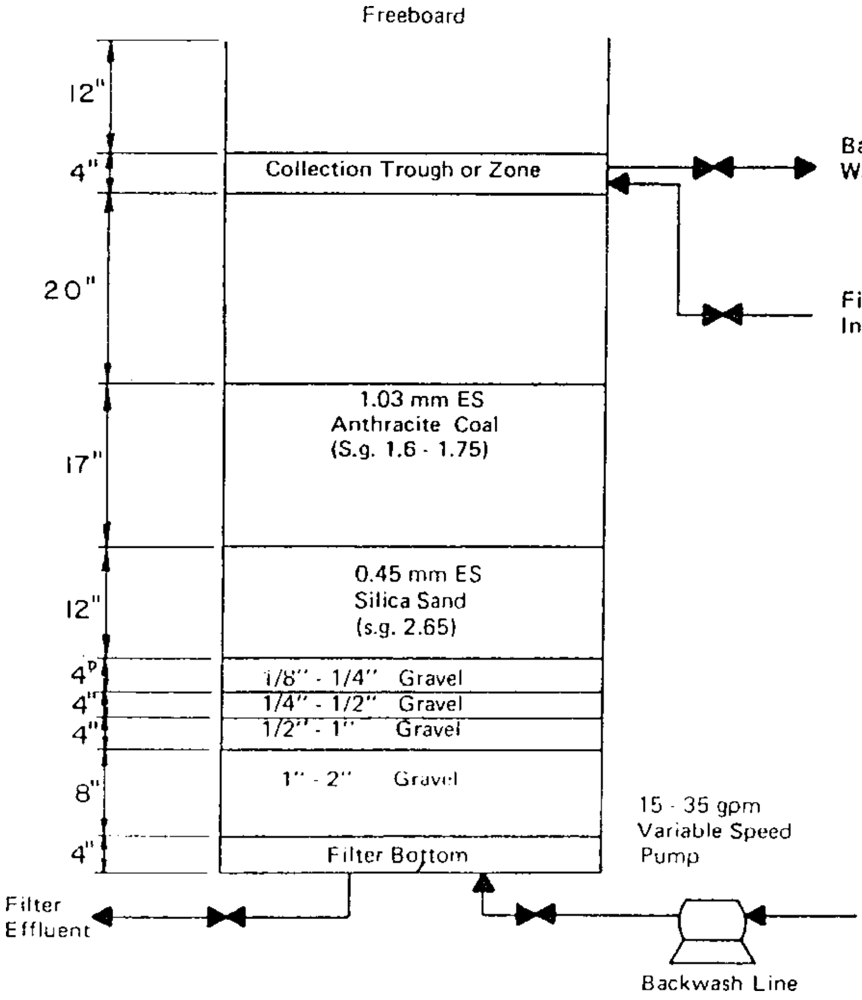


Fig. 18.7. Filter bed diagram (13, 18).

Figure 18.7 shows a typical filter bed diagram for the construction of a bench-scale or pilot filter.

8. PROCEDURE AND APPARATUS FOR SIMULATION OF CHEMICAL COAGULATION, FLOTATION, AND FILTRATION

An innovative physicochemical treatment system consisting of static rapid mixing, static flocculation, flotation, and filtration (filtration also includes granular activated carbon) can be used for both water purification and wastewater treatment.

The procedure and apparatus for simulation of the innovative physicochemical treatment system are partially covered by other sections (Section 8. Procedures and Apparatus for

Simulation of Chemical Coagulation Flotation and Filtration), Experiment (I) (Section 9. Coagulation and Flocculation with Hydrolyzine Metallic Salts) and Experiment (II) (Section 10. Coagulation and Flocculation with Organic Polymers), with a few modifications and additions.

The innovative physicochemical treatment system requires production of light and small pin flocs for subsequent separation by flotation. Accordingly the rapid mixing at 100 rpm shall be less than 30 s, and the flocculation at 15–30 rpm shall have a maximum detention time of 15 min.

The flocculated water should be immediately filtered by either a Whatman No. 40 filter paper (or equivalent) or a simulated bench-scale filtration column. For quick chemical dosage determination and the innovative treatment system simulation, the Whatman filter paper is recommended. For further confirmation testing the bench-scale filtration column shall be constructed and operated according to the design criteria recommended by the Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers (22, 23).

Alternatively, the flocculated water can be filtered by a filtration bed consisting of only 11 in. of fine quartz sand (effective size = 0.35 mm; uniformity coefficient 1.6 or less). The fine quartz sand can be supported by fine plastic screen (250 μm size) with either expanded metal support or porous plate support. This filtration apparatus is a simulation of an automatic backwash filter (ABF).

9. EXPERIMENT (I) COAGULATION AND FLOCCULATION WITH HYDROLYZINE METALLIC SALTS

9.1. Background

Coagulation and flocculation processes are an important part of water and wastewater treatment. Coagulation or destabilization of a colloidal suspension results in joining of minute particles by physical and chemical processes. Flocculation results in formation of a larger, settleable structure by bridging (1). These are commonly the first processes in a water treatment sequence to remove either colloidal matter or color. Adsorption of ionic forms also occurs to varying degrees depending on the type of ion involved and the presence and amounts of other chemical constituents in the water or wastewater.

Analysis of water or wastewater preparatory to the design of a treatment sequence often involves coagulation and flocculation laboratory experiments. Aluminum or iron salts may be used to coagulate particles and to form settleable flocs composed of the hydrous metal oxide precipitates and impurities. These tests, called jar tests, are widely used for control of plant operations and are routinely performed by treatment plant operators. The coagulation and flocculation tests serve to indicate the optimum chemical dosages for removal of turbidity and color, including the need for pH adjustment, and the necessity for the supplemental use of activated carbon. Jar tests, furthermore, yield a wealth of qualitative information on the rate of agglomeration as a function of energy input (paddle speed), the settleability of the floc formed, and the clarity of the supernatant water (which might be related to the subsequent length of filter run).

Coagulation and flocculation experiments may also be used, in conjunction with other tests, to study basic processes including, for example, the kinetics of reaction, and the removal of colloidal and trace constituents from aqueous solutions.

9.2. *Objectives*

To conduct jar tests on a synthetic or natural surface water in order to estimate an optimum dosage of aluminum sulfate or ferric sulfate for the removal of suspended matter or color.

9.3. *Procedure*

9.3.1. *Determination of Optimum Coagulant Dosage*

1. Collect 20–50 L of natural surface water. Analyze the water for pH, turbidity, alkalinity, and color after filtration. Alternately, make up a clay suspension with tap water. Record both the water temperature at time of test and ambient air temperature. If the raw water is clear and colorless, it may be desirable to augment the suspended matter with kaolin, montmorillonite, illite, or bentonite clay and the color with an extract from boiled leaves or with instant coffee. Turbidity might be increased to about 50 turbidity units and color to about 100 color units.
2. Calculate the amount of alkalinity required to react with the maximum dosage of aluminum or ferric sulfate. If necessary, augment the natural alkalinity of water by the addition of 0.1N Na_2CO_3 so that the alkalinity will be at least 25 mg/L as $CaCO_3$ equivalent if the reaction is complete. Measure the pH.
3. Place 1-L aliquots in the 1-L beakers of the six-jar laboratory stirrer and check stirrer operation. A light table will facilitate viewing of the contents of the beakers. Prepare portions of the aluminum or ferric sulfate solution, which will yield 10–100 mg/L when added to the sample aliquots.
4. At the start of the 1 min rapid mix at 100 rpm, add the coagulant solutions to the five beakers keeping one beaker as a control.
5. Flocculate at 30 rpm for 20 min or longer, if necessary. Record the elapsed time before a visible floc is formed. If large flocs are formed, it may be desirable to reduce the paddle speed. Note the size and appearance of the floc formed.
6. After flocculation, remove the paddles and settle for 30 min.
7. Measure the turbidity or color of the supernatant in each jar, taking care not to disturb the sediment in sampling. Measure the pH of the supernatant and the depth of sludge. If possible, estimate the volume of sludge which might be produced by treating 1 MG of the tested water. Select the optimum dosage on the basis of supernatant clarity and settleability of floc.
8. If satisfactory results are not obtained, repeat the jar test experiment with another range of coagulant dosages. The test also may be repeated, if appropriate, to further narrow the range of dosages near the optimum. Estimate the range of dosages over which this coagulant would be effective.

9.3.2. *Determination of Optimum pH*

1. Repeat the jar test in Sect. 9.3.1 using the observed optimum dosage of coagulant but adjusting sample pH to 6–9 with sodium hydroxide or sulfuric acid prior to adding coagulant.
2. Measure final pH, turbidity and color of the supernatant of each sample. Measure the depth of sludge in the beaker.
3. Plot turbidity and color vs. initial pH and against final pH. Select optimum initial pH based on use of the optimum coagulant dosage determined in Sect. 9.3.1.

9.3.3. Microscopic Examination

1. If a microscope is available, examine samples of the colored and turbid waters and the supernatant. Describe the nature of the material observed. Using a calibrated grid in the ocular, estimate the size of the particles present.

9.3.4. Coagulation in Conjunction with Activated Carbon for Reduction of Color

1. If the color of the water is not reduced sufficiently using the coagulant alone, investigate removal efficiency using activated carbon in varying dosages. Develop a procedure such that the color is successfully reduced to an acceptable level for a public water supply.

9.3.5. Effect of Mixing Time and Intensity (Aggregation Kinetics)

1. If a different size or configuration of paddles is available, investigate the effect on coagulation and flocculation of varying paddle size and varying mixing intensities. Tapered flocculation may be simulated by reducing paddle speeds (power input) during the course of mixing.
2. Prepare identical (optimum) coagulant dosages for all six beakers.
3. Use the same rapid mix as before but vary the time of slow mix at 30 rpm. Use 5, 10, 15, 20, 30, and 45 min for the six jars respectively. Terminate mixing by carefully lifting the paddle from the beaker at the appropriate time.
4. Allow 30 min for settling.
5. Measure color, turbidity, and pH of the supernatant in each beaker.

9.3.6. Removal of Microorganisms

1. With a prepared microbiological culture, such as *E. coli*, examine the efficiency of removal of viable organisms using a coagulation procedure similar to the preceding.

9.4. Analysis

1. Prepare tables for comparison of coagulant dosages with alkalinity, pH, color, turbidity, and other changes observed. Plot the inverse of turbidity and color vs. coagulant dosage as part of the analysis.
2. Comment on the differences between coagulation with iron and aluminum salts. Define the pH ranges over which each salt should result in effective coagulation.

10. EXPERIMENT (II) COAGULATION AND FLOCCULATION WITH ORGANIC POLYMERS

10.1. Background

Polyelectrolytes are high molecular weight polymeric substances used in water purification and waste treatment to aid in the clarification of turbid suspensions or the dewatering of sludges. These compounds consist of a long chain organic backbone with various types of ionic (cationic or anionic) or nonionic solubilizing groups. Because of the extremely long chain lengths one end or segment of the polymer molecule is capable of reacting independently of the other end or segments. The individual segments are adsorbed onto the surfaces of the dispersed particles, thus creating bridging between the normally stable (unsettleable) sol particles (3). Under proper conditions of time, temperature, concentration, and mixing, this bridging leads to a settleable or filterable floc. This mechanism of destabilization by polymers is known as flocculation (1). Although electrostatic interactions between polyelectrolyte and particle are important it has been observed that anionic (negative) polymers will destabilize negative sols.

Polyelectrolytes may be obtained that vary significantly in molecular weight and composition, as well as charge. These may be natural products, such as some starches and gums, or synthetically produced polymers. At the present time there is no analytical way to predict the behavior or applicability of a given polymer with a particular water or wastewater. Performance and optimum doses are usually judged using the jar test procedure similar to the evaluation of metal coagulants. Although polymers are less sensitive to pH variations than metal coagulants, the dose required for optimum clarification varies over much wider ranges.

10.2. Objective

The objective of this experiment is to evaluate various polymers for clarification of turbid suspensions and the determination of their optimum doses.

10.3. Procedure

1. Natural water is collected or suspensions of clay are prepared as described in Experiment (I).
2. Two or more different cationic polymers are selected for evaluation. Suitable portions of each are carefully weighed and dissolved by slowly adding to water using a magnetic stirrer. These stock solutions should be freshly prepared every 2 weeks.
3. Six well-mixed 500-mL volumes of the turbid suspension are transferred to 1-L beakers, which are then placed under the paddles of the jar test apparatus. The current is turned on and the speed of the paddles is set to about 85 rpm.
4. Just prior to experimentation, aliquots of a polymer solution are diluted in small beakers to 100-mL total volume. These are prepared so that the final 600-mL experimental solutions contain polymer concentrations of 0, 0.5, 5.0, 10.0, and 30 mg/L.
5. These polymer solutions are added rapidly but carefully to each of the beakers and allowed to rapidly mix for 10 s. Following this the paddles speed is reduced to 25 rpm. Qualitative observations of floc formation and the clarity of suspensions for each sample are taken and recorded.
6. After 20 min of slow mixing the stirring is stopped and similar observations are made and recorded. A further 30 min of quiescent settling is permitted after which samples from the top 200 mL of each suspension are withdrawn for absorbance or turbidity measurements. Qualitative observations are also recorded.
7. This procedure is repeated for the other polymer and the results are compared. Usually the polymer requiring the smallest dose for good clarification is selected for further testing. The actual selection should be made on the basis of least cost per dose.
8. For the next set of experiments a similar series of polymer solutions are prepared such that the minimum optimum dose is bracketed. For example, if 10 mg/L were the smallest concentration giving good results, then the next series would consist of 2, 4, 6, 8, 10, and 12 mg/L. Note that the control sample is no longer required but that one sample is repeated to check on the reproducibility of the results.

The procedure is repeated. Another series over a smaller range of concentrations may also be run if necessary.

10.4. Analysis

The general procedure outlined above does not guarantee meaningful or even reproducible results. Good techniques and attention to details are required. Occasionally the mixing speeds and time periods specified are inadequate for good results with specific polymers or turbid suspensions. One is being asked to make judgments on the experimental procedure. For example, sometime only a very few µg of polymer/L will result in the most effective clarification although the minimum dose for the first series of experiments calls for 0.5 mg/L (500 µg/L).

There is no substitute for planning and preparation before experimentation. Determination of concentrations and hence weights of polymer to be used in the preparation of stock solutions should be based on the experimental convenience of delivering a series of volumes for dilution. These decisions, as well as a clear understanding of what is to be accomplished, should be done before starting any experiment.

Procedures for handling of the samples collected for absorbance or turbidity measurements should also be worked out beforehand. For spectrophotometric measurements, the most sensitive wavelength to apply can be determined from the absorption spectrum of the suspension.

11. EXPERIMENT (III) BATCH LABORATORY DISSOLVED AIR FLOTATION TEST

11.1. Background

11.1.1. Flotation Principles

Flotation is the separation of suspended solid particles, and sometimes dispersed liquids, from a liquid phase. This is done by the addition of a gas phase, usually air, in fine bubbles to the liquid phase. The rising bubbles either adhere to or are trapped in the particle structure, resulting in an increase in the buoyancy and a rise of the bubble–particle complex. Particles having a density even greater than liquid can be separated by this means. Separation by flotation does not depend so much on the size and the relative density of the particles as it does on their surface properties. Essentially, the surface properties of the particulate matter determine how particles will adhere to the injected bubbles (6, 7).

Flotation was first developed in the early 1900 in the mining industry as a means of separating an ore into a concentrate. Later it was applied to wastewater treatment to remove suspended solids, grease, and oil. In the paper industry it has been used in the treatment of "white water", that is, finely suspended fibers in water from the paper machines or digesters. Favorable results have been obtained with oil and also with algae.

Two flotation methods are in use depending on the way the bubbles are produced. In IAF bubbles are generated by passing the gas through some kind of disperser: porous media, perforated tubes (spargers), revolving impellers, etc. Bubble diameter is in the order of 1,000 µm. In DAF bubbles are produced when the pressure of a supersaturated solution is lowered to atmospheric pressure. This is done by saturating the liquid at high pressure and releasing the pressure. In either case, the air-particle aggregate rises to the surface where it is skimmed off, and the clarified liquid is withdrawn from the bottom of the tank. In DAF, bubble sizes are small, ranging from 30 to 120 μm. Sometimes the clarified liquid or rather a part of it is charged with gas under pressure, and then the pressure is released and mixed with new wastewater, supplying the bubbles for the latter's particles flotation.

11.1.2. Performance and Design Features

The performance of a flotation system depends on having sufficient air bubbles to float substantially all suspended solids. An insufficient quantity of air will result in only partial flotation of the solids, and excessive air will yield no improvement. The performance of a flotation unit in terms of effluent quality and solids concentration in the float can be related to an air/solids ratio, which is usually defined as lb of air released/lb of solids in the influent waste. In general, the air/solids ratio needed will increase with the percent solids in the wastewater. Also, to get higher solids removal, that is, lower solids content in the effluent, requires a higher air/solids ratio. In both cases, the results will vary with the nature of the solids in the feed. Addition of coagulating agents can also modify the results.

The rise velocity closely follows Stokes' Law. The rise velocity of a solids–air mixture will vary from 1 to 5 in./min and will increase with increasing air–solids ratio. The rise velocity is related to the hydraulic loading, expressed in gpm/ft^2 of surface area or overflow velocity. The primary variables for flotation design are pressure, recycle ratio, feed solids concentration, retention period, and addition of coagulating agents (6, 7).

The principal components of a dissolved-air flotation system are a pressurizing pump, air injection facilities, a pressure retention tank, a back pressure regulating valve, and a flotation basin. The pressure in the pressure retention tank used for air dissolution is created by the mechanical action of the pump impeller used in the pumping of the flow.

The flotation tank can be designed in accordance to the design criteria established by the American Petroleum Institute (API):

1. The tank's depth to width ratio (D/W) = 0.3–0.5.
2. The maximum horizontal velocity (V_H) shall not exceed 3.0 ft/min. The flow, Q, to be used in determining the cross-sectional area and horizontal velocity must include the flow added as recycle.
3. The rate of rise, V_T in ft/min, is to be determined in a laboratory bench scale test procedure that is outlined in Sect. 11.2.
4. The factor for short circuiting and turbulence F_S, is assumed to be equal to 1.4.
5. The effective flotation basin length $L = (V_H F_S / V_T) D$.

Mechanical flight type skimmers may be used on the top of the flotation basin to remove floated solids. A bottom collector may also be incorporated to remove any heavy settleable solids not amenable to flotation.

11.2. Procedure

It is possible to estimate the flotation performance of a water/wastewater in a cell by means of a batch laboratory test. Rate of separation data may be conveniently obtained in the laboratory from treatment tests performed on the raw water or wastewater in question. Generally, the procedure used in obtaining rate of separation data is by observing the solids–liquid interface and recording its travel with time.

In the tests, the rate of rise of the major portion of solids is recorded. At times, the solids–liquid interface may be vague and good judgment must be exercised in following this interface. Care should be taken to avoid following the interface formed by the air bubbles alone. In general, this interface lags behind the solids–liquid interface.

A suggested procedure for the performance of laboratory flotation tests and the equipment needed is as follows:

Assume that a recirculation ratio of 0.33 is to be tried.

1. Place 750 mL of a representative sample of the raw water or wastewater in a 1-L graduated glass cylinder.
2. Fill the pressure cell to approximately three-fourths full with recycle water. It is desirable that the operation of the pressure cell closely simulate the recirculation of effluent as used in the full-scale flotation system. The returned effluent (recycle water) may be developed by repeated flotation of several different portions of raw water/wastewater. After the recycle water has been developed and used in the flotation tests, samples may then be withdrawn for chemical analysis.
3. Secure the cover gasket and cover of the pressure cell, making certain all the valves are closed.
4. Inject air into the cell until a pressure of 45–70 psig is attained and maintained during testing. Record the pressure.
5. Shake the cell vigorously for 30–120 s. Record the shaking time.
6. Release 250 mL of the liquid that has been pressurized into the graduated cylinder. The volume of liquid in the graduated cylinder will then total to 1,000 mL (750 mL raw and 250 mL pressurized). The ratio of volumes of recycle water to the raw water/wastewater is called the recycle rate. Thus, the recycle rate used in this test is 33%. The most suitable recycle rate can be determined by repeated tests at varying rates of recycle and usually is not less than 20% and no more than 50%. To facilitate the introduction of the air-charged recycle water to the graduated cylinder, a rubber tube may be connected to the petcock on the pressure cell. After clearing the rubber tube of air (allow some liquid to escape through the tube by opening the petcock. Sufficient liquid should be removed until it has a milky appearance), the air-charged recycle water is introduced through the rubber tube into the graduated cylinder. The end of the tube should be placed near the bottom of the cylinder.
7. Obtain the following information:
   (a) Record waste temperature, pH, operating pressure, recycle rate, and flotation detention time.
   (b) Record rate of separation data. A detention time of 3–10 min is usually used. Record the detention time. If flotation is not complete in 10 min, longer detention times may be used. The form in Table 18.3 is suggested for obtaining the rate of separation data.

   The ultimate data desired is the position of the interface at various intervals throughout the test. The column labeled "Volume" is used as a convenient means of obtaining the position of the interface at any given time. For example, in the hypothetical case shown above, a 1-L cylinder was used in the test. At the beginning of the test the solids–liquid interface is at the bottom of the cylinder or at zero volume. As flotation progresses, the solids–liquid interface moves progressively up the height of the cylinder. The position of the interface at any given time may be conveniently obtained using the appropriate mark on the cylinder as a reference. After the test, the marks may be converted to ft of height by actual measurement. Note whether any solids settled in the cylinder during the test.

Table 18.3
Suggested form for obtaining position of interface (POI)

Time (min)	Volume (mL)	POI (Position of interface) (ft)
0	0	0
1	100	0.115
2	350	0.411
3	500	0.589
4	650	0.766
5	800	0.946
6	950	1.122
7	950	1.122
8	950	1.122

The obtained data are plotted using time in min as the abscissa and P0I in ft as the ordinate. The slope of the straight line portion of the curve represents the rate of particle rise in ft/min.

(c) Record the floated scum volume obtained after 3–10 min of flotation.

(d) After the flotation is completed, a sample of the raw water/wastewater and treated effluent should be collected for analysis. The sample of treated effluent should be carefully withdrawn from the cylinder either through the use of a petcock installed in the side and near the bottom of the cylinder or through the use of a siphon inserted in the cylinder. Sufficient liquid should be withdrawn to complete the desired analysis; however, care should be taken to avoid the break up of the scum blanket.

Determine suspended solids and pH. The pH of the effluent is the same as that of the raw water/wastewater itself if no chemical treatment is used. If possible, a small portion of the floated scum should be analyzed for total solids content.

8. Relate the effluent suspended solids and the float solids to the calculated air/solids ratio. When the recycle flow pressurization system is used, the air/solids ratio can be computed by

$$A/S = 1.3aV_r(FP - 1)/VX, \tag{6}$$

where a is the air saturation (mL/L) (at 0°C and 1 atm.), V_r the pressurized volume (L), P the absolute pressure (atm.), V the water/wastewater volume (L), X the influent suspended solids concentration (mg/L), A the mass of air required, S the mass of solids present, and F is the correction for nonsaturation. (In the laboratory it may be assumed that shaking is thorough and sufficiently long so that equilibrium is attained and $F = 1$.)

When pressurized recycle is not used (i.e., full flow pressurization system), the A/S ratio can be calculated from Eq. (1)

$$A/S = 1.3a(FP - 1)/X \tag{1}$$

9. Should chemical flocculation with flotation be desired, the chemical(s) may be added into the raw water/wastewater after step "1" is completed. Flocculation may be carried out, for convenience, in another vessel. Care should be taken not to break up the floc when transferring the water/wastewater to the cylinder. Enough time for flocculation should be allowed before introducing the air-charged recycle water. Under appropriate conditions, a floc may be formed by gentle

agitation of the water/wastewater after the chemical is added. Because of the peculiarities of some floc formations, they may break up readily upon any excessive agitation after being formed. This is most readily noticed when a liquid with a performed floc is transferred from the cylinder used in the jar mixing test to the cylinder used in the flocculation test. If the flocs do breakup and do not reform immediately, it is suggested that the transfer to the flotation cell not be made and that flotation be accomplished in the vessel where the floc was formed. The procedures for running this test are the same. However, withdrawing of the clarified liquid, as described in step "7" of the procedure will probably be through a siphon.

In flotation of a particular water/wastewater, it is quite possible that the test using the recirculation ratio of 0.33/1 may not yield the best results. Therefore, the tests described above may be repeated with other recirculation ratios until the optimum ratio is obtained.

11.3. Problems and Questions

1. Use the data obtained in the experiment to make a preliminary specification of a continuous DAF unit to treat 100 gpm of the wastewater to bring the suspended solids concentration down to an acceptable level. The specification should include: the pressure, the recycle ratio, the depth and horizontal area of the flotation tank, the addition of chemicals per 1,000 gal of wastewater, and the means of removing and disposing of the floated sludge.
2. What must be the nature of the solids–air–water interface for successful flotation? What must be the density of an air–solids–oil complex, relative to water?

12. EXPERIMENT (IV) INDUCED (DISPERSED) AIR FLOTATION AND FOAM SEPARATION

12.1. Background

Two common methods of flotation are currently in use: DAF and IAF. In IAF, gas bubbles are generated by introducing the gas phase by an impeller, through porous media, or a jet eductor mixer. Bubble diameter is in the order of 1,000 μm.

An IAF cell is usually operated as a foam separation process unit, which involves selective adsorption of surface-active substances at the gas–liquid interface of rising air bubbles, and the subsequent separation of the surface-active substance(s) from the cell surface as condensed foam. The process has been used to a wide extent in the metallurgical industry and in the paper and pulp industry. Air addition to a typical dispersed air flotation cell is about 400% of the influent flow by volume. In potable water treatment by foam separation, about 90% of turbidity can be successfully removed (8, 9).

Among the methods of foam separation, foam fractionation usually implies the removal of dissolved (or sometimes colloidal) solute. The overflowing foam, after collapse, is called the foamate. On the other hand, froth flotation usually implies the removal of solids and solutes in the foam phase.

The foamer is composed of a shallow tank with a feed well where raw water/wastewater, recycled water, and chemicals enter. A recycle pump feeds an ejector that discharges tangentially into the tank, creating a circular movement of bulk liquid in the tank. With a blower, air is added into the ejector at low pressure. This air is dispersed in the ejector and enters into the tank, producing a large amount of foam that travels to the top of the circulating bulk liquid. The foam is continuously collected by the foam collector and extracted into the foam suction tank, where a suction blower holds a light vacuum. The foam collapses in the foam suction tank and is extracted continuously by a water lock and discharged into a collection tank. The purified water is discharged in the center of the tank at the bottom opening and overflows the telescopic adjustable weir.

12.2. Objectives

The objective of this experiment is to operate a commercial IAF cell for separating dissolved surface-active agents from industrial process water. The objective is to understand the IAF's hydraulic structure, its operational procedure, and to conduct surfactant concentration tests on the influent, effluent, and foamate for estimating the water quality and treatment efficiency.

12.3. Procedure

12.3.1. Sample Preparation and Pretreatment

Describe the influent sample to be treated and any necessary pretreatment procedures. Collect enough size of influent sample for subsequent surfactant analysis.

12.3.2. Investigation of the Commercial IAF Cell

Describe the commercial flotation cell to be tested. Document the operational procedures.

12.3.3. Pilot Plant Operation and Investigations

1. Operate the dispersed air flotation cell continuously for at least 10 min or until the cell reaches the steady-state condition.
2. Record the temperature, influent flow rate, effluent flow rate, foam flow rate, recycle flow rate (if any), pressure at the air blower inlet, size of the flotation cell, water depth, etc.
3. Collect liquid samples from the effluent compartment and foam collection tank for subsequent surfactant analysis.

12.4. Analysis

1. Make material balances for flows and surfactants based on the measured flows and concentrations.
2. Calculate the treatment efficiency, detention time, and hydraulic loading rate.
3. Answer the following questions:
   (a) Can a DAF cell be operated as a foam separation process-unit?
   (b) Why does the IAF process need large volume of air for separation of impurities?
   (c) What type of substances can be separated by foam separation?
4. Draw your own meaningful conclusions.

13. EXPERIMENT (V) PILOT PLANT OPERATION OF A DAF CELL

13.1. Background

In a DAF system, a recycled subnatant flow is pressurized from 30 to 70 psig and then is saturated with air in the pressure tank. The pressurized effluent is then mixed with the influent sludge and subsequently released into the flotation tank. The excess dissolved air separates from solution, which is now under atmospheric pressure, and the minute (average diameter 80 μm) rising gas bubbles attach themselves to particles which form the floating sludge blanket. The thickened blanket is skimmed off and pumped to the downstream sludge handling facilities while the subnatant is returned to the plant. Polyelectrolytes are frequently used as flotation aids to enhance performance and create a thicker sludge blanket.

DAF is the most common form of flotation thickening in use in the USA and has been used for many years to thicken waste activated sludges, and to a lesser degree to thicken combined sludges. DAF has widespread industrial wastewater applications.

13.2. *Objectives*

The objectives of this experiment are to operate a commercial DAF cell for separating fibers (or other suspended solids) from industrial process water, in order to understand the hydraulic structure, operational procedures of the flotation unit, and to conduct suspended solids tests on the influent, effluent, and scum for estimating the water quality and treatment efficiency.

13.3. *Procedure*

13.3.1. Sample Preparation and Determination of Optimum Coagulant Dosage

Describe the sample to be treated and any necessary coagulation procedure. Collect at least 0.5 L of flotation influent for subsequent solid analysis.

13.3.2. Investigation of a Commercial DAF Cell

Describe the commercial flotation cell to be tested. Document the operational procedure.

13.3.3. Pilot Plant Operation and Investigations

1. Operate the flotation cell continuously for at least 15 min or until the unit reaches steady-state condition.
2. Record the temperature, influent flow rate, effluent flow rate, recycle flow rate, air pressure at the pressurization retention tank, size of the flotation cell, water depth, scum thickness, rotation speeds of the air distribution, and scum collection units.
3. Collect liquid samples from the effluent compartment and the scum layer for subsequent solids analysis.
4. Make material balances for flows and solids.
5. Calculate the air-to-solids ratio, recirculation ratio, and treatment efficiency.
6. Draw your own meaningful conclusions.

NOMENCLATURE

a = Air solubility (air saturation at 0°C and 1 atm.), mL/L
a_r = Air released at atmospheric pressure at 100% saturation, mL/L
A = Mass of air flow rate, mg/s
D = Tank's depth, m (ft)

E = Suspended solids removal, %
F = Correction for nonsaturation (fraction of saturation attained in the retention tank)
F_S = Factor for short circuiting and turbulence
P = Absolute pressure, atm
P_e = Pressure after air release, psi absolute
P_r = Pressure before release, psi absolute
Q = Flow rate
S = Mass of solids present
V = Water/wastewater volume, L
V_H = Horizontal velocity
V_i = Volume of influent used, mL
V_r = Volume of recycle water used, mL
V_r = Pressurized volume, L
V_T = Rate of rise, ft/min
W = Tank's width, m (ft)
X = Suspended solids concentration in influent, mg/L
X_c = Suspended solids concentration in clarified subnatant, mg/L
X_e = Suspended solids concentration in effluent, mg/L
X_r = Suspended solids concentration in recycle water, mg/L

REFERENCES

1. Shammas NK (2005) Coagulation and flocculation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ, pp 103–140
2. Wang LK, Vaccari DA, Li Y, Shammas NK (2005) Chemical precipitation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ, pp 141–198
3. Wang LK, Chang CC, Shammas NK (2005) Polymeric adsorption and regenerant distillation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ, pp 545–572
4. Hung YT, Lo HH, Wang LK, Taricska JR, Li KH (2005) Granular activated carbon adsorption. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ, pp 573–634
5. Hung YT, Lo HH, Wang LK, Taricska JR, Li KH (2006) Powdered activated carbon adsorption. In: Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical treatment processes. Humana Press, Totowa, NJ, pp 123–153
6. Wang LK, Fahey EM, Wu Z (2005) Dissolved air flotation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ, pp 431–500
7. Krofta M, Wang LK (2000) Flotation engineering, 1st edn. Lenox Institute of Water Technology, Lenox, MA, Technical Manual No. Lenox/1–06–2000/368
8. Wang LK (2006) Adsorptive bubble separation and dispersed air flotation. In: Wang LK, Hung YT, Shammas NK (eds) Advanced physicochemical treatment processes. Humana Press, Totowa, NJ, pp 123–154
9. Krofta M, Wang LK (1999) Flotation and related adsorptive bubble separation processes, Technical Manual No. Lenox 7-25-1999/348, 4th edn. Lenox Institute of Water Technology, Lenox, MA

10. Chen JP, Higgins FB, Chang SY, Hung YT (2005) Mixing. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ, pp 47–102
11. Chen JP, Chang SY, Huang JYC, Baumann ER, Hung YT (2005) Gravity filtration. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ, pp 501–544
12. Shammas NK, Kumar IJ, Chang SY (2005) Sedimentation. In: Wang LK, Hung YT, Shammas NK (eds) Physicochemical treatment processes. Humana Press, Totowa, NJ, pp 379–430
13. Wang LK, Wang MHS (1995) Laboratory simulation of water and wastewater treatment processes. Water Treat 10(33):261–282
14. Edzwald JK (1992) Dissolved air flotation: laboratory and pilot plant investigations. AWWA Research Foundation and American Water Works Association (AWWA), Denver, CO, p 108
15. AEESP (2010) Environmental engineering processes laboratory manual, Association of Environmental Engineering and Science Professors, available on a CD from AEESP, http://www.aeesp.org/publications/publications.htm, January
16. FL Smidth Minerals (2010) Flotation concentration testing. http://www.flsmidthminerals.com/Parts-Service/Test+Centers/Flotation+Concentration+Testing/Flotation+Concentration+Testing.htm
17. WPCF (1980). Sludge thickening. Water Pollution Control Federation, Washington DC. Manual #FD-1, 163 pp
18. Krofta M, Wang LK (1982) Potable water treatment by dissolved air flotation and filtration. Journal Am Water Works Assoc 74:304–310
19. Wang MHS (1972) Separation of lignin from aqueous solution by adsorptive bubble separation processes. Ph.D. thesis. Rutgers University, New Brunswick, NJ, 241 pp
20. Krofta M, Wang LK, Wang MHS (1985) Laboratory Simulation and Optimization of physical-chemical treatment processes. US Dept. Commerece, National Technical Information Service, Springfield, VA. Tech Report NTIS-PB86-188794/AS. 42 pages, Jan. 1985
21. APHA, WEF and AWWA (2005) Standard methods for the examination of water and wastewater. Eaton AD, Clesceri LS, Rice EW, Greenberg AE (eds) 21st edn. American Public Health Association, Washington, DC
22. GLUMRB-SPPHEM (2007) Recommended standards for water works. Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers. Health Research Inc., Albany, NY
23. GLUMRB-SPPHEM (2004) Recommended standards for wastewater facilities. Great Lakes-Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers. Health Research Inc., Albany, NY

Appendix: Conversion Factors for Environmental Engineers

Lawrence K. Wang

CONTENTS

Abstract With the current trend toward metrication, the question of using a consistent system of units has been a problem. Wherever possible, the authors of this *Handbook of Environmental Engineering* series have used the British system (fps) along with the metric equivalent (mks, cgs, or SIU) or vice versa. For the convenience of the readers around the world, this book provides a detailed Conversion Factors for Environmental Engineers. In addition, the basic and supplementary units, the derived units and quantities, important physical constants, the properties of water, and the Periodic Table of the elements, are also presented in this document.

Keywords Conversion factors • British units • metric units • physical constants • water properties • periodic table of the elements • environmental engineers • Lenox Institute of Water Technology • mks (meter-kilogram-second) • cgs (centimeter-gram-second) • SIU (Système international d'unités; International System of Units) • fps (foot-pound-second).

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1. CONSTANTS AND CONVERSION FACTORS

Multiply	*by*	*to obtain*
abamperes	10	amperes
abamperes	2.99796×10^{10}	statamperes
abampere-turns	12.566	gilberts
abcoulombs	10	coulombs (abs)
abcoulombs	2.99796×10^{10}	statcoulombs
abcoulombs/kg	30,577	statcoulombs/dyne
abfarads	1×10^{9}	farads (abs)
abfarads	8.98776×10^{20}	statfarads
abhenries	1×10^{-9}	henries (abs)
abhenries	1.11263×10^{-21}	stathenries
abohms	1×10^{-9}	ohms (abs)
abohms	1.11263×10^{-21}	statohms
abvolts	3.33560×10^{-11}	statvolts
abvolts	1×10^{-8}	volts (abs)
abvolts/centimeters	2.540005×10^{-8}	volts (abs)/inch
acres	0.4046	ha
acres	43,560	square feet
acres	4047	square meters
acres	1.562×10^{-3}	square miles
acres	4840	square yards
acre-feet	43,560	cubic feet
acre-feet	1233.5	cubic meters
acre-feet	325,850	gallons (U.S.)
amperes (abs)	0.1	abamperes
amperes (abs)	1.036×10^{-5}	faradays/second
amperes (abs)	2.9980×10^{9}	statamperes
ampere-hours (abs)	3600	coulombs (abs)
ampere-hours	0.03731	faradays
amperes/sq cm	6.452	amps/sq in
amperes/sq cm	10^{4}	amps/sq meter
amperes/sq in	0.1550	amps/sq cm
amperes/sq in	1550.0	amps/sq meter
amperes/sq meter	10^{-4}	amps/sq cm
amperes/sq meter	6.452×10^{-4}	amps/sq in
ampere-turns	1.257	gilberts
ampere-turns/cm	2.540	amp-turns/in
ampere-turns/cm	100.0	amp-turns/meter
ampere-turns/cm	1.257	gilberts/cm
ampere-turns/in	0.3937	amp-turns/cm
ampere-turns/in	39.37	amp-turns/meter
ampere-turns/in	0.4950	gilberts/cm

Multiply	*by*	*to obtain*
ampere-turns/meter	0.01	amp-turns/cm
ampere-turns/meter	0.0254	amp-turns/in
ampere-turns/meter	0.01257	gilberts/cm
angstrom units	1×10^{-8}	centimeters
angstrom units	3.937×10^{-9}	inches
angstrom unit	1×10^{-10}	meter
angstrom unit	1×10^{-4}	micron or μm
ares	0.02471	acre (U.S.)
ares	1076	square feet
ares	100	square meters
ares	119.60	sq yards
assay tons	29.17	grams
astronomical unit	1.495×10^{8}	kilometers
atmospheres (atm)	0.007348	tons/sq inch
atmospheres	76.0	cms of mercury
atmospheres	101.325	kN/m^2 (or kPa)
atmospheres	1.013	bar
atmospheres	1.01325×10^{6}	dynes/square centimeter
atmospheres	33.90	ft of water (at 4°C)
atmospheres	29.92	inches of mercury (at 0°C)
atmospheres	1.033228	kg/sq cm
atmospheres	10,332	kg/sq meter
atmospheres	760.0	millimeters of mercury
atmospheres	14.696	pounds/square inch
atmospheres	1.058	tons/sq foot
avograms	1.66036×10^{-24}	grams
bags, cement	94	pounds of cement
bar (pressure)	10^{5}	Newton/m^2
bar (pressure)	14.504	lb/sq in
bar (pressure)	100.657	kPa
barleycorns (British)	1/3	inches
barleycorns (British)	8.467×10^{-3}	meters
barrels (British, dry)	5.780	cubic feet
barrels (British, dry)	0.1637	cubic meters
barrels (British, dry)	36	gallons (British)
barrels, cement	170.6	kilograms
barrels, cement	376	pounds of cement
barrels, cranberry	3.371	cubic feet
barrels, cranberry	0.09547	cubic meters
barrels, oil	5.615	cubic feet
barrels, oil	0.1590	cubic meters
barrels, oil	42	gallons (U.S.)
barrels, (U.S., dry)	4.083	cubic feet
barrels (U.S., dry)	7056	cubic inches

Multiply	*by*	*to obtain*
barrels (U.S., dry)	0.11562	cubic meters
barrels (U.S., dry)	105.0	quarts (dry)
barrels (U.S., liquid)	4.211	cubic feet
barrels (U.S., liquid)	0.1192	cubic meters
barrels (U.S., liquid)	31.5	gallons (U.S.)
bars	0.98692	atmospheres
bars	10^6	dynes/sq cm
bars	1.0197×10^4	kg/sq meter
bars	1000	millibar
bars	750.06	mm of Hg (0°C)
bars	2089	pounds/sq ft
bars	14.504	pounds/sq in
barye	1.000	dynes/sq cm
board feet	1/12	cubic feet
board feet	144 sq.in. × 1 in.	cubic inches
boiler horsepower	33,475	BTU (mean)/hour
boiler horsepower	34.5	pounds of water evaporated from and at 212°F (per hour)
bolts (U.S., cloth)	120	linear feet
bolts (U.S., cloth)	36.576	meters
bougie decimales	1	candles (int)
BTU (mean)	251.98	calories, gram (g. cal)
BTU (mean)	0.55556	centigrade heat units (chu)
BTU (mean)	1.0548×10^{10}	ergs
BTU (mean)	777.98	foot-pounds
BTU (mean)	3.931×10^{-4}	horsepower-hrs (hp-hr)
BTU (mean)	1055	joules (abs)
BTU (mean)	0.25198	kilograms, cal (kg cal)
BTU (mean)	107.565	kilogram-meters
BTU (mean)	2.928×10^{-4}	kilowatt-hr (Kwh)
BTU (mean)	10.409	liter-atm
BTU (mean)	6.876×10^{-5}	pounds of carbon to CO_2
BTU (mean)	0.29305	watt-hours
BTU (mean)/cu ft	37.30	joule/liter
BTU/hour	0.2162	foot-pound/sec
BTU/hour	0.0700	gram-cal/sec
BTU/hour	3.929×10^{-4}	horsepower-hours (hp-hr)
BTU/hour	0.2930711	watt (w)
BTU/hour (feet)°F	1.730735	joule/sec (m)°k
BTU/hour (feet^2)	3.15459	joule/m^2-sec
BTU (mean)/hour(feet^2)°F	1.3562×10^{-4}	gram-calorie/second (cm^2)°C
BTU (mean)/hour(feet^2)°F	3.94×10^{-4}	horsepower/(ft^2)°F
BTU (mean)/hour(feet^2)°F	5.678264	joule/sec (m^2)°k
BTU (mean)/hour(feet^2)°F	4.882	kilogram-calorie/hr (m^2)°C

Multiply	*by*	*to obtain*
BTU (mean)/hour(feet^2)°F	5.682×10^{-4}	watts/(cm^2)°C
BTU (mean)/hour(feet^2)°F	2.035×10^{-3}	watts/(in^2)°C
BTU (mean)/(hour)(feet^2)(°F/inch)	3.4448×10^{-4}	calories, gram (15°C)/ sec (cm^2) (°C/cm)
BTU (mean)/(hour)(feet^2)(°F/in.)	1	chu/(hr)(ft^2)(°C/in)
BTU (mean)/(hour)(feet^2)(°F/inch)	1.442×10^{-3}	joules (abs)/(sec)(cm^2) (°C/cm)
BTU (mean)/(hour)(feet^2)(°F/inch)	1.442×10^{-3}	watts/(cm^2) (°C/cm)
BTU/min	12.96	ft lb/sec
BTU/min	0.02356	hp
BTU/min	0.01757	kw
BTU/min	17.57	watts
BTU/min/ft^2	0.1221	watts/sq inch
BTU/pound	0.5556	calories-gram(mean)/gram
BTU/pound	0.555	kg-cal/kg
BTU/pound/°F	1	calories, gram/gram/°C
BTU/pound/°F	4186.8	joule/kg/°k
BTU/second	1054.350	watt (W)
buckets (British, dry)	1.818×10^4	cubic cm
buckets (British, dry)	4	gallons (British)
bushels (British)	1.03205	bushels (U.S.)
bushels (British)	1.2843	cubic feet
bushels (British)	0.03637	cubic meters
bushels (U.S.)	1.2444	cubic feet
bushels (U.S.)	2150.4	cubic inch
bushels (U.S.)	0.035239	cubic meters
bushels (U.S.)	35.24	liters (L)
bushels (U.S.)	4	pecks (U.S.)
bushels (U.S.)	64	pints (dry)
bushels (U.S.)	32	quarts (dry)
butts (British)	20.2285	cubic feet
butts (British)	126	gallons (British)
cable lengths	720	feet
cable lengths	219.46	meters
calories (thermochemical)	0.999346	calories (Int. Steam Tables)
calories, gram (g. cal or simply cal.)	3.9685×10^{-3}	BTU (mean)
calories, gram (mean)	0.001459	cubic feet atmospheres
calories, gram (mean)	4.186×10^7	ergs
calories, gram (mean)	3.0874	foot-pounds
calories, gram (mean)	4.186	joules (abs)
calories, gram (mean)	0.001	kg cal (calories, kilogram)
calories, gram (mean)	0.42685	kilograms-meters
calories, gram (mean)	0.0011628	watt-hours
calories, gram (mean)/gram	1.8	BTU (mean)/pound
cal/gram-°C	4186.8	joule/kg-°k

Multiply	*by*	*to obtain*
candle power (spherical)	12.566	lumens
candles (int)	0.104	carcel units
candles (int)	1.11	hefner units
candles (int)	1	lumens (int)/steradian
candles (int)/square centimeter	2919	foot-lamberts
candles (int)/square centimeter	3.1416	lamberts
candles (int)/square foot	3.1416	foot-lamberts
candles (int)/square foot	3.382×10^{-3}	lamberts
candles (int)/square inch	452.4	foot-lamberts
candles (int)/square inch	0.4870	lamberts
candles (int)/square inch	0.155	stilb
carats (metric)	3.0865	grains
carats (metric)	0.2	grams
centals	100	pounds
centares (centiares)	1.0	sq meters
centigrade heat units (chu)	1.8	BTU
centigrade heat units (chu)	453.6	calories, gram (15°C)
centigrade heat units (chu)	1897.8	joules (abs)
centigrams	0.01	grams
centiliters	0.01	liters
centimeters	0.0328083	feet (U.S.)
centimeters	0.3937	inches (U.S.)
centimeters	0.01	meters
centimeters	6.214×10^{-6}	miles
centimeters	10	millimeters
centimeters	393.7	mils
centimeters	0.01094	yards
cm of mercury	0.01316	atm
cm of mercury	0.4461	ft of water
cm of mercury	136.0	kg/square meter
cm of mercury	1333.22	newton/meter^2 (N/m^2)
cm of mercury	27.85	psf
cm of mercury	0.1934	psi
cm of water (4°C)	98.0638	newton/meter^2 (N/m^2)
centimeters-dynes	1.020×10^{-3}	centimeter-grams
centimeter-dynes	1.020×10^{-8}	meter-kilograms
centimeter-dynes	7.376×10^{-8}	pound-feet
centimeter-grams	980.7	centimeter-dynes
centimeter-grams	10^{-5}	meter-kilograms
centimeter-grams	7.233×10^{-5}	pound-feet
centimeters/second	1.969	fpm (ft/min)
centimeters/second	0.0328	fps (ft/sec)
centimeters/second	0.036	kilometers/hour
centimeters/second	0.1943	knots

Multiply	*by*	*to obtain*
centimeters/second	0.6	m/min
centimeters/second	0.02237	miles/hour
centimeters/second	3.728×10^{-4}	miles/minute
cms/sec./sec.	0.03281	feet/sec/sec
cms/sec./sec.	0.036	kms/hour/sec
cms/sec./sec.	0.02237	miles/hour/sec
centipoises	3.60	kilograms/meter hour
centipoises	10^{-3}	kilograms/meter second
centipoises	0.001	newton-sec/m^2
centipoises	2.089×10^{-5}	pound force second/square foot
centipoises	2.42	pounds/foot hour
centipoises	6.72×10^{-4}	pounds/foot second
centistoke	1.0×10^{-6}	meter^2/sec
chains (engineers' or Ramden's)	100	feet
chains (engineers' or Ramden's)	30.48	meters
chains (surveyors' or Gunter's)	66	feet
chains (surveyors' or Gunter's)	20.12	meters
chaldrons (British)	32	bushels (British)
chaldrons (U.S.)	36	bushels (U.S.)
cheval-vapours	0.9863	horsepower
cheval-vapours	735.5	watts (abs)
cheval-vapours heures	2.648×10^{6}	joules (abs)
chu/(hr)(ft^2)(°C/in.)	1	BTU/(hr)(ft^2)(°F/in.)
circular inches	0.7854	square inches
circular millimeters	7.854×10^{-7}	square meters
circular mils	5.067×10^{-6}	square centimeters
circular mils	7.854×10^{-7}	square inches
circular mils	0.7854	square mils
circumferences	360	degrees
circumferences	400	grades
circumferences	6.283	radians
cloves	8	pounds
coombs (British)	4	bushels (British)
cords	8	cord feet
cords	$8' \times 4' \times 4'$	cubic feet
cords	128	cubic feet
cords	3.625	cubic meters
cord-feet	$4' \times 4' \times 1'$	cubic feet
coulombs (abs)	0.1	abcoulombs
coulombs (abs)	6.281×10^{18}	electronic charges
coulombs (abs)	2.998×10^{9}	statcoulombs
coulombs (abs)	1.036×10^{-5}	faradays
coulombs/sq cm	64.52	coulombs/sq in
coulombs/sq cm	10^{4}	coulombs/sq meter

Multiply	*by*	*to obtain*
coulombs/sq in	0.1550	coulombs/sq cm
coulombs/sq in	1550	coulombs/sq meter
coulombs/sq meter	10^{-4}	coulombs/sq cm
coulombs/sq meter	6.452×10^{-4}	coulombs/sq in
cubic centimeters	3.531445×10^{-5}	cubic feet (U.S.)
cubic centimeters	6.102×10^{-2}	cubic inches
cubic centimeters	10^{-6}	cubic meters
cubic centimeters	1.308×10^{-6}	cubic yards
cubic centimeters	2.6417×10^{-4}	gallons (U.S.)
cubic centimeters	0.001	liters
cubic centimeters	0.033814	ounces (U.S., fluid)
cubic centimeters	2.113×10^{-3}	pints (liq.)
cubic centimeters	1.057×10^{-3}	quarts (liq.)
cubic feet (British)	0.9999916	cubic feet (U.S.)
cubic feet (U.S.)	0.8036	bushels (dry)
cubic feet (U.S.)	28317.016	cubic centimeters
cubic feet (U.S.)	1728	cubic inches
cubic feet (U.S.)	0.02832	cubic meters
cubic feet (U.S.)	0.0370	cubic yard
cubic feet (U.S.)	7.48052	gallons (U.S.)
cubic feet (U.S.)	28.31625	liters
cubic feet (U.S.)	59.84	pints (liq.)
cubic feet (U.S.)	29.92	quarts (liq.)
cubic feet of common brick	120	pounds
cubic feet of water (60°F)	62.37	pounds
cubic foot-atmospheres	2.7203	BTU (mean)
cubic foot-atmospheres	680.74	calories, gram (mean)
cubic foot-atmospheres	2116	foot-pounds
cubic foot-atmospheres	2869	joules (abs)
cubic foot-atmospheres	292.6	kilogram-meters
cubic foot-atmospheres	7.968×10^{-4}	kilowatt-hours
cubic feet/hr	0.02832	m^3/hr
cubic feet/minute	472.0	cubic cm/sec
cubic feet/minute	1.6992	cu m/hr
cubic feet/minute	0.0283	cu m/min
cubic feet/minute	0.1247	gallons/sec
cubic feet/minute	0.472	liter/sec
cubic feet/minute	62.4	lbs of water/min
cubic feet/min/1000 cu ft	0.01667	liter/sec/cu m
cubic feet/second	1.9834	acre-feet/day
cubic feet/second	1.7	cu m/min
cubic feet/second	0.02832	m^3/sec
cubic feet/second	448.83	gallons/minute
cubic feet/second	1699	liter/min

Multiply	*by*	*to obtain*
cubic feet/second	28.32	liters/sec
cubic feet/second (cfs)	0.64632	million gallons/day (MGD)
cfs/acre	0.07	m^3/sec-ha
cfs/acre	4.2	cu m/min/ha
cfs/sq mile	0.657	cu m/min/sq km
cubic inches (U.S.)	16.387162	cubic centimeters
cubic inches (U.S.)	5.787×10^{-4}	cubic feet
cubic inches (U.S.)	1.0000084	cubic inches (British)
cubic inches (U.S.)	1.639×10^{-5}	cubic meters
cubic inches (U.S.)	2.143×10^{-5}	cubic yards
cubic inches (U.S.)	4.329×10^{-3}	gallons (U.S.)
cubic inches (U.S.)	1.639×10^{-2}	liters
cubic inches (U.S.)	16.39	mL
cubic inches (U.S.)	0.55411	ounces (U.S., fluid)
cubic inches (U.S.)	0.03463	pints (liq.)
cubic inches (U.S.)	0.01732	quarts (liq.)
cubic meters	8.1074×10^{-4}	acre-feet
cubic meters	8.387	barrels (U.S., liquid)
cubic meters	28.38	bushels (dry)
cubic meters	10^6	cubic centimeters
cubic meters	35.314	cubic feet (U.S.)
cubic meters	61,023	cubic inches (U.S.)
cubic meters	1.308	cubic yards (U.S.)
cubic meters	264.17	gallons (U.S.)
cubic meters	1000	liters
cubic meters	2113	pints (liq.)
cubic meters (m^3)	1057	quarts (liq.)
cubic meters/day	0.183	gallons/min
cubic meters/ha	106.9	gallons/acre
cubic meters/hour	0.2272	gallons/minute
cubic meters/meter-day	80.53	gpd/ft
cubic meters/minute	35.314	cubic ft/minute
cubic meters/second	35.314	cubic ft/sec
cubic meters/second	22.82	MGD
cubic meters/sec-ha	14.29	cu ft/sec-acre
cubic meters/meters^2-day	24.54	gpd/ft^2
cubic yards (British)	0.9999916	cubic yards (U.S.)
cubic yards (British)	0.76455	cubic meters
cubic yards (U.S.)	7.646×10^5	cubic centimeters
cubic yards (U.S.)	27	cubic feet (U.S.)
cubic yards (U.S.)	46,656	cubic inches
cubic yards (U.S.)	0.76456	cubic meters
cubic yards (U.S.)	202.0	gallons (U.S.)
cubic yards (U.S.)	764.6	liters

Multiply	*by*	*to obtain*
cubic yards (U.S.)	1616	pints (liq.)
cubic yards (U.S.)	807.9	quarts (liq.)
cubic yards of sand	2700	pounds
cubic yards/minute	0.45	cubic feet/second
cubic yards/minute	3.367	gallons/second
cubic yards/minute	12.74	liters/second
cubits	45.720	centimeters
cubits	1.5	feet
dalton	1.65×10^{-24}	gram
days	1440	minutes
days	86,400	seconds
days (sidereal)	86164	seconds (mean solar)
debye units (dipole moment)	10^{18}	electrostatic units
decigrams	0.1	grams
deciliters	0.1	liters
decimeters	0.1	meters
degrees (angle)	60	minutes
degrees (angle)	0.01111	quadrants
degrees (angle)	0.01745	radians
degrees (angle)	3600	seconds
degrees/second	0.01745	radians/seconds
degrees/second	0.1667	revolutions/min
degrees/second	0.002778	revoltuions/sec
degree Celsius	$°F = (°C \times 9/5) + 32$	Fahrenheit
degree Celsius	$°K = °C + 273.15$	Kelvin
degree Fahrenheit	$°C = (°F - 32) \times 5/9$	Celsius
degree Fahrenheit	$°K = (°F + 459.67)/1.8$	Kelvin
degree Rankine	$°K = °R/1.8$	Kelvin
dekagrams	10	grams
dekaliters	10	liters
dekameters	10	meters
drachms (British, fluid)	3.5516×10^{-6}	cubic meters
drachms (British, fluid)	0.125	ounces (British, fluid)
drams (apothecaries' or troy)	0.1371429	ounces (avoirdupois)
drams (apothecaries' or troy)	0.125	ounces (troy)
drams (U.S., fluid or apoth.)	3.6967	cubic cm
drams (avoirdupois)	1.771845	grams
drams (avoirdupois)	27.3437	grains
drams (avoirdupois)	0.0625	ounces
drams (avoirdupois)	0.00390625	pounds (avoirdupois)
drams (troy)	2.1943	drams (avoirdupois)
drams (troy)	60	grains

Multiply	*by*	*to obtain*
drams (troy)	3.8879351	grams
drams (troy)	0.125	ounces (troy)
drams (U.S., fluid)	3.6967×10^{-6}	cubic meters
drams (U.S., fluid)	0.125	ounces (fluid)
dynes	0.00101972	grams
dynes	10^{-7}	joules/cm
dynes	10^{-5}	joules/meter (newtons)
dynes	1.020×10^{-6}	kilograms
dynes	1×10^{-5}	newton (N)
dynes	7.233×10^{-5}	poundals
dynes	2.24809×10^{-6}	pounds
dyne-centimeters (torque)	7.3756×10^{-8}	pound-feet
dynes/centimeter	1	ergs/square centimeter
dynes/centimeter	0.01	ergs/square millimeter
dynes/square centimeter	9.8692×10^{-7}	atmospheres
dynes/square centimeter	10^{-6}	bars
dynes/square centimeter	2.953×10^{-5}	inch of mercury at 0°C
dynes/square centimeter	4.015×10^{-4}	inch of water at 4°C
dynes/square centimeter	0.01020	kilograms/square meter
dynes/square centimeter	0.1	newtons/square meter
dynes/square centimeter	1.450×10^{-5}	pounds/square inch
electromagnetic fps units of magnetic permeability	0.0010764	electromagnetic cgs units of magnetic permeability
electromagnetic fps units of magnetic permeability	1.03382×10^{-18}	electrostatic cgs units of magnetic permeability
electromagnetic cgs units, of magnetic permeability	1.1128×10^{-21}	electrostatic cgs units of magnetic permeability
electromagnetic cgs units of mass resistance	9.9948×10^{-6}	ohms (int)-meter-gram
electronic charges	1.5921×10^{-19}	coulombs (abs)
electron-volts	1.6020×10^{-12}	ergs
electron-volts	1.0737×10^{-9}	mass units
electron-volts	0.07386	rydberg units of energy
electronstatic cgs units of Hall effect	2.6962×10^{31}	electromagnetic cgs units of Hall effect
electrostatic fps units of charge	1.1952×10^{-6}	coulombs (abs)
electrostatic fps units of magnetic permeability	929.03	electrostatic cgs units of magnetic permeability
ells	114.30	centimeters
ells	45	inches
ems, pica (printing)	0.42333	centimeters
ems, pica (printing)	1/6	inches
ergs	9.4805×10^{-11}	BTU (mean)

Multiply	*by*	*to obtain*
ergs	2.3889×10^{-8}	calories, gram (mean)
ergs	1	dyne-centimeters
ergs	7.3756×10^{-8}	foot-pounds
ergs	0.2389×10^{-7}	gram-calories
ergs	1.020×10^{-3}	gram-centimeters
ergs	3.7250×10^{-14}	horsepower-hrs
ergs	10^{-7}	joules (abs)
ergs	2.390×10^{-11}	kilogram-calories (kg cal)
ergs	1.01972×10^{-8}	kilogram-meters
ergs	0.2778×10^{-13}	kilowatt-hrs
ergs	0.2778×10^{-10}	watt-hours
ergs/second	5.692×10^{-9}	BTU/min
ergs/second	4.426×10^{-6}	foot-pounds/min
ergs/second	7.376×10^{-8}	foot-pounds/sec
ergs/second	1.341×10^{-10}	horsepower
ergs/second	1.434×10^{-9}	kg-calories/min
ergs/second	10^{-10}	kilowatts
farad (international of 1948)	0.9995	farad (F)
faradays	26.80	ampere-hours
faradays	96,500	coulombs (abs)
faradays/second	96,500	amperes (abs)
farads (abs)	10^{-9}	abfarads
farads (abs)	10^{6}	microfarads
farads (abs)	8.9877×10^{11}	statfarads
fathoms	6	feet
fathom	1.829	meter
feet (U.S.)	1.0000028	feet (British)
feet (U.S.)	30.4801	centimeters
feet (U.S.)	12	inches
feet (U.S.)	3.048×10^{-4}	kilometers
feet (U.S.)	0.30480	meters
feet (U.S.)	1.645×10^{-4}	miles (naut.)
feet (U.S.)	1.893939×10^{-4}	miles (statute)
feet (U.S.)	304.8	millimeters
feet (U.S.)	1.2×10^{4}	mils
feet (U.S.)	1/3	yards
feet of air (1 atmosphere, 60°F)	5.30×10^{-4}	pounds/square inch
feet of water	0.02950	atm
feet of water	0.8826	inches of mercury
feet of water at 39.2°F	0.030479	kilograms/square centimeter
feet of water at 39.2°F	2988.98	newton/meter^2 (N/m^2)
feet of water at 39.2°F	304.79	kilograms/square meter
feet of water	62.43	pounds/square feet (psf)
feet of water at 39.2°F	0.43352	pounds/square inch (psi)

Multiply	*by*	*to obtain*
feet/hour	0.08467	mm/sec
feet/min	0.5080	cms/sec
feet/min	0.01667	feet/sec
feet/min	0.01829	km/hr
feet/min	0.3048	meters/min
feet/min	0.01136	miles/hr
feet/sec	30.48	cm/sec
feet/sec	1.097	km/hr
feet/sec	0.5921	knots
feet/sec	18.29	meters/min
feet/sec	0.6818	miles/hr
feet/sec	0.01136	miles/min
feet/sec/sec	30.48	cm/sec/sec
feet/sec/sec	1.097	km/hr/sec
feet/sec/sec	0.3048	meters/sec/sec
feet/sec/sec	0.6818	miles/hr/sec
feet/100 feet	1.0	percent grade
firkins (British)	9	gallons (British)
firkins (U.S.)	9	gallons (U.S.)
foot-candle (ft-c)	10.764	lumen/sq m
foot-poundals	3.9951×10^{-5}	BTU (mean)
foot-poundals	0.0421420	joules (abs)
foot-pounds	0.0012854	BTU (mean)
foot-pounds	0.32389	calories, gram (mean)
foot-pounds	1.13558×10^{7}	ergs
foot-pounds	32.174	foot-poundals
foot-pounds	5.050×10^{-7}	hp-hr
foot-pounds	1.35582	joules (abs)
foot-pounds	3.241×10^{-4}	kilogram-calories
foot-pounds	0.138255	kilogram-meters
foot-pounds	3.766×10^{-7}	kwh
foot-pounds	0.013381	liter-atmospheres
foot-pounds	3.7662×10^{-4}	watt-hours (abs)
foot-pounds/minute	1.286×10^{-3}	BTU/minute
foot-pounds/minute	0.01667	foot-pounds/sec
foot-pounds/minute	3.030×10^{-5}	hp
foot-pounds/minute	3.241×10^{-4}	kg-calories/min
foot-pounds/minute	2.260×10^{-5}	kw
foot-pounds/second	4.6275	BTU (mean)/hour
foot-pounds/second	0.07717	BTU/minute
foot-pounds/second	0.0018182	horsepower
foot-pounds/second	0.01945	kg-calories/min
foot-pounds/second	0.001356	kilowatts
foot-pounds/second	1.35582	watts (abs)

Multiply	*by*	*to obtain*
furlongs	660.0	feet
furlongs	201.17	meters
furlongs	0.125	miles (U.S.)
furlongs	40.0	rods
gallons (Br.)	3.8125×10^{-2}	barrels (U.S.)
gallons (Br.)	4516.086	cubic centimeters
gallons (Br.)	0.16053	cu ft
gallons (Br.)	277.4	cu inches
gallons (Br.)	1230	drams (U.S. fluid)
gallons (Br.)	4.54596	liters
gallons (Br.)	7.9620×10^{4}	minims (Br.)
gallons (Br.)	7.3783×10^{4}	minims (U.S.)
gallons (Br.)	4545.96	mL
gallons (Br.)	1.20094	gallons (U.S.)
gallons (Br.)	160	ounces (Br., fl.)
gallons (Br.)	153.72	ounces (U.S., fl.)
gallons (Br.)	10	pounds (avoirdupois) of water at 62°F
gallons (U.S.)	3.068×10^{-4}	acre-ft
gallons (U.S.)	0.031746	barrels (U.S.)
gallons (U.S.)	3785.434	cubic centimeters
gallons (U.S.)	0.13368	cubic feet (U.S.)
gallons (U.S.)	231	cubic inches
gallons (U.S.)	3.785×10^{-3}	cubic meters
gallons (U.S.)	4.951×10^{-3}	cubic yards
gallons (U.S.)	1024	drams (U.S., fluid)
gallons (U.S.)	0.83268	gallons (Br.)
gallons (U.S.)	0.83267	imperial gal
gallons (U.S.)	3.78533	liters
gallons (U.S.)	6.3950×10^{4}	minims (Br.)
gallons (U.S.)	6.1440×10^{4}	minims (U.S.)
gallons (U.S.)	3785	mL
gallons (U.S.)	133.23	ounces (Br., fluid)
gallons (U.S.)	128	ounces (U.S., fluid)
gallons	8	pints (liq.)
gallons	4	quarts (liq.)
gal water (U.S.)	8.345	lb of water
gallons/acre	0.00935	cu m/ha
gallons/day	4.381×10^{-5}	liters/sec
gallons/ton	4.1721	liter/metric ton (L/T)
gpd/acre	0.00935	cu m/day/ha
gpd/acre	9.353	liter/day/ha
gallons/capita/day	3.785	liters/capita/day
gpd/cu yd	5.0	L/day/cu m

Multiply	*by*	*to obtain*
gpd/ft	0.01242	cu m/day/m
gpd/sq ft	0.0408	cu m/day/sq m
gpd/sq ft	1.698×10^{-5}	cubic meters/hour/sq meter
gpd/sq ft	0.283	cu meter/minute/ha
gpm (gal/min)	8.0208	cfh (cu ft/hr)
gpm	2.228×10^{-3}	cfs (cu ft/sec)
gpm	4.4021	cubic meters/hr
gpm	0.00144	MGD
gpm	0.0631	liters/sec
gpm/sq ft	2.445	cu meters/hour/sq meter
gpm/sq ft	40.7	L/min/sq meter
gpm/sq ft	0.679	liter/sec/sq meter
gallons/sq ft	40.743	liters/sq meter
gausses (abs)	3.3358×10^{-4}	electrostatic cgs units of magnetic flux density
gausses (abs)	0.99966	gausses (int)
gausses (abs)	1	lines/square centimeter
gausses (abs)	6.452	lines/sq in
gausses (abs)	1	maxwells (abs)/square centimeters
gausses (abs)	6.4516	maxwells (abs)/square inch
gausses (abs)	10^{-8}	webers/sq cm
gausses (abs)	6.452×10^{-8}	webers/sq in
gausses (abs)	10^{-4}	webers/sq meter
gilberts (abs)	0.07958	abampere turns
gilberts (abs)	0.7958	ampere turns
gilberts (abs)	2.998×10^{10}	electrostatic cgs units of magneto motive force
gilberts/cm	0.7958	amp-turns/cm
gilberts/cm	2.021	amp-turns/in
gilberts/cm	79.58	amp-turns/meter
gills (Br.)	142.07	cubic cm
gills (Br.)	5	ounces (British, fluid)
gills (U.S.)	32	drams (fluid)
gills	0.1183	liters
gills	0.25	pints (liq.)
grade	0.01571	radian
grains	0.036571	drams (avoirdupois)
grains	0.01667	drams (troy)
grains (troy)	1.216	grains (avdp)
grains (troy)	0.06480	grams
grains (troy)	6.480×10^{-5}	kilograms
grains (troy)	64.799	milligrams
grains (troy)	2.286×10^{-3}	ounces (avdp)
grains (troy)	2.0833×10^{-3}	ounces (troy)

Multiply	*by*	*to obtain*
grains (troy)	0.04167	pennyweights (troy)
grains	1/7000	pounds (avoirdupois)
grains	1.736×10^{-4}	pounds (troy)
grains	6.377×10^{-8}	tons (long)
grains	7.142×10^{-8}	tons (short)
grains/imp gal	14.254	mg/L
grains/imp. gal	14.254	parts/million (ppm)
grains/U.S. gal	17.118	mg/L
grains/U.S. gal	17.118	parts/million (ppm)
grains/U.S. gal	142.86	lb/mil gal
grams	0.5611	drams (avdp)
grams	0.25721	drams (troy)
grams	980.7	dynes
grams	15.43	grains
grams	9.807×10^{-5}	joules/cm
grams	9.807×10^{-3}	joules/meter (newtons)
grams	10^{-3}	kilograms
grams	10^{3}	milligrams
grams	0.0353	ounces (avdp)
grams	0.03215	ounces (troy)
grams	0.07093	poundals
grams	2.205×10^{-3}	pounds
grams	2.679×10^{-3}	pounds (troy)
grams	9.842×10^{-7}	tons (long)
grams	1.102×10^{-6}	tons (short)
grams-calories	4.1868×10^{7}	ergs
gram-calories	3.0880	foot-pounds
gram-calories	1.5597×10^{-6}	horsepower-hr
gram-calories	1.1630×10^{-6}	kilowatt-hr
gram-calories	1.1630×10^{-3}	watt-hr
gram-calories	3.968×10^{-3}	British Thermal Units (BTU)
gram-calories/sec	14.286	BTU/hr
gram-centimeters	9.2967×10^{-8}	BTU (mean)
gram-centimeters	2.3427×10^{-5}	calories, gram (mean)
gram-centimeters	980.7	ergs
gram-centimeters	7.2330×10^{-5}	foot-pounds
gram-centimeters	9.8067×10^{-5}	joules (abs)
gram-centimeters	2.344×10^{-8}	kilogram-calories
gram-centimeters	10^{-5}	kilogram-meters
gram-centimeters	2.7241×10^{-8}	watt-hours
grams-centimeters^2 (moment of inertia)	2.37305×10^{-6}	pounds-feet^2
grams-centimeters^2 (moment of inertia)	3.4172×10^{-4}	pounds-inch^2
gram-centimeters/second	1.3151×10^{-7}	hp

Multiply	*by*	*to obtain*
gram-centimeters/second	9.8067×10^{-8}	kilowatts
gram-centimeters/second	0.065552	lumens
gram-centimeters/second	9.80665×10^{-5}	watt (abs)
grams/cm	5.600×10^{-3}	pounds/inch
grams/cu cm	62.428	pounds/cubic foot
grams/cu cm	0.03613	pounds/cubic inch
grams/cu cm	8.3454	pounds/gallon (U.S.)
grams/cu cm	3.405×10^{-7}	pounds/mil-foot
grams/cu ft	35.314	grams/cu meter
grams/cu ft	10^{6}	micrograms/cu ft
grams/cu ft	35.314×10^{6}	micrograms/cu meter
grams/cu ft	35.3145×10^{3}	milligrams/cu meter
grams/cu ft	2.2046	pounds/1000 cu ft
grams/cu m	0.43700	grains/cubic foot
grams/cu m	0.02832	grams/cu ft
grams/cu m	28.317×10^{3}	micrograms/cu ft
grams/cu m	0.06243	pounds/cu ft
grams/liter	58.417	grains/gallon (U.S.)
grams/liter	9.99973×10^{-4}	grams/cubic centimeter
grams/liter	1000	mg/L
grams/liter	1000	parts per million (ppm)
grams/liter	0.06243	pounds/cubic foot
grams/liter	8.345	lb/1000 gal
grams/sq centimeter	2.0481	pounds/sq ft
grams/sq centimeter	0.0142234	pounds/square inch
grams/sq ft	10.764	grams/sq meter
grams/sq ft	10.764×10^{3}	kilograms/sq km
grams/sq ft	1.0764	milligrams/sq cm
grams/sq ft	10.764×10^{3}	milligrams/sq meter
grams/sq ft	96.154	pounds/acre
grams/sq ft	2.204	pounds/1000 sq ft
grams/sq ft	30.73	tons/sq mile
grams/sq meter	0.0929	grams/sq ft
grams/sq meter	1000	kilograms/sq km
grams/sq meter	0.1	milligrams/square cm
grams/sq meter	1000	milligrams/sq meter
grams/sq meter	8.921	pounds/acre
grams/sq meter	0.2048	pounds/1000 sq ft
grams/sq meter	2.855	tons/sq mile
g (gravity)	9.80665	meters/sec^2
g (gravity)	32.174	ft/sec^2
hand	10.16	cm
hands	4	inches
hectare (ha)	2.471	acre

Multiply	*by*	*to obtain*
hectares	1.076×10^5	sq feet
hectograms	100	grams
hectoliters	100	liters
hectometers	100	meters
hectowatts	100	watts
hemispheres	0.5	spheres
hemispheres	4	spherical right angles
hemispheres	6.2832	steradians
henries (abs)	10^9	abhenries
henries	1000.0	millihenries
henries (abs)	1.1126×10^{-12}	stathenries
hogsheads (British)	63	gallons (British)
hogsheads (British)	10.114	cubic feet
hogsheads (U.S.)	8.422	cubic feet
hogsheads (U.S.)	0.2385	cubic meters
hogsheads (U.S.)	63	gallons (U.S.)
horsepower	2545.08	BTU (mean)/hour
horsepower	42.44	BTU/min
horsepower	7.457×10^9	erg/sec
horsepower	33,000	ft lb/min
horsepower	550	foot-pounds/second
horsepower	7.6042×10^6	g cm/sec
horsepower, electrical	1.0004	horsepower
horsepower	10.70	kg.-calories/min
horsepower	0.74570	kilowatts (g = 980.665)
horsepower	498129	lumens
horsepower, continental	736	watts (abs)
horsepower, electrical	746	watts (abs)
horsepower (boiler)	9.803	kw
horsepower (boiler)	33.479	BTU/hr
horsepower-hours	2545	BTU (mean)
horsepower-hours	2.6845×10^{13}	ergs
horsepower-hours	6.3705×10^7	ft poundals
horsepower-hours	1.98×10^6	foot-pounds
horsepower-hours	641,190	gram-calories
horsepower-hours	2.684×10^6	joules
horsepower-hours	641.7	kilogram-calories
horsepower-hours	2.737×10^5	kilogram-meters
horsepower-hours	0.7457	kilowatt-hours (abs)
horsepower-hours	26,494	liter atmospheres (normal)
horsepower-hours	745.7	watt-hours
horsepower/1000 ft^3	0.0263	kw/m^3
hours	4.167×10^{-2}	days
hours	60	minutes

Multiply	*by*	*to obtain*
hours	3600	seconds
hours	5.952×10^{-3}	weeks
hundredweights (long)	112	pounds
hundredweights (long)	0.05	tons (long)
hundredweights (short)	1600	ounces (avoirdupois)
hundredweights (short)	100	pounds
hundredweights (short)	0.0453592	tons (metric)
hundredweights (short)	0.0446429	tons (long)
inches (British)	2.540	centimeters
inches (U.S.)	2.54000508	centimeters
inches (British)	0.9999972	inches (U.S.)
inches	2.540×10^{-2}	meters
inches	1.578×10^{-5}	miles
inches	25.40	millimeters
inches	10^{3}	mils
inches	2.778×10^{-2}	yards
inches^2	6.4516×10^{-4}	meter^2
inches^3	1.6387×10^{-5}	meter^3
in. of mercury	0.0334	atm
in. of mercury	1.133	ft of water
in. of mercury (0°C)	13.609	inches of water (60°F)
in. of mercury	0.0345	kgs/square cm
in. of mercury at 32°F	345.31	kilograms/square meter
in. of mercury	33.35	millibars
in. of mercury	25.40	millimeters of mercury
in. of mercury (60°F)	3376.85	newton/meter^2
in. of mercury	70.73	pounds/square ft
in. of mercury at 32°F	0.4912	pounds/square inch
in. of water	0.002458	atmospheres
in. of water	0.0736	in. of mercury
in. of water (at 4°C)	2.540×10^{-3}	kgs/sq cm
in. of water	25.40	kgs/square meter
in. of water (60°F)	1.8663	millimeters of mercury (0°C)
in. of water (60°F)	248.84	newton/meter^2
in. of water	0.5781	ounces/square in
in. of water	5.204	pounds/square ft
in. of water	0.0361	psi
inches/hour	2.54	cm/hr
international ampere	.9998	ampere (absolute)
international volt	1.0003	volts (absolute)
international volt	1.593×10^{-19}	joules (absolute)
international volt	9.654×10^{4}	joules
joules	9.480×10^{-4}	BTU
joules (abs)	10^{7}	ergs

Multiply	*by*	*to obtain*
joules	23.730	foot poundals
joules (abs)	0.73756	foot-pounds
joules	3.7251×10^{-7}	horsepower hours
joules	2.389×10^{-4}	kg-calories
joules (abs)	0.101972	kilogram-meters
joules	9.8689×10^{-3}	liter atmospheres (normal)
joules	2.778×10^{-4}	watt-hrs
joules-sec	1.5258×10^{33}	quanta
joules/cm	1.020×10^{4}	grams
joules/cm	10^{7}	dynes
joules/cm	100.0	joules/meter (newtons)
joules/cm	723.3	poundals
joules/cm	22.48	pounds
joules/liter	0.02681	BTU/cu ft
joules/m^2-sec	0.3167	BTU/ft^2-hr
joules/sec	3.41304	BTU/hr
joules/sec	0.056884	BTU/min
joules/sec	1×10^{7}	erg/sec
joules/sec	44.254	ft lb/min
joules/sec	0.73756	ft lb/sec
joules/sec	1.0197×10^{4}	g cm/sec
joules/sec	1.341×10^{-3}	hp
joules/sec	0.01433	kg cal/min
joules/sec	0.001	kilowatts
joules/sec	668	lumens
joules/sec	1	watts
kilograms	564.38	drams (avdp)
kilograms	257.21	drams (troy)
kilograms	980,665	dynes
kilograms	15,432	grains
kilograms	1000	grams
kilograms	0.09807	joules/cm
kilograms	9.807	joules/meter (newtons)
kilograms	1×10^{6}	milligrams
kilograms	35.274	ounces (avdp)
kilograms	32.151	ounces (troy)
kilograms	70.93	poundals
kilograms	2.20462	pounds (avdp)
kilograms	2.6792	pounds (troy)
kilograms	9.84207×10^{-4}	tons (long)
kilograms	0.001	tons (metric)
kilograms	0.0011023	tons (short)
kilogram-calories	3.968	British Thermal Units (BTU)
kilogram-calories	3086	foot-pounds

Multiply	*by*	*to obtain*
kilogram-calories	1.558×10^{-3}	horsepower-hours
kilogram-calories	4186	joules
kilogram-calories	426.6	kilogram-meters
kilogram-calories	4.186	kilojoules
kilogram-calories	1.162×10^{-3}	kilowatt-hours
kg-cal/min	238.11	BTU/hr
kg-cal/min	3.9685	BTU/min
kg-cal/min	6.9770×10^{8}	erg/sec
kg-cal/min	3087.4	ft-lb/min
kg-cal/min	51.457	ft-lb/sec
kg-cal/min	7.1146×10^{5}	g cm/sec
kg-cal/min	0.0936	hp
kg-cal/min	69.769	joules/sec
kg-cal/min	0.0698	kw
kg-cal/min	46636	lumens
kg-cal/min	69.767	watts
kgs-cms. squared	2.373×10^{-3}	pounds-feet squared
kgs-cms. squared	0.3417	pounds-inches squared
kilogram-force (kgf)	9.80665	newton
kilogram-meters	0.0092967	BTU (mean)
kilogram-meters	2.3427	calories, gram (mean)
kilogram-meters	9.80665×10^{7}	ergs
kilogram-meters	232.71	ft poundals
kilogram-meters	7.2330	foot-pounds
kilogram-meters	3.6529×10^{-6}	horsepower-hours
kilogram-meters	9.80665	joules (abs)
kilogram-meters	2.344×10^{-3}	kilogram-calories
kilogram-meters	2.52407×10^{-6}	kilowatt-hours (abs)
kilogram-meters	2.7241×10^{-6}	kilowatt-hours
kilogram-meters	0.096781	liter atmospheres (normal)
kilogram-meters	6.392×10^{-7}	pounds carbon to CO_2
kilogram-meters	9.579×10^{-6}	pounds water evap. at 212°F
kilograms/cubic meter	10^{-3}	grams/cubic cm
kilograms/cubic meter	0.06243	pounds/cubic foot
kilograms/cubic meter	3.613×10^{-5}	pounds/cubic inch
kilograms/cubic meter	3.405×10^{-10}	pounds/mil. foot
kilograms/m^3-day	0.0624	lb/cu ft-day
kilograms/cu meter-day	62.43	pounds/1000 cu ft-day
kilograms/ha	0.8921	pounds/acre
kilograms/meter	0.6720	pounds/foot
kilograms/sq cm	980,665	dynes
kilograms/sq cm	0.96784	atmosphere
kilograms/sq cm	32.81	feet of water
kilograms/sq cm	28.96	inches of mercury

Multiply	*by*	*to obtain*
kilograms/sq cm	735.56	mm of mercury
kilograms/sq cm	2048	pounds/sq ft
kilograms/sq cm	14.22	pounds/square inch
kilograms/sq km	92.9×10^{-6}	grams/sq ft
kilograms/sq km	0.001	grams/sq meter
kilograms/sq km	0.0001	milligrams/sq cm
kilograms/sq km	1.0	milligrams/sq meter
kilograms/sq km	8.921×10^{-3}	pounds/acre
kilograms/sq km	204.8×10^{-6}	pounds/1000 sq ft
kilograms/sq km	2.855×10^{-3}	tons/sq mile
kilograms/sq meter	9.6784×10^{-5}	atmospheres
kilograms/sq meter	98.07×10^{-6}	bars
kilograms/sq meter	98.0665	dynes/sq centimeters
kilograms/sq meter	3.281×10^{-3}	feet of water at 39.2°F
kilograms/sq meter	0.1	grams/sq centimeters
kilograms/sq meter	2.896×10^{-3}	inches of mercury at 32°F
kilograms/sq meter	0.07356	mm of mercury at 0°C
kilograms/sq meter	0.2048	pounds/square foot
kilograms/sq meter	0.00142234	pounds/square inch
kilograms/sq mm.	10^{6}	kg/square meter
kilojoule	0.947	BTU
kilojoules/kilogram	0.4295	BTU/pound
kilolines	1000.0	maxwells
kiloliters	10^{3}	liters
kilometers	10^{5}	centimeters
kilometers	3281	feet
kilometers	3.937×10^{4}	inches
kilometers	10^{3}	meters
kilometers	0.53961	miles (nautical)
kilometers	0.6214	miles (statute)
kilometers	10^{6}	millimeters
kilometers	1093.6	yards
kilometers/hr	27.78	cm/sec
kilometers/hr	54.68	feet/minute
kilometers/hr	0.9113	ft/sec
kilometers/hr	0.5396	knot
kilometers/hr	16.67	meters/minute
kilometers/hr	0.2778	meters/sec
kilometers/hr	0.6214	miles/hour
kilometers/hour/sec	27.78	cms/sec/sec
kilometers/hour/sec	0.9113	ft/sec/sec
kilometers/hour/sec	0.2778	meters/sec/sec
kilometers/hour/sec	0.6214	miles/hr/sec
kilometers/min	60	kilometers/hour

Multiply	*by*	*to obtain*
kilonewtons/sq m	0.145	psi
kilopascal (kPa)	1	kN/m^2
kilopascal (kPa)	0.2691	in Hg (60°F)
kilopascal (kPa)	0.145	lb/in^2
kilopascal (kPa)	0.0099	atm
kilowatts	56.88	BTU/min
kilowatts	4.425×10^4	foot-pounds/min
kilowatts	737.6	ft-lb/sec
kilowatts	1.341	horsepower
kilowatts	14.34	kg-cal/min
kilowatts	10^3	watts
kilowatt-hrs	3413	BTU (mean)
kilowatt-hrs	3.600×10^{13}	ergs
kilowatt-hrs	2.6552×10^6	foot-pounds
kilowatt-hrs	859,850	gram-calories
kilowatt-hrs	1.341	horsepower hours
kilowatt-hrs	3.6×10^6	joules
kilowatt-hrs	860.5	kg-calories
kilowatt-hrs	3.6709×10^5	kilogram-meters
kilowatt-hrs	3.53	pounds of water evaporated from and at 212°F
kilowatt-hrs	22.75	pounds of water raised from 62° to 212°F
knots	6080	feet/hr
knots	1.689	feet/sec
knots	1.8532	kilometers/hr
knots	0.5144	meters/sec
knots	1.0	miles (nautical)/hour
knots	1.151	miles (statute)/hour
knots	2,027	yards/hr
lambert	2.054	candle/in^2
lambert	929	footlambert
lambert	0.3183	stilb
langley	1	15° gram-calorie/cm^2
langley	3.6855	BTU/ft^2
langley	0.011624	Int. kw-hr/m^2
langley	4.1855	joules (abs)/cm^2
leagues (nautical)	3	miles (nautical)
leagues (statute)	3	miles (statute)
light years	63,274	astronomical units
light years	9.4599×10^{12}	kilometers
light years	5.8781×10^{12}	miles
lignes (Paris lines)	1/12	ponces (Paris inches)
lines/sq cm	1.0	gausses

Multiply	*by*	*to obtain*
lines/sq in	0.1550	gausses
lines/sq in	1.550×10^{-9}	webers/sq cm
lines/sq in	10^{-8}	webers/sq in
lines/sq in	1.550×10^{-5}	webers/sq meter
links (engineer's)	12.0	inches
links (Gunter's)	0.01	chains (Gunter's)
links (Gunter's)	0.66	feet
links (Ramden's)	0.01	chains (Ramden's)
links (Ramden's)	1	feet
links (surveyor's)	7.92	inches
liters	8.387×10^{-3}	barrels (U.S.)
liters	0.02838	bushels (U.S. dry)
liters	1000.028	cubic centimeters
liters	0.035316	cubic feet
liters	61.025	cu inches
liters	10^{-3}	cubic meters
liters	1.308×10^{-3}	cubic yards
liters	270.5179	drams (U.S. fl)
liters	0.21998	gallons (Br.)
liters	0.26417762	gallons (U.S.)
liters	16,894	minims (Br.)
liters	16,231	minims (U.S.)
liters	35.196	ounces (Br. fl)
liters	33.8147	ounces (U.S. fl)
liters	2.113	pints (liq.)
liters	1.0566828	quarts (U.S. liq.)
liter-atmospheres (normal)	0.096064	BTU (mean)
liter-atmospheres (normal)	24.206	calories, gram (mean)
liter-atmospheres (normal)	1.0133×10^{9}	ergs
liter-atmospheres (normal)	74.735	foot-pounds
liter-atmospheres (normal)	3.7745×10^{-5}	horsepower hours
liter-atmospheres (normal)	101.33	joules (abs)
liter-atmospheres (normal)	10.33	kilogram-meters
liter-atmospheres (normal)	2.4206×10^{-2}	kilogram calories
liter-atmospheres (normal)	2.815×10^{-5}	kilowatt-hours
liter/cu m-sec	60.0	cfm/1000 cu ft
liters/minute	5.885×10^{-4}	cubic feet/sec
liters/minute	4.403×10^{-3}	gallons/sec
liter/person-day	0.264	gpcd
liters/sec	2.119	cu ft/min
liters/sec	3.5316×10^{-2}	cu ft/sec
liters/sec	15.85	gallons/minute
liters/sec	0.02282	MGD
$\log_{10}N$	2.303	$\log_e N$ or ln N
$\log_e N$ or ln N	0.4343	$\log_{10} N$

Multiply	*by*	*to obtain*
lumens	0.07958	candle-power (spherical)
lumens	0.00147	watts of maximum visibility radiation
lumens/sq. centimeters	1	lamberts
lumens/sq cm/steradian	3.1416	lamberts
lumens/sq ft	1	foot-candles
lumens/sq ft	10.764	lumens/sq meter
lumens/sq ft/steradian	3.3816	millilamberts
lumens/sq meter	0.09290	foot-candles or lumens/sq
lumens/sq meter	10^{-4}	phots
lux	0.09290	foot-candles
lux	1	lumens/sq meter
lux	10^{-4}	phots
maxwells	0.001	kilolines
maxwells	10^{-8}	webers
megajoule	0.3725	horsepower-hour
megalines	10^{6}	maxwells
megohms	10^{12}	microhms
megohms	10^{6}	ohms
meters	10^{10}	angstrom units
meters	100	centimeters
meters	0.5467	fathoms
meters	3.280833	feet (U.S.)
meters	39.37	inches
meters	10^{-3}	kilometers
meters	5.396×10^{-4}	miles (naut.)
meters	6.2137×10^{-4}	miles (statute)
meters	10^{3}	millimeters
meters	10^{9}	millimicrons
meters	1.09361	yards (U.S.)
meters	1.179	varas
meter head of water (20°C)	9.79	kN/m^2
meter head of water (20°C)	0.00979	N/mm^2
meter head of water (20°C)	1.42	pound/sq in
meter-candles	1	lumens/sq meter
meter-kilograms	9.807×10^{7}	centimeter-dynes
meter-kilograms	10^{5}	centimeter-grams
meter-kilograms	7.233	pound-feet
meters/minute	1.667	centimeters/sec
meters/minute	3.281	feet/minute
meters/minute	0.05468	feet/second
meters/minute	0.06	kilograms/hour
meters/minute	0.03238	knots
meters/minute	0.03728	miles/hour

Multiply	*by*	*to obtain*
meters/second	196.8	feet/minute
meters/second	3.281	feet/second
meters/second	3.6	kilometers/hour
meters/second	0.06	kilometers/min
meters/second	1.944	knots
meters/second	2.23693	miles/hour
meters/second	0.03728	miles/minute
meters/sec/sec	100.0	cm/sec/sec
meters/sec/sec	3.281	feet/sec/sec
meters/sec/sec	3.6	km/hour/sec
meters/sec/sec	2.237	miles/hour/sec
microfarad	10^{-6}	farads
micrograms	10^{-6}	grams
micrograms/cu ft	10^{-6}	grams/cu ft
micrograms/cu ft	35.314×10^{-6}	grams/cu m
micrograms/cu ft	35.314	microgram/cu m
micrograms/cu ft	35.314×10^{-3}	milligrams/cu m
micrograms/cu ft	2.2046×10^{-6}	pounds/1000 cu ft
micrograms/cu m	28.317×10^{-9}	grams/cu ft
micrograms/cu m	10^{-6}	grams/ cu m
micrograms/cu m	0.02832	micrograms/cu ft
micrograms/cu m	0.001	milligrams/cu m
micrograms/cu m	62.43×10^{-9}	pounds/1000 cu ft
micrograms/cu m	$\frac{0.02404}{\text{molecular weight of gas}}$	ppm by volume (20°C)
micrograms/cu m	834.7×10^{-6}	ppm by weight
micrograms/liter	1000.0	micrograms/cu m
micrograms/liter	1.0	milligrams/cu m
micrograms/liter	62.43×10^{-9}	pounds/cu ft
micrograms/liter	$\frac{24.04}{\text{molecular weight of gas}}$	ppm by volume (20°C)
micrograms/liter	0.834.7	ppm by weight
microhms	10^{-12}	megohms
microhms	10^{-6}	ohms
microliters	10^{-6}	liters
microns	10^{4}	angstrom units
microns	1×10^{-4}	centimeters
microns	3.9370×10^{-5}	inches
microns	10^{-6}	meters
miles (naut.)	6080.27	feet
miles (naut.)	1.853	kilometers
miles (naut.)	1.853	meters
miles (naut.)	1.1516	miles (statute)

Multiply	*by*	*to obtain*
miles (naut.)	2027	yards
miles (statute)	1.609×10^5	centimeters
miles (statute)	5280	feet
miles (statute)	6.336×10^4	inches
miles (statute)	1.609	kilometers
miles (statute)	1609	meters
miles (statute)	0.8684	miles (naut.)
miles (statute)	320	rods
miles (statute)	1760	yards
miles/hour	44.7041	centimeter/second
miles/hour	88	feet/min
miles/hour	1.4667	feet/sec
miles/hour	1.6093	kilometers/hour
miles/hour	0.02682	km/min
miles/hour	0.86839	knots
miles/hour	26.82	meters/min
miles/hour	0.447	meters/sec
miles/hour	0.1667	miles/min
miles/hour/sec	44.70	cms/sec/sec
miles/hour/sec	1.4667	ft/sec/sec
miles/hour/sec	1.6093	km/hour/sec
miles/hour/sec	0.4470	m/sec/sec
miles/min	2682	centimeters/sec
miles/min	88	ft/sec
miles/min	1.609	km/min
miles/min	0.8684	knots/min
miles/min	60	miles/hour
miles-feet	9.425×10^{-6}	cu inches
millibars	0.00987	atmospheres
millibars	0.30	inches of mercury
millibars	0.75	millimeters of mercury
milliers	10^3	kilograms
millimicrons	1×10^{-9}	meters
milligrams	0.01543236	grains
milligrams	10^{-3}	grams
milligrams	10^{-6}	kilograms
milligrams	3.5274×10^{-5}	ounces (avdp)
milligrams	2.2046×10^{-6}	pounds (avdp)
milligrams/assay ton	1	ounces (troy)/ton (short)
milligrams/cu m	283.2×10^{-6}	grams/cu ft
milligrams/cu m	0.001	grams/cu m
milligrams/cu m	1000.0	micrograms/cu m
milligrams/cu m	28.32	micrograms/cu ft

Multiply	*by*	*to obtain*
milligrams/cu m	1.0	micrograms/liter
milligrams/cu m	62.43×10^{-6}	pounds/1000 cu ft
milligrams/cu m	$\frac{24.04}{\text{molecular weight of gas}}$	ppm by volume (20°C)
milligrams/cu m	0.8347	ppm by weight
milligrams/joule	5.918	pounds/horsepower-hour
milligrams/liter	0.05841	grains/gallon
milligrams/liter	0.07016	grains/imp. gal
milligrams/liter	0.0584	grains/U.S. gal
milligrams/liter	1.0	parts/million
milligrams/liter	8.345	lb/mil gal
milligrams/sq cm	0.929	grams/sq ft
milligrams/sq cm	10.0	grams/sq meter
milligrams/sq cm	10^4	kilograms/sq km
milligrams/sq cm	10^4	milligrams/sq meter
milligrams/sq cm	2.048	pounds/1000 sq ft
milligrams/sq cm	89.21	pounds/acre
milligrams/sq cm	28.55	tons/sq mile
milligrams/sq meter	92.9×10^{-6}	grams/sq ft
milligrams/sq meter	0.001	grams/sq meter
milligrams/sq meter	1.0	kilograms/sq km
milligrams/sq meter	0.0001	milligrams/sq cm
milligrams/sq meter	8.921×10^{-3}	pounds/acre
milligrams/sq meter	204.8×10^{-6}	pounds/1000 sq ft
milligrams/sq meter	2.855×10^{-3}	tons/sq mile
millihenries	0.001	henries
milliters	1	cubic centimeters
milliliters	3.531×10^{-5}	cu ft
milliliters	6.102×10^{-2}	cu in
milliliters	10^{-6}	cu m
milliliters	2.642×10^{-4}	gal (U.S.)
milliliters	10^{-3}	liters
milliliters	0.03381	ounces (U.S. fl)
millimeters	0.1	centimeters
millimeters	3.281×10^{-3}	feet
millimeters	0.03937	inches
millimeters	10^{-6}	kilometers
millimeters	0.001	meters
millimeters	6.214×10^{-7}	miles
millimeters	39.37	mils
millimeters	1.094×10^{-3}	yards
millimeters of mercury	1.316×10^{-3}	atmospheres
millimeters of mercury	0.0394	inches of mercury

Multiply	*by*	*to obtain*
millimeters of mercury (0°C)	0.5358	inches of water (60°F)
millimeters of mercury	1.3595×10^{-3}	kg/sq cm
millimeter of mercury (0°C)	133.3224	newton/meter^2
millimeters of mercury	0.01934	pounds/sq in
millimeters/sec	11.81	feet/hour
million gallons	306.89	acre-ft
million gallons	3785.0	cubic meters
million gallons	3.785	mega liters (1×10^6)
million gallons/day (MGD)	1.547	cu ft/sec
MGD	3785	cu m/day
MGD	0.0438	cubic meters/sec
MGD	43.808	liters/sec
MGD/acre	9360	cu m/day/ha
MGD/acre	0.039	cu meters/hour/sq meter
mils	0.002540	centimeters
mils	8.333×10^{-5}	feet
mils	0.001	inches
mils	2.540×10^{-8}	kilometers
mils	25.40	microns
mils	2.778×10^{-5}	yards
miner's in.	1.5	cu ft/min
miner's inches (Ariz., Calif. Mont., and Ore.)	0.025	cubic feet/second
miner's in. (Colorado)	0.02604	cubic feet/second
miner's inches (Idaho, Kan., Neb., Nev., N. Mex., N. Dak., S.Dak. and Utah)	0.020	cubic feet/second
minims (British)	0.05919	cubic centimeter
minims (U.S.)	0.06161	cubic centimeters
minutes (angles)	0.01667	degrees
minutes (angles)	1.852×10^{-4}	quadrants
minutes (angles)	2.909×10^{-4}	radians
minutes (angle)	60	seconds (angle)
months (mean calendar)	30.4202	days
months (mean calendar)	730.1	hours
months (mean calendar)	43805	minutes
months (mean calendar)	2.6283×10^6	seconds
myriagrams	10	kilograms
myriameters	10	kilometers
myriawatts	10	kilowatts
nepers	8.686	decibels
newtons	10^5	dynes
newtons	0.10197	kilograms

Multiply	*by*	*to obtain*
newtons	0.22481	pounds
newtons/sq meter	1.00	pascals (Pa)
noggins (British)	1/32	gallons (British)
No./cu.cm.	28.316×10^{3}	No./cu ft
No./cu.cm.	10^{6}	No./cu meter
No./cu.cm.	1000.0	No./liter
No./cu.ft.	35.314×10^{-6}	No./cu cm
No./cu.ft.	35.314	No./cu meter
No./cu.ft.	35.314×10^{-3}	No./liter
No./cu. meter	10^{-6}	No./cu cm
No./cu. meter	28.317×10^{-3}	No./cu ft
No./cu. meter	0.001	No./liter
No./liter	0.001	No./cu cm
No./liter	28.316	No./cu ft
No./liter	1000.0	No./cu meter
oersteds (abs)	1	electromagnetic cgs units of magnetizing force
oersteds (abs)	2.9978×10^{10}	electrostatic cgs units of magnetizing force
ohms	10^{9}	abohms
ohms	1.1126×10^{-12}	statohms
ohms	10^{-6}	megohms
ohms	10^{6}	microhms
ohms (International)	1.0005	ohms (absolute)
ounces (avdp)	16	drams (avoirdupois)
ounces (avdp)	7.2917	drams (troy)
ounces (avdp)	437.5	grains
ounces (avdp)	28.349527	grams
ounces (avdp)	0.028350	kilograms
ounces (avdp)	2.8350×10^{4}	milligrams
ounces (avdp)	0.9114583	ounces (troy)
ounces (avdp)	0.0625	pounds (avoirdupois)
ounces (avdp)	0.075955	pounds (troy)
ounces (avdp)	2.790×10^{-5}	tons (long)
ounces (avdp)	2.835×10^{-5}	tons (metric)
ounces (avdp)	3.125×10^{-5}	tons (short)
ounces (Br. fl)	2.3828×10^{-4}	barrels (U.S.)
ounces (Br. fl)	1.0033×10^{-3}	cubic feet
ounces (Br. fl)	1.73457	cubic inches
ounces (Br. fl)	7.6860	drams (U.S. fl)
ounces (Br. fl)	6.250×10^{-3}	gallons (Br.)
ounces (Br. fl)	0.07506	gallons (U.S.)
ounces (Br. fl)	2.84121×10^{-2}	liters
ounces (Br. fl)	480	minims (Br.)

Multiply	*by*	*to obtain*
ounces (Br. fl)	461.160	minims (U.S.)
ounces (Br. fl)	28.4121	mL
ounces (Br. fl)	0.9607	ounces (U.S. fl)
ounces (troy)	17.554	drams (avdp)
ounces (troy)	8	drams (troy)
ounces (troy)	480	grains (troy)
ounces (troy)	31.103481	grams
ounces (troy)	0.03110	kilograms
ounces (troy)	1.09714	ounces (avoirdupois)
ounces (troy)	20	pennyweights (troy)
ounces (troy)	0.068571	pounds (avdp)
ounces (troy)	0.08333	pounds (troy)
ounces (troy)	3.061×10^{-5}	tons (long)
ounces (troy)	3.429×10^{-5}	tons (short)
ounces (U.S. fl)	2.48×10^{-4}	barrels (U.S.)
ounces (U.S. fl)	29.5737	cubic centimeters
ounces (U.S. fl)	1.0443×10^{-3}	cubic feet
ounces (U.S. fl)	1.80469	cubic inches
ounces (U.S. fl)	8	drams (fluid)
ounces (U.S. fl)	6.5053×10^{-3}	gallons (Br.)
ounces (U.S. fl)	7.8125×10^{-3}	gallons (U.S.)
ounces (U.S. fl)	29.5729	milliliters
ounces (U.S. fl)	499.61	minims (Br.)
ounces (U.S. fl)	480	minims (U.S.)
ounces (U.S. fl)	1.0409	ounces (Br. fl)
ounces/sq inch	4309	dynes/sq cm
ounces/sq. inch	0.0625	pounds/sq inch
paces	30	inches
palms (British)	3	inches
parsecs	3.260	light years
parsecs	3.084×10^{13}	kilometers
parsecs	3.084×10^{16}	meters
parsec	19×10^{12}	miles
parts/billion (ppb)	10^{-3}	mg/L
parts/million (ppm)	0.07016	grains/imp. gal.
parts/million	0.058417	grains/gallon (U.S.)
parts/million	1.0	mg/liter
parts/million	8.345	lbs/million gallons
ppm by volume (20°C)	$\frac{\text{molecular weight of gas}}{24.04}$	micrograms/liter
ppm by volume (20°C)	$\frac{\text{molecular weight of gas}}{0.02404}$	micrograms/cu meter

Multiply	*by*	*to obtain*
ppm by volume (20°C)	$\frac{\text{molecular weight of gas}}{24.04}$	milligrams/cu meter
ppm by volume (20°C)	$\frac{\text{molecular weight of gas}}{28.8}$	ppm by weight
ppm by volume (20°C)	$\frac{\text{molecular weight of gas}}{385.1 \times 10^{6}}$	pounds/cu ft
ppm by weight	1.198 × 10^{-3}	micrograms/cu meter
ppm by weight	1.198	micrograms/liter
ppm by weight	1.198	milligrams/cu meter
ppm by weight	$\frac{28.8}{\text{molecular weight of gas}}$	ppm by volume (20°C)
ppm by weight	7.48 × 10^{-6}	pounds/cu ft
pascal (Pa; N/m^2)	1.4504 x 10^{-4}	pounds/sq ft
pascal (Pa; N/m^2)	2.0885 x 10^{-2}	pounds/sq ft
pascal (Pa; N/m^2)	2.9613 x 10^{-4}	in Hg (60°F)
pascal (Pa; N/m^2)	4.0187 x 10^{-3}	in H_2O (60°F)
pecks (British)	0.25	bushels (British)
pecks (British)	554.6	cubic inches
pecks (British)	9.091901	liters
pecks (U.S.)	0.25	bushels (U.S.)
pecks (U.S.)	537.605	cubic inches
pecks (U.S.)	8.809582	liters
pecks (U.S.)	8	quarts (dry)
pennyweights	24	grains
pennyweights	1.555174	grams
pennyweights	0.05	ounces (troy)
pennyweights (troy)	4.1667 × 10^{-3}	pounds (troy)
perches (masonry)	24.75	cubic feet
phots	929.0	foot-candles
phots	1	lumen incident/sq cm
phots	10^4	lux
picas (printers')	1/6	inches
pieds (French feet)	0.3249	meters
pints (dry)	33.6003	cubic inches
pints (liq.)	473.179	cubic centimeters
pints (liq.)	0.01671	cubic feet
pints (liq.)	4.732 × 10^{-4}	cubic meters
pints (liq.)	6.189 × 10^{-4}	cubic yards
pints (liq.)	0.125	gallons
pints (liq.)	0.4732	liters
pints (liq.)	16	ounces (U.S. fluid)
pints (liq.)	0.5	quarts (liq.)
planck's constant	6.6256 × 10^{-27}	erg-seconds
poise	1.00	gram/cm sec

Multiply	*by*	*to obtain*
poise	0.1	newton-second/meter^2
population equivalent (PE)	0.17	pounds BOD
pottles (British)	0.5	gallons (British)
pouces (Paris inches)	0.02707	meters
pouces (Paris inches)	0.08333	pieds (Paris feet)
poundals	13,826	dynes
poundals	14.0981	grams
poundals	1.383×10^{-3}	joules/cm
poundals	0.1383	joules/meter (newton)
poundals	0.01410	kilograms
poundals	0.031081	pounds
pounds (avdp)	256	drams (avdp)
pounds (avdp)	116.67	drams (troy)
pounds (avdp)	444,823	dynes
pounds (avdp)	7000	grains
pounds (avdp)	453.5924	grams
pounds (avdp)	0.04448	joules/cm
pounds (avdp)	4.448	joules/meter (newtons)
pounds (avdp)	0.454	kilograms
pounds (avdp)	4.5359×10^5	milligrams
pounds (avdp)	16	ounces (avdp)
pounds (avdp)	14.5833	ounces (troy)
pounds (avdp)	32.17	poundals
pounds (avdp)	1.2152778	pounds (troy)
pounds (avdp)	4.464×10^{-4}	tons (long)
pounds (avdp)	0.0005	tons (short)
pounds (troy)	210.65	drams (avdp)
pounds (troy)	96	drams (troy)
pounds (troy)	5760	grains
pounds (troy)	373.2418	grams
pounds (troy)	0.37324	kilograms
pounds (troy)	3.7324×10^5	milligrams
pounds (troy)	13.1657	ounces (avdp)
pounds (troy)	12.0	ounces (troy)
pounds (troy)	240.0	pennyweights (troy)
pounds (troy)	0.8229	pounds (avdp)
pounds (troy)	3.6735×10^{-4}	tons (long)
pounds (troy)	3.7324×10^{-4}	tons (metric)
pounds (troy)	4.1143×10^{-4}	tons (short)
pounds (avdp)-force	4.448	newtons
pounds-force-sec/ft^2	47.88026	newton-sec/meter^2
pounds (avdp)-mass	0.4536	kilograms
pounds-mass/ft^3	16.0185	kilogram/meter^3
pounds-mass/ft-sec	1.4882	mewton-sec/meter^2

Multiply	*by*	*to obtain*
pounds of BOD	5.882	population equivalent (PE)
pounds of carbon to CO_2	14,544	BTU (mean)
pounds of water	0.0160	cu ft
pounds of water	27.68	cu in
pounds of water	0.1198	gallons
pounds of water evaporated at 212°F	970.3	BTU
pounds of water per min	2.699×10^{-4}	cubic feet/sec
pound-feet	13,825	centimeter-grams
pound-feet (torque)	1.3558×10^{7}	dyne-centimeters
pound-feet	0.1383	meter-kilograms
pounds-feet squared	421.3	kg-cm squared
pounds-feet squared	144	pounds-inches squared
pounds-inches squared	2926	kg-cm squared
pounds-inches squared	6.945×10^{-3}	pounds-feet squared
pounds/acre	0.0104	grams/sq ft
pounds/acre	0.1121	grams/sq meter
pounds/acre	1.121	kg/ha
pounds/acre	112.1	kilograms/sq km
pounds/acre	0.01121	milligrams/sq cm
pounds/acre	112.1	milligrams/sq meter
pounds/acre	0.023	pounds/1000 sq ft
pounds/acre	0.32	tons/sq mile
pounds/acre/day	0.112	g/day/sq m
pounds/cu ft	0.0160	g/mL
pounds/cu ft	16.02	kg/cu m
pounds/cu ft	16.018×10^{9}	micrograms/cu meter
pounds/cu ft	16.018×10^{6}	micrograms/liter
pounds/cu ft	16.018×10^{6}	milligrams/cu meter
pounds/cu ft	$\frac{385.1 \times 10^{6}}{\text{molecular weight of gas}}$	ppm by volume (20° C)
pounds/cu ft	133.7×10^{3}	ppm by weight
pounds/cu ft	5.787×10^{-4}	lb/cu in
pounds/cu ft	5.456×10^{-9}	pounds/mil-foot
pounds/1000 cu ft	0.35314	grams/cu ft
pounds/1000 cu ft	16.018	grams/cu m
pounds/1000 cu ft	353.14×10^{3}	micrograms/cu ft
pounds/1000 cu ft	16.018×10^{6}	microgram/cu m
pounds/1000 cu ft	16.018×10^{3}	milligrams/cu m
pounds/cubic inch	27.68	grams/cubic cm
pounds/cubic inch	2.768×10^{4}	kgs/cubic meter
pounds/cubic inch	1728	pounds/cubic foot
pounds/cubic inch	9.425×10^{-6}	pounds/mil foot
pounds/day/acre-ft	3.68	g/day/cu m

Multiply	*by*	*to obtain*
pounds/day/cu ft	16	kg/day/cu m
pounds/day/cu yd	0.6	kg/day/cu m
pounds/day/sq ft	4,880	g/day/sq m
pounds/ft	1.488	kg/m
pounds/gal	119.947	g/liter
pounds/1000-gal	120	g/1000-liters
pounds/horsepower-hour	0.169	mg/joule
pounds/in	178.6	g/cm
pounds/mil-foot	2.306×10^6	gms/cu cm
pounds/mil gal	0.12	g/cu m
pounds/sq ft	4.725×10^{-4}	atmospheres
pounds/sq ft	0.01602	ft of water
pounds/sq ft	0.01414	inches of mercury
pounds/sq ft	4.8824×10^{-4}	kgs/sq cm
pounds/sq ft	4.88241	kilograms/square meter
pounds/sq ft	47.9	newtons/sq m
pounds/sq ft	6.944×10^{-3}	pounds/sq inch
pounds/1000 sq ft	0.4536	grams/sq ft
pounds/1000 sq ft	4.882	grams/sq meter
pounds/1000 sq ft	4882.4	kilograms/sq km
pounds/1000 sq ft	0.4882	milligrams/sq cm
pounds/1000 sq ft	4882.4	milligrams/sq meter
pounds/1000 sq ft	43.56	pounds/acre
pounds/1000 sq ft	13.94	tons/sq mile
pounds/sq in	0.068046	atmospheres
pounds/sq in	2.307	ft of water
pounds/sq in	70.307	grams/square centimeter
pounds/sq in	2.036	in of mercury
pounds/sq in	0.0703	kgs/square cm
pounds/sq in	703.07	kilograms/square meter
pounds/sq in	51.715	millimeters of mercury
pounds/sq in	6894.76	newton/meter^2
pounds/sq in	51.715	millimeters of mercury at 0°C
pounds/sq in	144	pounds/sq foot
pounds/sq in (abs)	1	pound/sq in (gage) + 14.696
pounds/ton	0.5	kg/metric ton; kg/T
proof(U.S.)	0.5	percent alcohol by volume
puncheons (British)	70	gallons (British)
quadrants (angle)	90	degrees
quadrants (angle)	5400	minutes
quadrants (angle)	3.24×10^5	seconds
quadrants (angle)	1.571	radians
quarts (dry)	67.20	cubic inches
quarts (liq.)	946.4	cubic centimeters

Multiply	*by*	*to obtain*
quarts (liq.)	0.033420	cubic feet
quarts (liq.)	57.75	cubic inches
quarts (liq.)	9.464×10^{-4}	cubic meters
quarts (liq.)	1.238×10^{-3}	cubic yards
quarts (liq.)	0.25	gallons
quarts (liq.)	0.9463	liters
quarts (liq.)	32	ounces (U.S., fl)
quarts (liq.)	0.832674	quarts (British)
quintals (long)	112	pounds
quintals (metric)	100	kilograms
quintals (short)	100	pounds
quires	24	sheets
radians	57.29578	degrees
radians	3438	minutes
radians	0.637	quadrants
radians	2.063×10^{5}	seconds
radians/second	57.30	degrees/second
radians/second	9.549	revolutions/min
radians/second	0.1592	revolutions/sec
radians/sec/sec	573.0	revs/min/min
radians/sec/sec	9.549	revs/min/sec
radians/sec/sec	0.1592	revs/sec/sec
reams	500	sheets
register tons (British)	100	cubic feet
revolutions	360	degrees
revolutions	4	quadrants
revolutions	6.283	radians
revolutions/minute	6	degrees/second
revolutions/minute	0.10472	radians/second
revolutions/minute	0.01667	revolutions/sec
revolutions/minute^2	0.0017453	radians/sec/sec
revs/min/min	0.01667	revs/min/sec
revs/min/min	2.778×10^{-4}	revs/sec/sec
revolutions/second	360	degrees/second
revolutions/second	6.283	radians/second
revolutions/second	60	revs/minute
revs/sec/sec	6.283	rads/sec/sec
revs/sec/sec	3600	revs/min/min
revs/sec/sec	60	revs/min/sec
reyns	6.8948×10^{6}	centipoises
rod	.25	chain (gunters)
rods	16.5	feet
rods	5.0292	meters
rods	3.125×10^{-3}	miles

Multiply	*by*	*to obtain*
rods (surveyors' means)	5.5	yards
roods (British)	0.25	acres
scruples	1/3	drams (troy)
scruples	20	grains
sections	1	square miles
seconds (mean solar)	1.1574×10^{-5}	days
seconds (angle)	2.778×10^{-4}	degrees
seconds (mean solar)	2.7778×10^{-4}	hours
seconds (angle)	0.01667	minutes
seconds (angle)	3.087×10^{-6}	quadrants
seconds (angle)	4.848×10^{-6}	radians
slugs	14.59	kilogram
slugs	32.174	pounds
space, entire (solid angle)	12.566	steradians
spans	9	inches
spheres (solid angle)	12.57	steradians
spherical right angles	0.25	hemispheres
spherical right angles	0.125	spheres
spherical right angles	1.571	steradians
square centimeters	1.973×10^{5}	circular mils
square centimeters	1.07639×10^{-3}	square feet (U.S.)
square centimeters	0.15499969	square inches (U.S.)
square centimeters	10^{-4}	square meters
square centimeters	3.861×10^{-11}	square miles
square centimeters	100	square millimeters
square centimeters	1.196×10^{-4}	square yards
square centimeters-square centimeter (moment of area)	0.024025	square inch-square inch
square chains (gunter's)	0.1	acres
square chains (gunter's)	404.7	square meters
square chains (Ramden's)	0.22956	acres
square chains (Ramden's)	10000	square feet
square feet	2.29×10^{-5}	acres
square feet	1.833×10^{8}	circular mils
square feet	144	square inches
square feet	0.092903	square meters
square feet	929.0341	square centimeters
square feet	3.587×10^{-8}	square miles
square feet	1/9	square yards
square feet/cu ft	3.29	sq m/cu m
square foot-square foot (moment of area)	20,736	square inch-square inch
square inches	1.273×10^{6}	circular mils
square inches	6.4516258	square centimeters

Multiply	*by*	*to obtain*
square inches	6.944×10^{-3}	square feet
square inches	645.2	square millimeters
square inches	10^{6}	square mils
square inches	7.71605×10^{-4}	square yards
square inches-inches sqd.	41.62	sq cm-cm sqd
square inches-inches sqd.	4.823×10^{-5}	sq feet-feet sqd
square kilometers	247.1	acres
square kilometers	10^{10}	square centimeters
square kilometers	10.76×10^{6}	square feet
square kilometers	1.550×10^{9}	square inches
square kilometers	10^{6}	square meters
square kilometers	0.3861006	square miles (U.S.)
square kilometers	1.196×10^{6}	square yards
square links (Gunter's)	10^{-5}	acres (U.S.)
square links (Gunter's)	0.04047	square meters
square meters	2.471×10^{-4}	acres (U.S.)
square meters	10^{4}	square centimeters
square meters	10.76387	square feet (U.S.)
square meters	1550	square inches
square meters	3.8610×10^{-7}	square miles (statute)
square meters	10^{6}	square millimeters
square meters	1.196	square yards (U.S.)
square miles	640	acres
square miles	2.78784×10^{7}	square feet
square miles	2.590	sq km
square miles	2.5900×10^{6}	square meters
square miles	3.098×10^{6}	square yards
square millimeters	1.973×10^{3}	circular mils
square millimeters	0.01	square centimeters
square millimeters	1.076×10^{-5}	square feet
square millimeters	1.550×10^{-3}	square inches
square mils	1.273	circular mils
square mils	6.452×10^{-6}	square centimeters
square mils	10^{-6}	square inches
square rods	272.3	square feet
square yard	2.1×10^{-4}	acres
square yards	8361	square centimeters
square yards	9	square feet
square yards	1296	square inches
square yards	0.8361	square meters
square yards	3.228×10^{-7}	square miles
square yards	8.361×10^{5}	square millimeters
statamperes	3.33560×10^{-10}	amperes (abs)
statcoulombs	3.33560×10^{-10}	coulombs (abs)
statcoulombs/kilogram	1.0197×10^{-6}	statcoulombs/dyne

Multiply	*by*	*to obtain*
statfarads	1.11263×10^{-12}	farads (abs)
stathenries	8.98776×10^{11}	henries (abs)
statohms	8.98776×10^{11}	ohms (abs)
statvolts	299.796	volts (abs)
statvolts/inch	118.05	volts (abs)/centimeter
statwebers	2.99796×10^{10}	electromagnetic cgs units of magnetic flux
statwebers	1	electrostatic cgs units of magnetic flux
stilb	2919	footlambert
stilb	1	int. candle cm^{-2}
stilb	3.142	lambert
stoke (kinematic viscosity)	10^{-4}	meter^2/second
stones (British)	6.350	kilograms
stones (British)	14	pounds
temp. (degs. C.) + 273	1	abs. temp. (degs. K.)
temps (degs. C.) + 17.8	1.8	temp. (degs. Fahr.)
temps. (degs. F.) + 460	1	abs. temp. (degs. R.)
temps. (degs. F.) − 32	5/9	temp. (degs. Cent.)
toises (French)	6	paris feet (pieds)
tons (long)	5.734×10^{5}	drams (avdp)
tons (long)	2.613×10^{5}	drams (troy)
tons (long)	1.568×10^{7}	grains
tons (long)	1.016×10^{6}	grams
tons (long)	1016	kilograms
tons (long)	3.584×10^{4}	ounces (avdp)
tons (long)	3.267×10^{4}	ounces (troy)
tons (long)	2240	pounds (avdp)
tons (long)	2722.2	pounds (troy)
tons (long)	1.12	tons (short)
Tons (metric) (T)	1000	kilograms
Tons (metric) (T)	2204.6	pounds
Tons (metric) (T)	1.1025	tons (short)
tons (short)	5.120×10^{5}	drams (avdp)
tons (short)	2.334×10^{5}	drams (troy)
tons (short)	1.4×10^{7}	grains
tons (short)	9.072×10^{5}	grams
tons (short)	907.2	kilograms
tons (short)	32,000	ounces (avdp)
tons (short)	29,166.66	ounces (troy)
tons (short)	2000	pounds (avdp)
tons (short)	2.430.56	pounds (troy)
tons (short)	0.89287	tons (long)
tons (short)	0.9078	Tons (metric) (T)

Multiply	*by*	*to obtain*
tons (short)/acre	2.2422	metric ton/ha
tons (short)/sq ft	9765	kg/sq meter
tons (short)/sq ft	13.89	pounds/sq inch
tons (short)/sq in	1.406×10^6	kg/sq meter
tons/sq mile	3.125	pounds/acre
tons/sq mile	0.07174	pounds/1000 sq ft
tons/sq mile	0.3503	grams/sq meter
tons/sq mile	350.3	kilograms/sq km
tons/sq mile	350.3	milligrams/sq meter
tons/sq mile	0.03503	milligrams/sq cm
tons/sq mile	0.03254	grams/sq ft
tons of water/24 hours	83.333	pounds of water/hr
tons of water/24 hours	0.16643	gallons/min
tons of water/24 hours	1.3349	cu ft/hr
torr (mm Hg, 0°C)	133.322	newton/meter^2
townships (U.S.)	23040	acres
townships (U.S.)	36	square miles
tuns	252	gallons
volts (abs)	10^8	abvolts
volts (abs)	3.336×10^{-3}	statvolts
volts (international of 1948)	1.00033	volts (abs)
volt/inch	.39370	volt/cm
watts (abs)	3.41304	BTU (mean)/hour
watts (abs)	0.0569	BTU (mean)/min
watts (abs)	0.01433	calories, kilogram (mean)/minute
watts (abs)	10^7	ergs/second
watts (abs)	44.26	foot-pounds/minute
watts (abs)	0.7376	foot-pounds/second
watts (abs)	0.0013405	horsepower (electrical)
watts (abs)	1.360×10^{-3}	horsepower (metric)
watts (abs)	1	joules/sec
watts (abs)	0.10197	kilogram-meters/second
watts (abs)	10^{-3}	kilowatts
watt-hours	3.415	British Thermal Units
watt-hours	3.60×10^{10}	ergs
watt-hours	2655	foot-pounds
watt-hours	859.85	gram-calories
watt-hours	1.34×10^{-3}	horsepower-hours
watt-hours	3.6×10^3	joule
watt-hours	0.8605	kilogram-calories
watt-hours	367.1	kilogram-meters
watt-hours	10^{-3}	kilowatt-hours
watt (international)	1.0002	watt (absolute)

Multiply	*by*	*to obtain*
watt/(cm^2)(°C/cm)	693.6	BTU/(hr)(ft^2)(°F/in)
wave length of the red line of cadmium	6.43847×10^{-7}	meters
webers	10^3	electromagnetic cgs units
webers	3.336×10^{-3}	electrostatic cgs units
webers	10^5	kilolines
webers	10^8	lines
webers	10^8	maxwells
webers	3.336×10^{-3}	statwebers
webers/sq in	1.550×10^7	gausses
webers/sq in	10^8	lines/sq in
webers/sq in	0.1550	webers/sq cm
webers/sq in	1,550	webers/sq meter
webers/sq meter	10^4	gausses
webers/sq meter	6.452×10^4	lines/sq in
webers/sq meter	10^{-4}	webers/sq cm
webers/sq meter	6.452×10^{-4}	webers/sq in
weeks	168	hours
weeks	10,080	minutes
weeks	604,800	seconds
yards	91.44	centimeters
yards	3	feet
yards	36	inches
yards	9.144×10^{-4}	kilometers
yards	0.91440	meters
yards	4.934×10^{-4}	miles (naut.)
yards	5.682×10^{-4}	miles (stat.)
yards	914.4	millimeters
years (sidereal)	365.2564	days (mean solar)
years (sidereal)	366.2564	days (sidereal)
years (tropical, mean solar)	365.2422	days (mean solar)
years (common)	8760	hours
years (tropical, mean solar)	8765.8128	hours (mean solar)
years (leap)	366	days
years (leap)	8784	hours
years (tropical, mean solar)	3.155693×10^7	seconds (mean solar)
years (tropical, mean solar)	1.00273780	years (sidereal)

2. BASIC AND SUPPLEMENTARY UNITS

A *meter (m)* is 1,650,763.73 wavelengths in vacuo of the radiation corresponding to the transition between the energy levels $2p_{10}$ and $5d_5$ of the krypton 86 atom.

A *kilogram (kg)* is the mass of the international prototype in the custody of the Bureau International des Poids et Mesures at Sevres in France.

A *second (sec)* is the interval occupied by 9,192,631,770 cycles of the radiation corresponding to the transition of the cesium-133 atom when unperturbed by exterior fields.

An *ampere* is the constant current that if maintained in two parallel rectilinear conductors of infinite length of negligible circular cross section and placed at a distance of one meter apart in vacuo would produce between these conductors a force equal to 2×10^{-7} newton per meter length.

A *kelvin* (°*K*) is the degree interval of the thermodynamic scale on which the temperature of the triple point of water is 273.16 degrees.

A *candle* is such that the luminance of a full radiator at the temperature of solidification of platinum is 60 units of luminous intensity per square centimeter.

A *mole (mol)* is the amount of substance which contains as many elementary units as there are atoms in 0.012 kg of carbon-12. The elementary unit must be specified and may be an atom, an ion, an electron, a photon, etc., or a given group of such entities.

A *radian* is the angle subtended at the center of a circle by an arc of the circle equal in length to the radius of the circle.

A *steradian* is the solid angle that, having its vertex at the center of a sphere, cuts off an area of the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere.

3. DERIVED UNITS AND QUANTITIES

The *liter* was defined in 1901 as the volume of 1 kilogram of pure water at normal atmospheric pressure and maximum density equal therefore to 1.000028 dm^3. This 1901 definition applied for the purpose of the 1963 Weights and Measures Acts.

By a resolution of the 12th Conference General des Poids et Mesures (CGPM) in 1964 the word *liter* is now recognized as a special name for the dm^3, but is not used to express high precision measurements. It is used widely in engineering and the retail business, where the discrepancy of 28 parts in 1 million is of negligible significance.

A *newton (N)* is the force that, when applied to a body of mass of one kilogram, gives it an acceleration of one meter per second per second.

Stress is defined as the resultant internal force per unit area resisting change in the shape or size of a body acted on by external forces, and is therefore measured in *newtons per square meter* (N/m^2).

A *bar* is a pressure equivalent to 100,000 newtons acting on an area of one square metor.

A *joule (J)* is the work done when the point of application of a force of one newton is displaced through a distance of one meter in the direction of the force.

A *watt* is equal to one joule per second.

Dynamic viscosity is the property of a fluid whereby it tends to resist relative motion within itself. It is the shear stress, i.e., the tangential force on unit area, between two infinite horizontal planes at unit distance apart, one of which is fixed while the other moves with unit velocity. In other words, it is the shear stress divided by the velocity gradient, i.e., $(N/m^2) \div (m/sec/m) = N\ sec/m^2$.

Kinematic viscosity is the dynamic viscosity of a fluid divided by its density, i.e., $(N\ sec/m^2)/(kg/m^3) = m^2/sec$.

Density of heat flow rate (or heat flux) is the heat flow rate (W) per unit area, i.e., W/m^2.

Coefficient of heat transfer is the heat flow rate (W) per unit area per unit temperature difference, i.e., $W/m^{2\circ}C$.

Thermal conductivity is the quantity of heat that will be conducted in unit time through unit area of a slab of material of unit thickness with a unit difference of temperature between the faces; in other words, the heat flow rate (W) per unit area per unit temperature gradient, i.e., $W/[m^2(^\circ C/m)] = W/m^\circ C$.

The *heat capacity* of a substance is the quantity of heat gained or lost by the substance per unit temperature change, i.e., $J/^\circ C$.

Specific heat capacity is the heat capacity per unit mass of the substance, i.e., $J/kg^\circ C$.

Internal energy is the kinetic energy possessed by the molecules of a substance due to temperature and is measured in joules (J).

Specific internal energy (u) is the internal energy per unit mass of the substance, i.e., J/kg. When a small amount of heat is added at constant volume the increase in specific internal energy is given by: du $= c_v\, dT$, where c_v is the specific heat capacity at constant volume, and dT is the increase in absolute temperature.

Specific enthalpy (h) is defined by the equation: $h = u + pv$, where p is the pressure and v is the specific volume. Specific enthalpy is measured in J/kg. When a small amount of heat is added to a substance at constant pressure, the increase in specific enthalpy is given by: $-dh = cp\, dT$, where cp is the specific heat capacity at constant pressure.

The *specific latent heat* of a substance is the heat gained per unit mass without an accompanying rise in temperature during a change of state at constant pressure. It is measured in J/kg.

The *entropy* (S) of a substance is such that when a small amount of heat is added, the increase in entropy is equal to the quantity of heat added (dQ) divided by the absolute temperature (T) at which the heat is absorbed; i.e., $dS = dQ/T$, measured in J/°K.

The *specific entropy* (s) of a substance is the entropy per unit mass, i.e., J/kg°K.

A *volt* is the difference of electric potential between two points of a conductor carrying a constant current of one ampere when the power dissipated is one watt.

A *weber* (Wb) is the magnetic flux through a conductor with a resistance of one ohm when reversal of the direction of the magnetic flux causes the transfer of one coulomb in the conductor loop.

Tesla: The magnetic flux density is the normal magnetic flux per unit area and is measured in *teslas*.

A *lumen*, the unit of luminous flux, is the flux emitted within unit solid angle of one steradian by a point source having a uniform intensity of one candle.

A *lux* is an illumination of one lumen per square meter.

Luminance is the luminous intensity per unit area of a source of light or of an illumination. It is measured in candles per square meter.

4. PHYSICAL CONSTANTS

Standard temperature and pressure (S.T.P.) = 273.15°K and 1.013 × 10^5 N/m^2
= 0°C and 1.013 bar
= 0°C and 760 mm Hg
Molecular volume of ideal gas at S.T.P. = 22.4 liters/mol
Gas constant (R) = 8.314 J/mol°K
$^{\mathrm{RT}}$(273.15°K) = 2.271 × 10^3 J/mol
Avogadro constant = 6.023 × 10^{23}/mol
Boltzmann constant = 1.3805 × 10^{-23} J/K
Faraday constant = 9.6487 × 10^4 °C/mol (= A s/mol)
Planck constant = 6.626 × 10^{-34} J sec
Stefan-Boltzman constant = 5.6697 × 10^{-8} W/m^2 K^4
Ice point of water = 273.15°K (0°C)
Triple point of water = 273.16°K (0.01°C)
Speed of light = 2.998 × 10^8 m/sec
Acceleration of gravity (standard) (Greenwich) = 9.80665 m/s^2 [take g as 9.81 m/s^2]
= 9.81188 m/s^2
Universal constant of gravitation = 6.670 × 10^{-11} Newton m^2/kg^2
Mass of hydrogen atom = 1.6734 × 10^{-27} kg

5. PROPERTIES OF WATER

U.S. Customary Units

Temperature (°F)	Specific weight, γ (lb/ft^3)	Mass density, ρ (lb-sec^2/ft^4)	Dynamic viscosity, $\mu \times 10^5$ (lb-sec/ft^2)	Kinematic viscosity, $v \times 10^5$ (ft^2/sec)	Surface tension[a], $\sigma \times 10^3$ (lb/ft)	Vapor pressure, p_v (lb/$in.^2$)	Bulk modulus[b], $E \times 10^{-3}$ (lb/$in.^2$)
32	62.42	1.940	3.746	1.931	5.18	0.09	290
40	62.43	1.938	3.229	1.664	5.14	0.12	295
50	62.41	1.936	2.735	1.410	5.09	0.18	300
60	62.37	1.934	2.359	1.217	5.04	0.26	312
70	62.30	1.931	2.050	1.059	5.00	0.36	320
80	62.22	1.927	1.799	0.930	4.92	0.51	323
90	62.11	1.923	1.595	0.826	4.86	0.70	326
100	62.00	1.918	1.424	0.739	4.80	0.95	329
110	61.86	1.913	1.284	0.667	4.73	1.24	331
120	61.71	1.908	1.168	0.609	4.65	1.69	333
130	61.55	1.902	1.069	0.558	4.60	2.22	332
140	61.38	1.896	0.981	0.514	4.54	2.89	330
150	61.20	1.890	0.905	0.476	4.47	3.72	328
160	61.00	1.896	0.838	0.442	4.41	4.74	326
170	60.80	1.890	0.780	0.413	4.33	5.99	322
180	60.58	1.883	0.726	0.385	4.26	7.51	318
190	60.36	1.876	0.678	0.362	4.19	9.34	313
200	60.12	1.868	0.637	0.341	4.12	11.52	308
212	59.83	1.860	0.593	0.319	4.04	14.7	300

[a] In contact with air; [b] At atmospheric pressure.

SI Units

Temperatue, (°C)	Specific weight, γ (kN/m^3)	Mass density, ρ (kg/m^3)	Dynamic viscosity, $\mu \times 10^3$ (N $\cdot$ s/m^2)	Kinematic viscosity, $v \times 10^6$ (m^2/s)	Surface tension[a], σ (N/m)	Vapor pressure, p_v (kN/m^2)	Bulk modulus[b], $E \times 10^{-6}$ (kN/m^2)
0	9.805	999.8	1.781	1.785	0.0765	0.61	1.98
5	9.807	1000.0	1.518	1.519	0.0749	0.87	2.05
10	9.804	999.7	1.307	1.306	0.0742	1.23	2.10
15	9.798	999.1	1.139	1.139	0.0735	1.70	2.15
20	9.789	998.2	1.002	1.003	0.0728	2.34	2.17
25	9.777	997.0	0.890	0.893	0.0720	3.17	2.22
30	9.764	995.7	0.798	0.800	0.0712	4.24	2.25
40	9.730	992.2	0.653	0.658	0.0696	7.38	2.28
50	9.689	988.0	0.547	0.553	0.0679	12.33	2.29
60	9.642	983.2	0.466	0.474	0.0662	19.92	2.28
70	9.589	977.8	0.404	0.413	0.0644	31.16	2.25
80	9.530	971.8	0.354	0.364	0.0626	47.34	2.20
90	9.466	965.3	0.315	0.326	0.0608	70.10	2.14
100	9.399	958.4	0.282	0.294	0.0589	101.33	2.07

[a] In contact with air; [b] At atmospheric pressure.

6. PERIODIC TABLE OF THE ELEMENTS (COMPLIMENTS OF THE LENOX INSTITUTE OF WATER TECHNOLOGY)

Groups ⇨ Periods & sub-shells ⇩	I IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIII	10	11 IB	12 IIB	13 IIIA	14 VIA	15 VA	16 VIA	17 VIIA	18 O
I IS	1 H 1.00794 Hydrogen																I H 1.00794 Hydrogen	2 He 4.00260 Helium
2 2s2p	3 Li 6.941 Lithium	4 Be 9.01218 Beryllium											5 B 10.811 Boron	6 C 12.011 Boron	7 N 14.0067 Nitrogen	8 O 15.9994 Oxygen	9 F 18.9984 Fluorine	10 Ne 20.179 Neon
3 3s3p	11 Na 22.9897 Sodium	12 Mg 24.305 Magnesium											13 Al 26.9815 Aluminum	14 Si 28.0855 Silicon	15 P 30.9738 Phosphorus	16 S 32.066 Sulfur	17 CI 35.4527 Chlorine	18 Ar 39.948 Argon
4 4s3d4p	19 K 39.098 Potassium	20 Ca 40.078 Calcium	21 Sc 44.9559 Scandium	22 Ti 47.88 Titanium	23 V 50.9415 Vanadium	24 Cr 51.996 Chromium	25 Mn 54.938 Manganese	26 Fe 55.847 Iron	27 Co 58.933 Cobalt	28 Ni 58.69 Nickel	29 Cu 63.546 Copper	30 Zn 65.39 Zinc	31 Ga 69,723 Gallium	32 Ge 69.561 Germanium	33 As 74.9216 Arsenic	34 Se 78.96 Selenium	35 Br 79.904 Bromine	36 Kr 83.80 Krypton
5 5s4d5p	37 Rb 85.468 Rubidium	38 Sr 87.62 Strontium	39 Y 88.9059 Yttrium	40 Zr 91.224 Zirconium	41 Nb 92.9064 Niobium	42 Mo 95.94 Molybdenum	43 Tc (98) Technetium	44 Ru 101.07 Ruthenium	45 Rh 102.906 Rhodium	46 Pd 106.42 Palladium	47 Ag 107.868 Silver	48 Cd 112.411 Cadmium	49 In 114.82 Indium	50 Sn 118.710 Tin	51 Sb 121.75 Antimony	52 Te 127.60 Tellurium	53 I 126.90 Iodine	54 Xe 131.29 Xenon
6 6s4f5d6p	55 Cs 132.905 Cesium	56 Ba 137.327 Barium	57 La 138.906 Lanthanum	72 Hf 178.49 Hafnium	73 Ta 180.948 Tantalum	74 W 183.85 Tungsten	75 Re 186.207 Rhenium	76 Os 190.2 Osmium	77 Ir 192.22 Iridium	78 Pt 195.08 Platinum	79 Au 196.97 Gold	80 Hg 200.59 Mercury	81 Tl 204.383 Thallium	82 Pb 207.2 Lead	83 Bi 208.98 Bismuth	84 Po (209) Polonium	85 At (210) Astatine	86 Rn (222) Radon
7 7s5f6d	87 Fr (223) Francium	88 Ra (226) Radium	89 Ac (227) Actinium	104 Rf (261) Rutherfordium	105 Ha (262) Dubnium	106 Sg (263) Seaborgium	107 Ns (262) Bohrium	108 Hs (265) Hassium	109 Mt (266) Meitnerium	110		112						

6 4f	58 Ce 140.116 Cerium	59 Pr 140.91 Praseodymium	60 Nd 144.24 Neodymium	61 Pm (145) Promethium	62 Sm 150.35 Samarium	63 Eu 107.26 Europium	64 Gd 157.25 Gadolinium	65 Tb 158.925 Terbium	66 Dy 162.50 Dysprosium	67 Ho 104.930 Holmium	68 Er 167.26 Erbium	69 Tm 168.934 Thulium	70 Yb 173.04 Ytterbium	71 Lu 174.967 Lutetium
7 5f	90 Th 232.038 Thorium	91 Pa (231) Protactinium	92 U 238.029 Uranium	93 Np (237) Neptunium	94 Pu (244) Plutonium	95 Am (243) Americium	96 Cm (247) Curium	97 Bk (247) Berkelium	98 Cf (251) Californium	99 Es (252) Einsteinium	100 Fm (257) Fermium	101 Md (258) Mendelevium	102 No (259) Nobelium	103 Lr (262) Lawrencium

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