

# Chapter 1

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## Introduction

The activated sludge process is the most common method of secondary wastewater treatment throughout the world. In most wastewater treatment plants, it is the process that is most critical to meeting treatment objectives, and receives the most operator attention. Supplying oxygen to the activated sludge basins typically consumes more than 50% of the total energy used in wastewater treatment. This represents a significant portion of the plant's operating budget.

It is therefore surprising to realize how poorly automated the activated sludge process is in most wastewater treatment plants.

This book has two objectives. The first, and most important, is to improve and sustain process performance and enable operators to consistently meet treatment objectives. The second objective is to provide the tools and techniques required to achieve the first objective while minimizing the energy requirements of the process. Fortunately, the two objectives are complementary—it isn't necessary to sacrifice process performance and stability in order to optimize energy use.

There are many unit processes employed in wastewater treatment of both municipal waste from primarily residential sources and industrial waste. The principal concern of this text is the automation and energy optimization of suspended growth activated sludge facilities.

## 1.1 BASIC CONCEPTS AND OBJECTIVES

The primary objective of the automation system is maintaining the required process performance. This objective must be kept in mind during all phases of the evaluation and design procedure. They don't build wastewater treatment plants to save energy—they build them to remove pollutants from wastewater. A treatment plant doesn't become a headline in the morning paper by using the same amount of electricity at the treatment plant that they did last year! Furthermore, in the United States and most of the world, a government body issues permits establishing the required level of treatment. Failure to meet the permit requirements can result in fines and other penalties.

The activated sludge process is an *aerobic biological* process. In the basic *activated sludge* process, organic pollutants in the influent waste stream are absorbed by microorganisms. In an aeration basin, the microbes are suspended in the wastewater, and this combination of biology, water, and pollutants is referred to as *mixed liquor*. The microbes are not suspended as individual organisms, but they form clumps or *floc* particles. The microorganisms utilize oxygen dissolved in the wastewater to metabolize the pollutants (Figure 1.1). After being carried through the aeration basin by the wastewater flow, the microorganisms pass into the secondary clarifier. In the clarifier, the floc settles to the bottom and the microbes are pumped back to the aeration basin for another cycle of removing pollutants. The settled microbes are called *sludge*. The treated wastewater passes to disinfection and then into the receiving water (Figure 1.2).

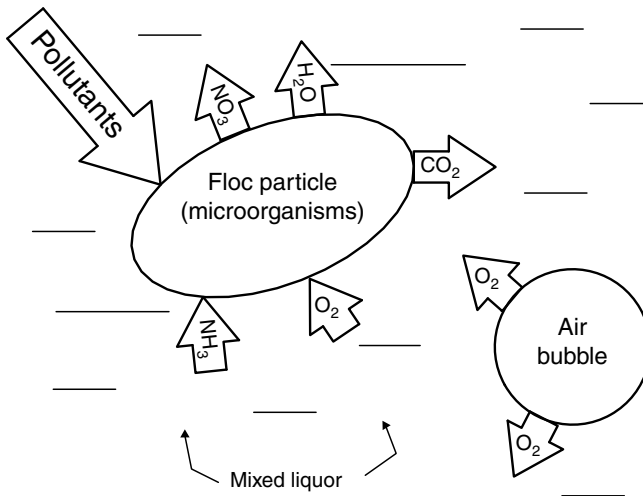
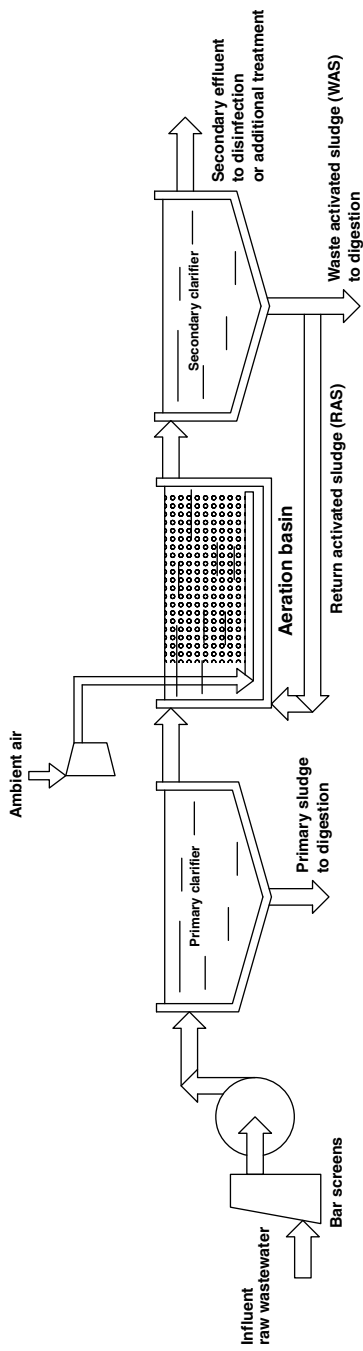


FIGURE 1.1 Simplified biological process



**FIGURE 1.2** Typical activated sludge treatment processes

The most prevalent pollutants fall into one of two categories. The first category consists of *carbonaceous* compounds—essentially the organic compounds that make up human and industrial waste. These are most often measured and reported as *biochemical oxygen demand* (BOD). The second principal category consists of *nitrogenous* compounds, the most significant of which is ammonia ( $\text{NH}_3$ ). Conversion of the ammonia to nitrate ( $\text{NO}_3$ ) is called nitrification. Phosphorus is a compound that is regulated in some permits, and its removal requires a high level of process control but little additional energy. Toxic compounds are sometimes a concern, as are odors, unsightly appearance, and pathogens.

The most significant effect of both carbonaceous and nitrogenous compounds is depletion of the oxygen in the receiving water to a level that is detrimental to aquatic life. In some respects, the purpose of the treatment facility is to supply the pollutants' oxygen demand in a controlled fashion so that the demand is not exerted on the receiving water.

The flow into a treatment process or facility is referred to as *influent*. The flow out of a process or facility is referred to as *effluent*. The load to the treatment plant is further categorized as *hydraulic load*, which is the volumetric flow rate, and *organic load*, which is the combination of carbonaceous and nitrogenous pollutants that must be treated. Both types of load influence the design and performance of the treatment processes. The concentration of pollutants varies from one facility to another and also varies with time within a given facility. In some instances, the organic load dominates treatment process design and performance, and in other instances, the hydraulic load is more significant.

Once the primary objective of pollution abatement is achieved, it is possible to move on to optimizing the operation of the treatment plant—providing the required treatment at the lowest cost. This can include many aspects of running the treatment plant, including optimal staffing, extending equipment life, and reducing chemical use. Automation can help optimize all of these. One of the most desirable goals of optimization is reducing energy cost, and automation is critical to its successful achievement.

Aeration is an energy-intensive process. Approximately half of all energy used in a typical wastewater treatment plant is used to provide oxygen to the microorganisms in the aeration basins. The usual source of oxygen is simply ambient air. The air is either mechanically mixed into the wastewater using surface aerators or diffused into the wastewater by bubbling air under pressure into the bottom of the aeration basin.

Note that the stated goal is reducing *energy cost*, not reducing *energy consumption*. When discussing electrical energy, the terms *energy*, *cost*, and *power* tend to be used interchangeably, at least in casual conversation. However, as professionals, it is important that we distinguish between these terms. They are related, but definitely distinct.

Energy is the ability to do work, or the amount of work done. It theoretically consumes a fixed amount of energy to move a given mass of water uphill a given distance, for example. Units of measure for energy are the same as those for work and include Joules, Watt-hours, and foot-pounds. In mechanics, energy is calculated as force  $\times$  distance.

**Equation 1.1**

$$E = F \cdot d$$

where

$$\begin{aligned} E &= \text{energy, ft lb}_f \\ F &= \text{force, lb}_f \\ d &= \text{distance, ft} \end{aligned}$$

Energy is available in many forms—heat, electricity, kinetic energy, potential energy, and so on. Aeration systems rely primarily on electricity, and it is the principal focus of aeration energy conservation efforts and aeration control system design.

Mechanical, heat, and electrical energy can be converted to one another. One British thermal unit (BTU), a common measurement of heat energy, is the equivalent of 778.2 ft lb or 0.0002931 kWh. Analyzing the conversion and transmission of energy consumes a great deal of engineering effort. In some cases, the conversion is intentional. For example, boilers and steam turbines convert heat energy to mechanical energy, and generators convert mechanical energy to electricity. In other cases, the conversion is unwanted, such as the heat generated by friction or the resistance in electrical circuits. The heat created by electricity is proportional to the resistance ( $R$ ) and the square of the current ( $I$ ) passing through it, and is often referred to as “ $I$  squared  $R$ ” or “ $I^2R$ ” losses.

Power is the rate of energy use or the rate of work. Power includes a time dependency. To move a given amount of water the same distance in 1 second takes more power than to do it in 1 hour, although the energy used is the same in both cases. Units of measure for power include Watts and horsepower. In mechanics, power is calculated as work divided by time:

**Equation 1.2**

$$\text{horsepower} = \frac{550 \text{ ft lb}_f}{\text{s}}$$

where

$$s = \text{time, seconds}$$

Pumping water is a common energy use in wastewater conveyance and treatment. Pumping power is a function of two variables. One is the flow rate—the weight of water being pumped. The other is the head—the pressure of the system, generally measured as the equivalent height to which the water is being lifted.

**Equation 1.3**

$$P_w = \frac{Q_w \cdot h \cdot SG}{3960}$$

where

$P_w$  = water power, hp

$h$  = pump head, ft

$Q_w$  = flow rate, gpm

SG = specific gravity, water = 1.0, dimensionless

In electrical systems, power is a function of voltage and current. The determination in direct current (DC) circuits is straightforward. For simple DC circuits:

**Equation 1.4**

$$P = V \cdot I$$

where

$P$  = power, W

$V$  = voltage or electromotive force (emf), V

$I$  = current, A

In alternating current (AC) circuits, additional considerations regarding phase and power factor must be considered:

**Equation 1.5 (Single-phase AC only)**

$$P = V \cdot I \cdot \text{PF}$$

**Equation 1.6 (Three-phase AC only)**

$$P = V \cdot I \cdot \sqrt{3} \cdot \text{PF}$$

where

$P$  = power, W

$V$  = voltage or electromotive force (emf), V

$I$  = current, A

PF = power factor, decimal

The basic unit of electrical power is the Watt, but that is too small a unit of measure for many applications. The kilowatt (kW), 1000 W, is most often used when discussing power requirements for motors and similar loads in a wastewater treatment plant.

Power requirements for pumps, blowers, and other process equipment are often given as brake horsepower (bhp). This is the power required at the shaft of the driven equipment. This may be converted to pump motor power in kilowatt:

**Equation 1.7**

$$P = \frac{\text{bhp} \cdot 0.746}{\eta_m \cdot \eta_{vfd}}$$

where

- $P$  = power, kW
- bhp = shaft power, hp
- $\eta_m$  = efficiency of motor, decimal
- $\eta_{vfd}$  = efficiency of variable-frequency drive if used, decimal

Power factor is a concept that is commonly misunderstood. Power factor in an AC system is the ratio between a system’s real power (used to perform work) and apparent power (VA or kVA). For three-phase loads, the apparent power is

**Equation 1.8**

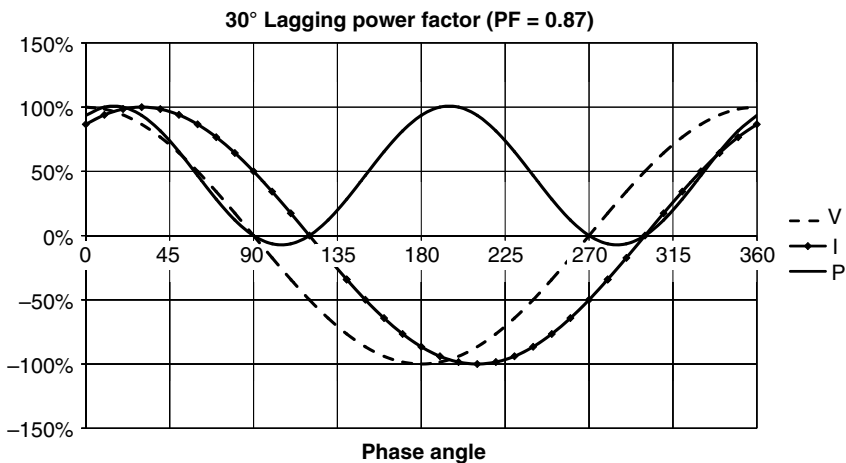
$$S = V \cdot I \cdot \sqrt{3} = \frac{P}{PF}$$

where

$S$  = apparent power, VA

In an AC system with inductive loads such as motors or transformers, the flow of current lags behind the rising voltage because the current flow must create a magnetic field in the inductor. Energy is stored in the inductor, and as the voltage drops, the magnetic field collapses, releasing current into the circuit. The real power waveform also lags behind the voltage waveform, and real power may be negative—in effect actually sending power back into the source.

The power factor is the cosine of the angle of phase difference between the voltage and the current waveforms (Figure 1.3). It is usually expressed as a decimal between 0 and 1, but may also be expressed as a percentage between 0 and 100%. The greater



**FIGURE 1.3** Effect of power factor

the phase shift, the lower the power factor is. In a circuit with purely resistive loads, the power factor is 1.0.

A system with a power factor less than 1 requires higher current from the electric utility to deliver the same real power to the load. This increases the  $I^2R$  losses in the transmission system, increasing the cost to the utility to deliver the useful power. Low power factors also require increasing the size of wires and switchgear, resulting in higher costs for transmission and distribution equipment.

Real power is the rate of energy usage. In electrical systems, energy consumption itself is usually measured and expressed in kilowatt-hours (kWh):

### Equation 1.9

$$E = P \cdot t$$

where

$E$  = energy, Wh or kWh

$P$  = power, W or kW

$t$  = time, h

Cost is an economic consideration. Consumption is one basis for the cost of energy, but far from the only one. Other factors that affect the cost of energy include time of day and rate of use. It's possible to reduce energy cost without any change in energy consumption. In most systems, the objective is to reduce the cost of energy, so the utility billing structure is just as important as the energy consumption itself.

This leads to consideration of *efficiency*, a term too commonly misused and abused. The concept is simple enough: Efficiency is the ratio of desired output to total input, usually expressed as a percent. For a pump, for example, efficiency is the ratio of "water power" to "shaft power." This is straightforward, and the terms are well defined. If we want to consider energy cost, however, we need to include the losses for the pump's motor, and if a variable speed drive is used, its losses must be accounted for. In other words, *system efficiency* has to be determined, and the pump efficiency alone isn't sufficient to determine the consumption of electricity.

A common term in pumping is "wire to water efficiency." This takes into account not only the efficiency of the pump itself but also the electric motor and variable-frequency drives (VFD):

### Equation 1.10

$$\eta_{ww} = \frac{(Q \cdot h / 3960) \cdot 0.746}{P_e} \cdot 100$$

where

$\eta_{ww}$  = system wire to water efficiency, %

$Q$  = flow rate, gpm

$h$  = pump head, ft

$P_e$  = total electrical input power to the pump system, kW

For blowers and compressors, it's more complicated—the blower efficiency used can be referred to as adiabatic, isentropic, polytropic, or isothermal. Further complicating the use of this term is that for any given device the efficiency varies depending on the load and other factors. Manufacturers of pumps and blowers like to quote their best efficiency point (BEP) value or the efficiency at the design point, but in fact, the equipment seldom operates at the exact flow and pressure corresponding to these points.

Even using system efficiency correctly in the analysis may not accurately reflect the actual energy use or cost. If a pump is throttled to reduce flow, the discharge pressure will increase. The pump and motor efficiencies may both decrease. The flow rate will also decrease, and consequently, the pump shaft power demand will also decrease. The drop in efficiency is more than offset by the drop in power, and throttling the pump will reduce the energy consumption and the energy cost.

Misuse of the term efficiency gets worse when we look at the general public. “Energy efficiency” is frequently used as a synonym for “energy conservation.” A vehicle’s “fuel efficiency” is often expressed in miles per gallon, although technically it should be the ratio of the engine output energy to the energy contained in the fuel consumed.

In this text, we will minimize the use of the term “efficiency” and take pains to clearly define it when it is used.

## 1.2 SAFETY

Electricity kills.

Some mistakes you only make once—then you're dead.

The first and most important task in development of any system is the integration of safety into design and commissioning procedures. An important task in any design process is verification that proper safety features are included in the design. The last task in system commissioning is training the operators in proper safety procedures and precautions.

Hazards in wastewater aeration systems come in many forms. Air under pressure in piping systems creates hazards. The pressure may be released suddenly and explosively. Most electrical equipment operates at dangerous voltage levels; lockout/tag out procedures, personal protective equipment (PPE), and proper test equipment and procedures must be used. Physical injury can result from rotating equipment starting automatically and unexpectedly. Belt drives can fail suddenly and catastrophically, sending belt fragments flying across a building; adequate guards and precautions must be taken. Confined spaces in wastewater treatment plants contain poisonous and explosive gases, many of them undetectable by humans; proper entry procedures and gas detection devices should be used. Aeration tanks are generally so turbulent that they represent an extreme drowning hazard; proper railings, lifelines, and a companion should be available. Sewage contains a variety of pathogens; appropriate inoculations should be obtained, and washing and disinfection procedures should be followed after exposure. Every construction site has open trenches,

and many instrumentation and control system components are installed in elevated locations; observation of surroundings, vigilance, and using appropriate procedures are essential.

This is far from a comprehensive list of hazards and threats found in wastewater treatment facilities. The intent of identifying potential hazards isn't to frighten the reader away from the field. The intent is to ensure that proper precautions and safety procedures are always followed, so the reader can enjoy a long career in the field!

The Occupational Safety and Health Administration (OSHA), the National Electric Code (NEC), and Underwriters Laboratories Inc. (UL) are among the many organizations and standards intended to promote safety in the workplace. Conformance with these standards is often a legal requirement, either because they are directly part of the law or because they have been incorporated into building codes by the local jurisdictions.

Safety procedures can, on occasion, seem burdensome. Sometimes the requirements seem to have been developed by someone who has never performed fieldwork. It doesn't matter. Safety precautions and safe work practices can never be ignored! Safety should be integrated into every part of automation and control system design and implementation.

### 1.3 THE IMPORTANCE OF AN INTEGRATED APPROACH

The successful operation of an activated sludge process requires knowledge in a variety of technical areas. As with any automation project, the successful aeration system design also involves integration of many aspects of instrumentation and control. Some familiarity with fluid mechanics, biology, chemistry, and electricity is also needed just to maintain minimum process performance. It shouldn't be a surprise that designing an aeration control system demands integration of many engineering disciplines.

There are many terms that are used interchangeably in common use, but should be distinguished during the design process. This text will make the following distinctions:

- *Measurement* is sensing and quantifying a physical parameter or real-world phenomenon.
- *Indication* is the display of measurements in a manner observable and useable by an operator.
- *Monitoring* is tracking and/or recording measurements on a regular or continuous basis.
- *Data acquisition* is a special category of monitoring where a computer is used to indicate and archive monitored measurements.
- *Control* is manipulating devices or equipment to change the performance of the process. Control may be manual or automatic.

- *Equipment protection* is a category of control where the objective is to prevent damage to process equipment by stopping it or shutting it down when operation falls outside defined safe parameters.
- *Process optimization* is a category of control where the intent is to maximize the performance of at least one aspect of the process.

The need to be proficient in instrumentation is an obvious starting point for designing an automatic aeration control system. You can't control what you can't measure. Many of the common instruments for process control—flow, pressure, level, and temperature—are found in aeration control systems. There are also a variety of analytic instruments not commonly found in other industries. For example, mixed liquor dissolved oxygen (DO) measurement is a critical parameter for aeration system control. The instrumentation is integrated into the control strategy as inputs to the control system. This is typical for any process automation, not just aeration systems.

Once the critical process measurements are obtained, the next step is to use them to automatically optimize process performance. The required control logic can be executed in a variety of ways. The simplest devices, such as relay logic and single-loop PID controllers, are still used. They are usually not up to the task of any but the most rudimentary control, and so they are seldom found in aeration control systems. On the opposite end of the complexity scale are full-blown distributed control systems (DCS). These are most often found in large facilities that were early adopters of process automation. Because of the cost and proprietary nature of the programming, use of DCS is decreasing in most wastewater treatment facilities.

The most common system architecture for wastewater treatment process automation is programmable logic controller (PLC) based. Because of the physical separation of process equipment, a number of PLCs are employed with each one dedicated to a process or piece of equipment. The individual PLCs are connected by a communications network. This allows sharing the equipment status and process parameters between PLCs, and coordinating the operation of the separate parts of the process and individual equipment. In most systems, the communications network also links the PLCs to a personal computer (PC). Human machine interface (HMI) or supervisory control and data acquisition (SCADA) software is used to display the measured process parameters, tune the system operation, trend critical data, and log alarms. In addition to the centralized SCADA system, most systems also have localized HMI panels for monitoring the process close to the equipment.

After the control logic is executed, it must act on the process through manipulation of final control elements. The final control elements for implementing the control logic aren't unique to water and wastewater. They include motor starters and variable-frequency drives for pumps, blowers, and general motor control. Valve operators are employed to modulate the flow of process fluids, and motor operators open and close slide gates in process channels.

Integrating the instrumentation, controllers, and final control elements is common to every process automation or monitoring project. Many other aspects of system integration are commonly applied in aeration control. Equipment protection, for

example, is typically included in process control systems. This makes economic sense, since the incremental cost of adding equipment protection to the control system is usually insignificant. The primary sensors are generally part of the control strategy, and the incremental sensors needed to provide equipment protection are a small percentage of total cost.

In addition to simple shutdown and equipment protection, incorporating protection and control into the system provides benefits to operators and owners. Alarm messages, trending of critical variables, and time and date stamps provide diagnostic tools for identifying the initial cause of the equipment failure. Including protection and control in a single system also enables start-up of standby machinery immediately after failure of the primary equipment. This ability obviously reduces operator aggravation, but even more importantly, it reduces or eliminates process upsets and maintains treatment levels.

The requirements for equipment protection are fairly straightforward. Allowable bearing temperatures, maximum motor currents, allowable range of flow, and so on are readily understood and usually well documented in the manufacturer’s operating manuals. An additional level of integration is required to incorporate the operating characteristics of the process equipment into the system. This is where the requirement for a cross-disciplinary approach to system design begins.

Process optimization requires a more in-depth understanding of the equipment’s performance. What is the BEP? How does it vary as the controlled devices are adjusted? How does the change of one parameter affect other aspects of the equipment operation? What is the response time of the equipment to control changes? These questions have implications on the control strategy.

An understanding of the variations in process loadings is necessary for developing the control logic. Unlike many industrial processes, loads to the treatment plant vary continuously and uncontrollably. Both hydraulic and organic loadings are affected by the daily fluctuations in population activity. These *diurnal* variations (Figure 1.4) are part of the challenge in developing an aeration control strategy. There are further

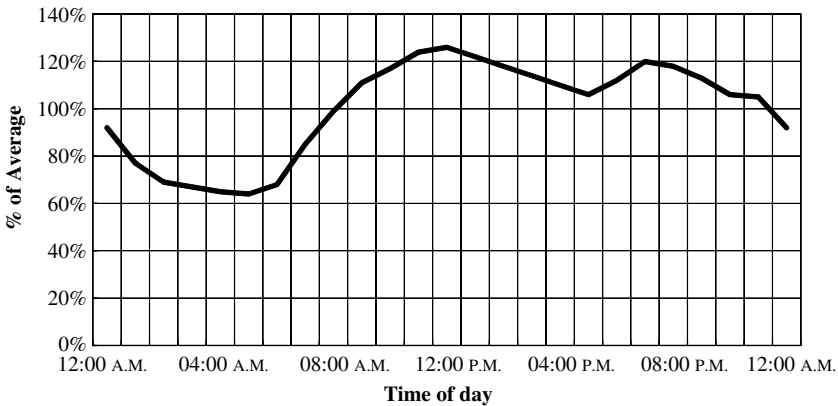


FIGURE 1.4 Typical diurnal hydraulic load variation

challenges from rain events, industrial slug loads, plant internal sidestreams, and seasonal temperature changes. These must all be accommodated in the control strategy.

A more demanding consideration is the process and energy implications of modulating process equipment. The operation of the equipment has an impact on the process—otherwise it wouldn't be needed—and on energy cost. Unlike many processes, activated sludge has a variety of complex interactions. Changes in one parameter, such as air flow rate, have a cascading effect. The oxygen transfer efficiency of the diffusers will change, the DO concentration will change, and the biology's rate of metabolism may change. This can affect settleability in the clarifiers, altering the concentration of the microbes in the return sludge to the aeration basins, further modifying process performance. Some of these reactions are very rapid; others may take hours or even days to occur.

## 1.4 IMPORTANCE OF OPERATOR INVOLVEMENT

There is generally no one who understands the operation of a treatment plant and the process interactions better than the plant operators. Every treatment plant is a unique combination of process equipment, loadings, and performance requirements—no two plants are the same. A “green field” plant, starting from scratch with a blank slate, is a rarity. It is absolutely essential to obtain the input of the operators and their experience with the facility and the process during the design stage and throughout the implementation and commissioning.

A lot of lip service is paid to the concept of operator involvement. Unfortunately, when operators express views that contradict the designer's preconceived ideas or don't match a “standard” design, the operator's opinion is often discounted or ignored. This is almost always a mistake. The plant staff may not be able to articulate the explanation for a potential problem, and they may not know the scientific basis for the phenomenon they observed. However, if an operator makes a statement about the advisability of a particular device or strategy, it behooves the designer to dig until he understands the basis for the statement. Then appropriate measures can be taken to either eliminate the cause or accommodate the occurrence in the system design or the control strategy.

When an operator makes cryptic statements such as “We tried that and it didn't work,” it's understandable that the result is frustration for the designer. Remember, however, that the operator is also frustrated to see past mistakes being repeated! The designer's normal response is to ignore the comment and proceed based on the designer's past experience, whether or not this conflicts with the operator's opinion. The designer instead should investigate the details, determine the circumstances, and come to understand the causes and science behind the statement. Then changes can be made to either eliminate the causes or accommodate the realities in the control strategy. This not only improves the performance of the system but also creates a valuable ally in the operations staff! Above all, the designer must avoid clinging to theoretical purity in the face of pragmatic reality.

It is a truism that if an operator is convinced a particular system or device won't work, it won't. This doesn't imply sabotage or negligence by the plant staff! In general wastewater treatment plant operators are well above average workers in their conscientiousness, capability, and professionalism. This statement is simply an acknowledgment of human nature. Commissioning a control system, debugging the program, and maintaining analytic instruments involve a lot of effort. Most treatment plants are minimally staffed, and many tasks compete for the operator's time and attention. It's to be expected that a system forced on an unwilling and skeptical staff won't receive extra effort and attention. The inevitable result is a self-fulfilling prophecy: "It won't work."

The configuration of HMI screens and SCADA systems are particularly important areas for operator involvement. They are the operator's window into the process. The operator must be able to quickly read the screens, turn data into information, and make decisions about how the process and the equipment are performing. Colors, grouping of displays, units of measure, trending, and alarm messages must be configured in ways that make sense to the operator, not necessarily to the designer. Navigation from screen to screen should be as intuitive as possible.

During commissioning, the operator's opinions should be solicited and accommodated. This creates "buy in" by the staff. If they can see that the intent is to provide a tool to make their job easier and the plant run better, they will devote the extra effort and attention needed to make the control system successful.

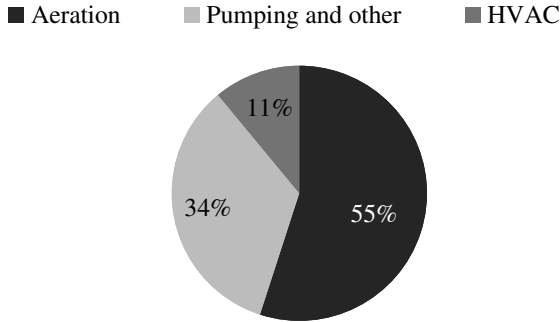
Above all the designer and start-up personnel must remember that it is the operator's plant, and they will live with the system for years. Acknowledging their needs and expertise isn't just good engineering—it's giving fellow professionals the respect they merit.

## **1.5 THE BENEFITS OF SUCCESSFUL AERATION PROCESS AUTOMATION**

When it's done right, an aeration control system is a win for all stakeholders. The supplier obtains a commercial success by providing a valuable service. The operating staff gets a useful tool for doing their job better and more efficiently. The owner and rate payers have a reduction in expense and operating costs for a necessary community service. The public in general benefits from a better environment. This all speaks to the triple bottom line: public, planet, and profit.

### **1.5.1 Energy Cost Reduction**

The justification for aeration controls is usually based on energy cost reduction. This can have a significant impact on a community's budget. Water treatment and wastewater treatment combined represent 3–4% of the total US energy consumption, with approximately equal amounts for each. For a typical municipality, these two treatment plants consume 30–60% of all the energy used by the municipality.



**FIGURE 1.5** Typical WWTP energy use

Inside the treatment plant, the aeration process is nearly always the largest single energy use, usually accounting for more than half of all the electric power used (Figure 1.5).

Clearly, the aeration process represents the first and best target for energy conservation and energy cost reduction. All indications show that energy cost will continue to escalate, and the potential benefit of aeration control will also increase.

The amount of energy savings obtainable from automation varies significantly from plant to plant. A conservative value for most plants is 25% reduction in energy cost for the aeration process by changing from manual control to automatic aeration system control. Most systems provide a simple payback of 3–5 years for the control system investment.

There is a wide variation in the savings and cost of aeration controls. Plant size, expressed in terms of hydraulic load, makes an obvious difference in the total value of the savings available. Note that small and large treatment plants generally have the same unit processes—large plants just have more and larger equipment. This is fortunate, as there are many more small plants than large ones (see Table 1.1). The

**TABLE 1.1** Operating Wastewater Treatment Plants in the United States (EPA, 2004)

Design Flow Range, mgd	Number of Facilities	Total Existing Flow, mgd	% Facilities
0–0.1	6,830	298	41.2%
>0.1–1.0	6,431	2,327	38.8%
>1.0–10.0	2,771	8,766	16.7%
>10.0–100.0	503	13,233	3.0%
>100.0	41	9,033	0.2%
Other	7	–	–
<b>Total</b>	<b>16,583</b>	<b>33,657</b>	<b>100.0%</b>

*percentage* savings available in a small facility may equal or even exceed the *percentage* savings available in a large plant.

A common metric for judging energy efficiency in wastewater treatment facilities is the amount of energy consumed per million gallons treated, kWh/mil gal. A typical activated sludge treatment plant uses between 2000 and 3000 kWh/mil gal treated, but there is a huge variation in that value. Some facilities use half the energy; others use several times that amount. Plant size is a factor, and in general, large plants use less energy per million gallons treated. Organic loading is another factor that affects the potential savings, and in many cases, this is more significant than hydraulic load. Plants that have a significant load from industrial facilities such as food processors may have organic loading larger than plants treating predominantly domestic wastewater. In these facilities, energy per pound of BOD removed, kWh/lb BOD, is a better metric for evaluating savings.

The level and type of treatment required by the plant's discharge permit changes the energy requirements. Adding nitrification, for example, can easily double the aeration system's power requirement. If the process design includes denitrification, the energy requirement will decrease because some oxygen is recaptured by the denitrification process.

The source and delivery method of the oxygen provided to the aeration process are other significant variables. In diffused aeration systems, the efficiency of the blowers and the oxygen transfer efficiency of the diffusers have an impact. In mechanical aeration systems, the oxygen transfer rate is a key parameter. Solids handling and sidestreams will also change the organic loading to the aeration basin.

Operator process control strategy will also affect energy use by the aeration system. Higher solids inventory (larger microbe population) directly affects the oxygen uptake rate. If the DO concentration in the mixed liquor is higher than necessary, it will result in increased air flow and aeration power. Operating unneeded aeration tanks at minimum air flow increases energy use without benefiting the process. Each of these factors affects others, and all must be integrated into the control system design.

One of the critical steps in developing an aeration control system is projecting the savings in energy costs. This establishes the size and complexity of the system, since the cost of the system must be offset by the savings in a reasonable time. If the savings are overestimated, the project will be a commercial failure, whether or not it is a technical success. Making accurate projections requires a detailed understanding of the process interactions.

There are two methods commonly used to determine if a proposed control system is cost-effective or to determine the best selection among alternates. Simple payback is commonly used for quick analysis, evaluation over short time frames, or for comparing alternative systems. The other, more sophisticated analysis is, based on present value or present worth. It includes consideration of the time value of money, potential earnings from other investments, and inflation. Simple payback is more common in evaluating control system additions to existing facilities, and present worth analysis is more common in evaluating large projects or comparing aspects that are part of a major facility modification.

**Equation 1.11**

$$P = \frac{C}{S}$$

where

- $P$  = simple payback period, the time required for the savings to offset the investment, years
- $C$  = net total initial cost for equipment and installation
- $S$  = net annual savings (energy and maintenance), \$/year

**Equation 1.12**

$$NPW = (PWF \cdot S) - C$$

**Equation 1.13**

$$PWF = \frac{(1 + r)^n - 1}{r \cdot (1 + r)^n}$$

**Equation 1.14**

$$r = \frac{R - I}{1 + I}$$

where

- NPW = net present worth of investment, \$, NPW > 0 means the investment is economically justified
- $S$  = annual savings, \$
- $C$  = capital cost for equipment and installation \$,
- $n$  = total evaluation period, years
- $I$  = annual inflation rate, decimal
- $R$  = annual discount rate, decimal, typically the interest rate or rate of return on alternate investments
- $r$  = effective annual discount rate, decimal
- PWF = present worth factor, dimensionless

Regardless of which method of economic analysis is used, there is a considerable level of uncertainty involved. The savings and equipment costs are typically known with a fair level of confidence, but will vary significantly with the accuracy of the initial assumptions and the analysis methodology. Greater levels of uncertainty are associated with estimated inflation rates and discount rates, as these are influenced by factors in the general economy outside the control of the system designer and which must be projected into the future. Many engineers assume that the more complex

present worth analysis will provide more accurate results. The longer the evaluation period, however, the greater the uncertainty associated with this method. The shorter the evaluation period, the smaller the difference in the results obtained from the two methods. For most projects, the simple payback method is recommended.

The ultimate decision on the project design must include intangible factors as well as economic evaluation. These intangibles include customer preferences, reliability, and experience. Engineering judgment should take precedence over blind adherence to predictions of economic effects, regardless of the calculation method.

### 1.5.2 Treatment Performance

From an operator's perspective, the most important benefit of a properly functioning aeration control system may well be improved process performance. They recognize the advantages of reduced energy cost, of course, but process performance is always the first priority. The operating reductions in energy expense justify the cost of the system, but the process improvement and stability provide a substantial impetus for adoption.

One guarantee of process failure is operating the aeration basin *oxygen limited*—not providing sufficient oxygen to the mixed liquor to support the metabolism of the organic load by the microorganisms. Even more significant, if the process operates at an oxygen deficit for an extended period the microbe population will change, with the population of less desirable microorganisms increasing. This has long-term negative implications for treatment performance. Proper aeration control can prevent this.

There are other process benefits derived from a successful aeration control system. Marginal DO concentrations in the mixed liquor may result in growth of undesirable filamentous organisms. Even if the required BOD removal or nitrification occurs, these filamentous organisms may not settle properly in the secondary clarifier. This can result in a permit violation for excess total suspended solids (TSS) in the effluent, may inhibit solids dewatering and may interfere with solids digestion. The same deleterious effect may result from excess aeration breaking up the floc and reducing settling or from filamentous organisms that grow after long-term operation at very high DO concentrations. The sludge volume index (SVI) is a measure of solids settleability, and experience has shown that SVI improves when DO control is operating.

The cost reduction associated with process improvement is difficult to quantify and using it in economic justification is not recommended. Furthermore, since process considerations override cost considerations, the impact of aeration control on treatment may be sufficient justification in itself, regardless of savings. This is particularly true in advanced processes, where traditional manual control methods may prove inadequate in providing the required level of treatment.

### 1.5.3 Improved Equipment Life

A wastewater treatment plant represents a significant capital expense, and is often one of the largest investments for a municipality. A large part of this investment is for

structures such as buildings and tanks, but a significant part of the investment is for equipment. Ensuring that the process equipment reaches the 20-year design life is an important part of the operators' responsibility. Machinery preventive maintenance and repair is a major expense and manpower requirement. Improvement in equipment life and reduction in maintenance expenses are benefits of most automation systems, and this is particularly true for aeration control.

The equipment protection functions are responsible for much of the improvement. By monitoring equipment operation and performance, the system can shut down machinery as soon as unsafe operating conditions are detected. This eliminates "run to failure" operation and reduces the scope and complexity of repairs. The early warning of operational problems will also provide diagnostic information to simplify and accelerate troubleshooting procedures.

The process equipment in a treatment plant must run 24 hours a day, 7 days a week, 365 days per year. It is simply not possible to stop operations because of a failure. Publicly owned treatment works are consequently required to have standby equipment for all critical functions. In order to keep all pieces of equipment operational, it must be run periodically. A machine that sits idle for months or years and is then started will not run long before failure occurs. By simplifying alternation of the running machinery or by automatic alternation, the aeration control system can provide uniform operating time for all of the process equipment.

Clearly, aeration control systems provide a great many benefits. Some of these are quantifiable as reductions in operating cost, and some are less easily defined. Obtaining these benefits requires integration of several areas of technology and a thorough understanding of the process and the process machinery. The analysis and design procedures that follow provide the guidance needed to successfully implement aeration control.

## EXAMPLE PROBLEMS

### Problem 1.1

- (a) Plant staff reports a pump motor current measurement of 223 A. From the plant electric bill, it is determined that the nominal plant supply voltage is 480 VAC three phase and the average plant power factor is 83%. What is the apparent power of the motor? What is the estimated power consumption?
- (b) Subsequent measurements with a power meter at the motor terminals show the actual motor voltage to be 469 V, and the measured motor power factor is 87.8%. What is the apparent and actual motor power with the revised data?

### Problem 1.2

The influent lift station at a treatment plant has a design capacity of 8 mgd. The station has three identical pumps with characteristic curve shown in Figure 1.6. The

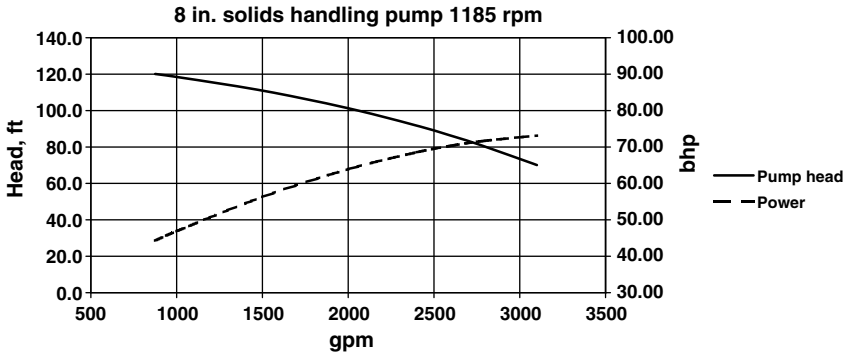


FIGURE 1.6 Problem 1.2 pump curve

average dry weather flow for the plant is 2 mgd, the reported discharge head is 80 ft, and the power consumption is measured as 58 kW using a true power meter at the motor control center.

- What is the operating flow rate of the pump?
- What is the corresponding pump shaft power?
- What is the wire to water efficiency?
- What is the pump efficiency?

**Problem 1.3**

What is the operating cost of the pump if the cost of electricity is \$0.08/kWh?

**Problem 1.4**

It is proposed that 75 hp variable-frequency drives be provided for the pump system in Problem 1.2. The installed cost of each drive is estimated at \$7500 each.

- Is this cost-effective if the billing is based on energy consumption only at \$0.08/kWh?
- Is this cost-effective if the billing is based on energy consumption at \$0.06/kWh and a demand charge of \$9.00/kW?

**Problem 1.5**

List at least three benefits obtained from automating the aeration process.