Emerging Biological Treatment Methods: Aerobic and Anaerobic

Researchers have uncovered fundamental concepts of biological waste treatment and engineers are designing systems to make the environment safe now and in the future.

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IN THE FIRST HALF of this century biological wastewater treatment plants were designed on a trial and error basis and emphasized structures and hydraulics. Design engineers knew next to nothing about the biological processes that were the very heart of the biological treatment plants that they were designing. Consequently, some biological treatment plants failed to provide the desired treatment.

Early Studies

Prior to the late 1940s and early 1950s, wastewater treatment design required little knowledge of biological concepts, and sanitary microbiology had no interest in treatment systems. The theory of biological wastewater treatment was limited to the point of non-existence. During this period, both faculty and students at M.I.T. recognized this void in the research and raised more questions than there were answers available. Laboratory experiments were developed to combine basic concepts with potential engineering systems. Although the research involved was still conducted on a trial and error basis, each experiment saw the number of trials producing errors quickly reduced, and each success led to a better understanding of treatment concepts.

One faculty member, C.N. Sawyer was heavily involved in biotreatment research for industrial wastewater treatment at this time. As a chemist, he approached biological treatment from a chemical point of view. He was interested in how much nitrogen and how much phosphorus were required for trickling filters and activated sludge. Sawyer found that sound biological treatment of industrial wastes required specific quantities of nitrogen and phosphorus, and that this treatment produced varying amounts of excess solids at different temperatures.[1,2,3]

At the same time, questions were being raised about the microorganisms that comprise biological treatment systems. Since sanitary bacteriology had limited answers and conventional bacteriology provided even

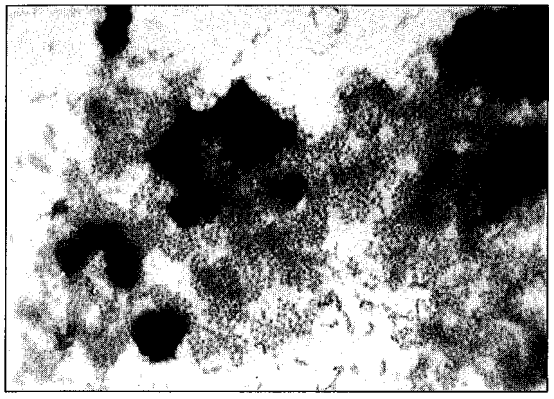

FIGURE 1. Young activated sludge grown on soluble organics showing individual bacteria around edges of dense clumps of bacteria (970 X).

fewer answers, it was necessary to start with aerobic bacteria and build a knowledge base to explain how these bacteria stabilized organic wastes and to discover what were the quantitative relationships exhibited under different environmental conditions. Since bacteria were not the only microorganisms involved in the treatment processes, the study expanded to include fungi, algae, protozoa, crustaceans and nematodes. The problem was defining microbiology under low food conditions. No one appreciated the impact that the specific environment played in the growth of particular microorganisms in mixed cultures.

A.M. Buswell in the early 1920s made extensive microscopic examinations of activated sludge and identified several groups of microorganisms from physical appearances.[4] Filamentous bacteria predominated in this activated sludge: *Crenothrix, Sphaerotilus,* and some *Zooglea ramigera.* In 1935, C.T. Butterfield isolated *Zooglea ramigera* in pure culture and stated that it was the primary floc-forming bacteria in activated sludge.[5] L.A. Allen attempted to evaluate the bacteria in activated sludge.[6] He found that homogenized sludge contained 2.2 billion bacteria per ml, but he was unable to isolate *Zooglea ramigera.* The bacteria he found were classified as *Achromobacter, Chromobacterium* and *Pseudomonas.*

There was little concern about the specific metabolism of zoogleal bacteria making up activated sludge. Researchers assumed that zoogleal bacteria grew in any substrate, since activated sludge was formed in most wastewater. Another assumption was that zoogleal bacteria were able to obtain food more efficiently by absorbing it into the gelatinous matrix surrounding the zoogleal bacteria. Since these assumptions had little impact on design, design engineers accepted them readily.

Floc Formation

In 1950 there were some interesting questions raised at M.I.T. about the role of *Zooglea ramigera* in activated sludge:

- If *Zooglea ramigera* was so important in activated sludge, why was it so difficult to isolate in pure culture?
- If the gelatinous material absorbed food so readily for the zoogleal bacteria, why was the gelatinous matrix impossible to stain with ordinary bacterial stains?
- How could one group of bacteria metabolize so many different types of organic compounds?

In an effort to answer these questions, researchers at M.I.T. employed a technique in which the aeration tank was simulated in pure culture aeration systems with a soluble organic substrate. Their results showed that several bacteria isolated in pure culture were capable of forming floc in the same manner as *Zooglea ramigera.*[7] Further studies revealed that many other common bacteria could be isolated from activated sludge and could form floc similar to the zoogleal bacteria.[8] There was no need for special zoogleal bacteria to produce activated sludge. It soon became apparent that almost any bacteria could be made to flocculate under the proper environmental conditions (see Figure 1). From the design engineering standpoint, this research changed the techniques required for activated sludge development.

Examination of floc indicated that motile bacteria predominated over non-motile bacteria because of their ability to remain dispersed, presenting a greater surface area to mass ratio for more efficient food gathering

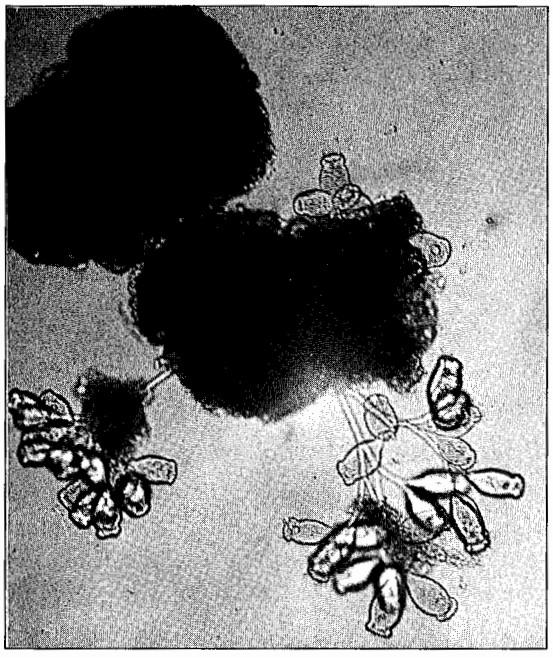

FIGURE 2. Colonies of stalked ciliated protozoa growing on dense clumps of bacteria in activated sludge (430 X).

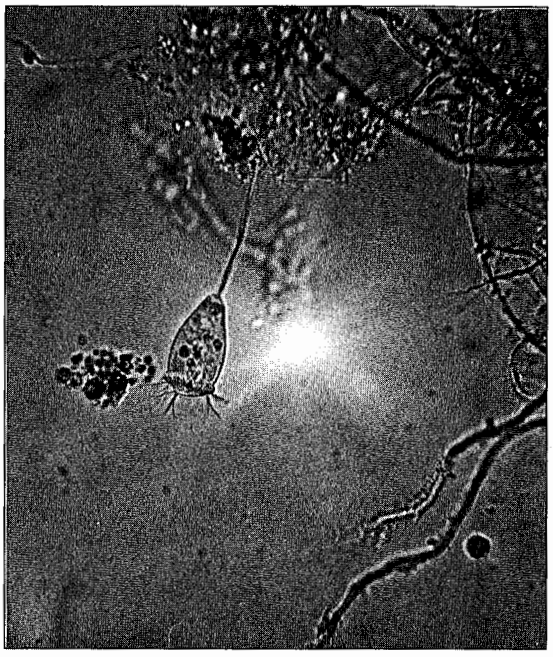

FIGURE 3. Single stalked ciliated protozoa *(Vorticella)*, showing the cilia used for catching dispersed bacteria, aids in the production of highly clarified effluent that is characteristic of a well-operating activated sludge system (970 X).

across the cell wall. As long as food remained unmetabolized, the motile bacteria remained dispersed. Once the food was metabolized, the bacteria could not remain motile and tended to form tiny aggregates under the mixed conditions created by aeration. Repeat feeding of fresh food resulted in the partial dispersion of active bacteria and the accumulation of dead bacteria residues. Examination of the dead bacteria residues indicated that these residues were predominantly polysaccharide materials that appeared similar to the gelatinous material produced by the zoogleal bacteria.

As Buswell had observed many years earlier, activated sludge was a mixture of bacteria and protozoa (see Figure 2). Research on mixtures of protozoa and bacteria confirmed earlier observations that protozoa play a secondary role in activated sludge by clarifying the liquid-dispersed bacteria and by producing additional dead cell mass to accumulate as inert suspended solids in the activated sludge floc (see Figure 3).[9] Thus, it was established that activated sludge floc can be created by all the different species of bacteria and protozoa that are able to grow in the aeration tank. Accumulation of inert suspended solids accompanied by aeration equipment mixing helps provide additional surfaces for flocculation. However, the microbes must have adequate metabolism time for floc formation of value to result.

Organic Metabolism

After having established the formation of activated sludge floc, attention was turned to the metabolism of organic matter by bacteria in the aeration tank. Hoover and Porges, in their 1952 study of activated sludge treatment of dairy waste, indicated that approximately 38% of the skim milk substrate was oxidized in 6 hours.[10] The remainder of the substrate was converted to microbial protoplasm that had an empirical formulation of $C_5H_7O_2N$. Once the skim milk was metabolized, the microbes underwent endogenous respiration with oxidation of the microbial mass produced by synthesis. Hoover and Porges thought that

it was possible to have complete oxidation of microbial solids so that no excess activated sludge would have to be removed from the system. However, total oxidation was not possible, since approximately 20% of the cell mass produced by synthesis remained as dead cell mass after endogenous respiration was complete.

Although Hoover and Porges' studies did not result in total oxidation, they stimulated further studies into the metabolism of various organics in order to delineate energy-synthesis relationships. Additional studies at M.I.T. indicated that metabolism could be grouped into major classes of organics such as carbohydrates, proteins, and fatty acids.[11] The resultant substrate energy was deemed critical for determining the synthesis of newly activated sludge. A later study pursued a different approach to data evaluation that permitted delineation of the break between synthesis and endogenous respiration.[12] This study revealed that different classes of organics exhibited different energy-synthesis relationships. It was not until continuously-fed activated sludge systems began to be operated in a completely mixed mode that the problem was found to reside with the batch-fed studies. In the batch-fed studies, the initial high-food concentration resulted in different patterns of metabolism for the major groups of organic compounds. Instead of being metabolized to normal cell protoplasm, carbohydrates were converted to polysaccharide. This slime production resulted in lower oxygen requirements for synthesis and increased dead cell mass accumulation since the microbes could not metabolize the slime. Amino acids and fatty acids furnished better results since, unlike carbohydrates, they could not be processed to slime.

The development of basic energy-synthesis relationships was handicapped by the failure of most investigators to recognize that endogenous respiration occurs at the same time as synthesis and that the two reactions are independent. When completely-mixed activated sludge systems operating on a continuously-fed basis were studied it was then possible to develop a simple evaluation of energy-synthesis and endogenous respiration relationships. Started at M.I.T. back in the 1950s and continued over the past 25 years without major change, these studies revealed that one-third of the energy in the biodegradable organics is oxidized. The energy released from this oxidation is then used to convert the remaining two-thirds of the energy into cell protoplasm which immediately undergoes endogenous respiration at 2%/hr at 20°C, based on the active microbial mass. The development of these fundamental relationships permitted the formulation of design equations for use in field scale designs.[13,14,15]

Field Applications

Design engineers in the 1950s were not thoroughly comfortable with the new ideas generated from the current research. Full scale plants would have to be designed, constructed and operated satisfactorily before they were going to accept the fundamental approach to activated sludge design.

Regulatory engineers did not readily accept the new ideas either. It took special situations to demonstrate that these concepts worked as well in the field as in the laboratory. Initial applications were with industrial wastes that could not be treated economically with conventional design concepts. In the 1950s industries were just beginning to look seriously at wastewater treatment and responded positively to new ideas that promised efficient treatment at relatively low cost.

The first application of basic concepts to engineering design was at a small cotton textile plant located in a residential area of New Jersey.[16] The wastewater from the plant contained highly alkaline, carbohydrate type wastes that were considered unsuitable for treatment with activated sludge. The pH was 11 to 12, indicating caustic alkalinity. Microorganisms in biological wastewater treatment prefer a pH range from 6 to 9 and are killed either by strong acids or caustics. In order to achieve the proper pH, acid is normally added to caustic wastewater in sufficient quantities to drop the pH down to somewhere between 7 and 8. The carbohydrates in these textile wastes were primarily starches that stimulated the growth of filamentous bacteria rather than

FIGURE 4. Filamentous bacteria creating a poorly flocculating activated sludge (100 X).

normal activated sludge bacteria. The filamentous activated sludge produced from carbohydrate wastewater appeared like large balls of cotton fibers and settled very poorly in the final clarifiers (see Figures 4 and 5). Laboratory studies showed that it was possible to treat this wastewater with activated sludge provided that the system was completely mixed. In order to employ the same concepts in the field design as used in the laboratory, the aeration tanks were designed in modular units so that the treatment system shifted as the plant production changed. Since this wastewater was deficient in nitrogen and phosphorus, supplemental N in the form of ammonium salts and P in the form of phosphate salts were added to provide the bacteria with these two essential nutrients. By using complete mixing with extended aeration (24 hours) it was possible to minimize the amounts of N and P supplied.

The high concentration of caustic in the wastewater had to be neutralized initially with sulfuric acid until the bacteria level rose to the levels required for carbohydrate metabolism. One of the primary end products of aerobic metabolism is carbon dioxide. This supply of carbon dioxide can accomplish the necessary neutralization of the incoming caustic as long as the caustic is not added too fast. The mixing of fresh wastewater with the activated sludge was able to neutralize the caustic at the same rate as it was added. Thus, no further injections of sulfuric acid were needed to keep the pH in the aeration tanks at a suitable level.

This plant clearly established the concepts of complete mixing in the field. Later, a process change resulted in a change from alkaline to acidic wastes. There was no change in the waste treatment efficiency of 97 to 98%. However, acid-enzymatic treatment of the cotton cloth proved unsatisfactory and the process was changed back to the normal caustic kiering. Eventually, black sulphur-type dye wastes were added to the treatment process. The success of this plant in treating textile wastes led to the adoption of these concepts for other types of textile waste problems in Pennsylvania. There is one interesting note. A large textile manufacturer requested that a major New York consulting firm examine this new treatment process and evaluate it for use in their own wastewater treatment process. The consulting firm sent a young engineer to examine the process. He took one look at the simple construction and left without even looking at the data. His report indicated that the process had no value and should not be considered. The net result was a more expensive treatment process for

FIGURE 5. Filamentous bacteria are shown congregating with dense bacterial clumps in a poor settling activated sludge (970 X).

the industry.

One of the major problems associated with industrial wastewater was developing a satisfactory technique for evaluating the organic strength of the wastewater. At that time, municipal wastewater treatment plant operators used a test that measured the amount of oxygen the microorganisms utilize in a completely closed system at 20°C over a five-day period under aerobic conditions, designated the BOD5. Since the solubility of oxygen in water is very low, about 9.1 mg/L at 20°C at sea level, the amount of organics must be low to permit the test to be accurately run. However, the amount of oxygen used over a five-day period is not the total oxygen required by the bacteria. The BOD5 test does not measure the theoretical oxygen demand of an organic compound. Industrial engineers have found the BOD5 frustrating to work with in testing industrial wastes. Sometimes it yielded accurate results; at other times it yielded totally inappropriate results. The search for a new test led to the dichromate COD test that furnished the total oxygen demand value in two to three hours. However, the COD test produced total oxidation rather than just microbial oxidation. COD data and BOD5 data were not correlated for many years. C.N. Sawyer and others showed that the problems with using the BOD5 test on industrial wastes were the requirements for nutrients and for a microbial seed that was acclimated to the wastewater being tested. The use of a reasonable population of acclimated bacteria allowed the BOD5 test to be used for evaluating industrial waste and municipal sewage.

The next major opportunity to apply these concepts came with pharmaceutical wastewater produced during the manufacture of penicillin. The process wastewater from the penicillin manufacturing facility had been blamed for creating problems at a new municipal trickling filter plant that serviced the facility. In an effort to alleviate the problems, the industry had constructed its own pretreatment plant for initial treatment of its wastewater prior to discharging into the municipal sewage system. There was concern that residual penicillin would be toxic to the microorganisms in the biological pretreatment plant and that the wastewater was too strong to produce the desired effluent quality. A single-stage, completely-mixed activated sludge plant was constructed and placed into operation with excellent results.[17] The influent BOD5 ranged from 5000-7000 mg/L and the effluent was under 50 mg/L. However, the removal of this organic load from the municipal wastewater treatment plant demonstrated that these industrial wastes had not been the cause of the treatment plant problems.

A third field application demonstration plant was a small chemical plant in Ontario that was faced with having to reduce the phenols in its wastewater. The process wastewater contained approximately 2000-3000 mg/L mixed phenolics with a COD from 6000-8000 mg/L. Research at M.I.T. on microbial metabolism of aromatic compounds had indicated that phenolic compounds could be treated biologically, if the completely-mixed biological reactor did not permit the phenol concentration to rise to the toxic level.[18] The treatment plant demonstrated that it was possible to design a single-stage activated sludge system capable of reducing the phenols in the effluent to under 0.1 mg/L. Official data from the Ontario Water Resources Commission indicated that the system yielded an effluent with only 0.4 mg/L phenol, a 99.99+% reduction. The stability of the system was verified when an accident ran the influent phenolics to 6000 mg/L. At that level, the biological system was definitely overloaded, but it recovered quickly.

These field installations were all concerned with industrial wastewater treatment. Efforts to apply these same principles to municipal wastewater were met with complete opposition from regulatory engineers responsible for approving the design plans and specifications of new treatment plants. The argument was used that industrial wastes were different from domestic wastewater and that, therefore, the treatment concepts were, and had to be, different. These excuses prevailed until the City of Grand Island, NE, needed a new wastewater treatment plant to handle the wastewater from a proposed meat

packing plant along with handling municipal wastewater. The problem of handling the combined municipal-industrial wastewater created the opportunity to demonstrate that complete-mixing activated sludge was able to treat municipal wastewater as well as industrial wastewater.[19]

Microbial Metabolism

The success of these industrial wastewater treatment plants stemmed from the research conducted at M.I.T. during the 1950s. One facet of that research dealt with the relationship between the chemical structure of the organic compounds in wastewater and the ability of microbes to metabolize those compounds. There had to be a relatively simple pattern of microbial processing of organics in wastewater. Starting with simple organic compounds, a series of studies were made in the laboratory that demonstrated the common patterns of metabolism for both energy and synthesis.[20,21,22]

The problems with certain industrial wastes and the incomplete metabolism of synthetic detergents provided the opportunity to further apply the fundamentals of microbial metabolism to real world situations. One of the studies determined that bacteria metabolized small, soluble organic molecules first and then metabolized more complex organic molecules. Metabolism of the small molecules always started at the most oxidized chemical group. Carboxyl groups (-COOH) were more reactive than hydroxyl groups (-OH); and hydroxyl groups were more reactive than methyl groups ($-CH_3$). Metabolism of each organic compound followed a simple pattern. Energy was released by the microbial oxidation reactions and then applied to synthesis reactions for the creation of new microbial mass.

Bacteria have the ability to take in organic molecules that have 12 carbon atoms or less without any difficulty. Larger molecules have to be broken down to small molecules before they can assimilated by the bacteria. Many compounds such as starch, cellulose and proteins must be hydrolyzed to simple sugars and amino acids before being metabolized. Large molecules that cannot be hydrolyzed can be metabolized; but the pattern is a little different. In this case, metabolism starts at the most reduced end at a methyl group ($-CH_3$) instead of starting at the most oxidized end of the molecule. The methyl group actually dissolves into the lipids making up part of the cell wall structure. The oxidation reactions begin at the methyl group dissolved in the cell and convert it to a carboxyl group (-COOH) which then fits into the normal pattern inside the cell. The molecule is then broken into units having two carbon atoms each, and the rest of the organic molecule is simply pulled inside the cell.

Examination of the various metabolic reactions with the different microorganisms indicated that they all followed the same general patterns. At first, it appeared that every bacteria and every organic compound followed special metabolic patterns with quite complex routes. Closer examination revealed that there were very few biochemical reactions within the microbial cell. In fact, the same reactions used for breaking organic compounds down for energy could be used for creating new organic compounds for cell mass. The energy levels of the various reactions determined whether the reaction was an oxidation reaction for energy or whether it was a reduction reaction for synthesis. There were only five primary reactions, regardless of the organic matter under metabolization. The primary reactions either added or removed two hydrogen atoms (2H), water (H_2O), carbon-carbon bonds (C-C), ammonia (NH_3) or phosphate (PO_4). Lesser reactions operating at a secondary level included the addition or removal of sulphur (S) as either sulfates ($-SO_4$), or sulfides (-SH) and chloride (Cl). The ability to remove the chloro group (-Cl) from certain organic compounds has proven of value in reducing the toxicity of these synthetic organics. The inherent simplicity of the biochemical reactions in metabolism lessens the problems in determining the biodegradation of new organics that are being synthesized for industrial application. Instead of having to uncover large and complex metabolic patterns, it is only necessary to examine a

few series of recurring reactions.

All biochemical reactions are catalyzed by enzymes that are specifically targeted for each reaction. These enzymes have three components: the apoenzyme, the coenzyme and metallic activators. The apoenzymes are large proteins that determine where the reaction will occur. The coenzymes determine the specific chemical reaction that occurs and the metallic activators are important in orienting the enzyme and in electron transfer. The microbes have very few enzymes and must use them repeatedly. For this reason the reactions require both the rapid regeneration of enzymes for reuse and the alteration of enzymes to produce new reactions. The apoenzyme tends to be the part of the enzyme that is changed most often while the coenzymes and the metallic activators often remain the same, since the same basic reaction is performed even though it may be at a new chemical point.

By understanding the basic biochemical reactions the microbes use in synthesis of their protoplasm, it is possible to estimate the potential reactions that the bacteria can bring about in metabolizing industrial organics, both natural and synthetic. Since bacteria synthesize aromatic compounds as part of their proteins, it was only natural to expect that bacteria should have the natural ability to metabolize phenol and phenolic derivatives, even though phenol is toxic and is used as a disinfectant. Even the key ingredient in Orlon, sulfonated acrylonitrile, could be metabolized in the correct environment.

During and after World War II synthetic detergents were produced and used extensively. The most common detergent was an alkyl benzene sulfonate (ABS) made from petroleum residues. Its expanded use after World War II created a serious problem in activated sludge plants and in streams receiving treated effluents. The microbes could not completely degrade the ABS syndet in a well-operating activated sludge plant. The remaining syndet foamed badly and covered the aeration tanks with a foam that was only partially stabilized by the residual proteins in the wastewater. Research at M.I.T. in the 1950s demonstrated that the problem was with the chemical structure of the ABS syndets.[23,24,25,26] The use of a crude petroleum fraction resulted in the synthesis of a large number of isomers with a general (rather than a specific) dodecylbenzene sulfonate structure. The bacteria separated the biodegradable and the non-biodegradable fractions and allowed the non-biodegradable fractions to accumulate in the liquid phase. It took considerable research to demonstrate to the detergent industry that the bacteria followed specific patterns of metabolism, and that a change in raw materials could produce more agreeable biodegradable syndets. Once the public demanded that the detergent industry change its product, the industry changed in the United States and Europe and the problem disappeared in these areas.

Mixing

In the early 1960s the advent of complete mixing concepts provoked discussions on the value of complete mixing versus plug flow activated sludge systems. Mathematically, plug flow systems produce a better quality effluent than completely mixed systems.[27] The effluent quality for a plug flow activated sludge system was predicated with the following equation:

$$F = (Fi)(e^{-Kt})$$

Where:

F = unmetabolized organics remaining, mg/L BOD5
Fi = initial organics, mg/L BOD5
K = metabolism factor, 1/hr
t = aeration time, hrs

The effluent quality for a completely mixed activated sludge system was predicated with this equation:

$$F = Fi/(Kt + 1)$$

The unmetabolized BOD5 will be less in the plug flow system than in the completely mixed system for reasonable aeration times. Twenty years later, there is still considerable discussion on the comparative merits of the two processes.

The complete mixing system produces a better environment than the plug flow system for maintaining a balanced microbial population over varying organic loading conditions that occur in the real world. Laboratory and field data proved that complete mixing activated sludge systems were superior to many activated sludge plants that were similar to plug flow systems since they possessed long, narrow aeration tanks (see Figure 6). However, research showed that the conventional activated sludge systems were not entirely plug flow systems. A significant body of research demonstrated that longitudinal mixing was significant in long, narrow aeration tanks.[28,29,30,31] The longitudinal mixing in the aeration tanks was found sufficient to create complete mixing. In actuality, these systems are partially mixed systems.

Other researchers at Northwestern felt that three compartments would produce better results than a single tank since the three tanks would better approach the plug flow concept.[32,33] Mathematically, the effluent quality from the three-compartment system should be superior to the single tank system. Researchers at M.I.T. in the early 1950s had already examined a multi-compartment system. The results with a ten-compartment aeration tank showed that stabilization was essentially complete after the third compartment. A three-compartment aeration tank was tested next. Stabilization was essentially complete after the first compartment. These results and the simplicity of a single tank system demonstrated that a single tank system was preferred over the multi-compartment aeration tank system.

The one factor that was overlooked in the mathematical analyses was oxygen transfer. All mathematical analyses of activated sludge systems were based on the assumption that oxygen was not limiting in the aeration tank. This was not entirely correct. Most, if not all, plug flow activated sludge systems and conventional activated sludge systems are oxygen limiting at the head end of the aeration tank where the organic concentration is high. Only the completely mixed system is able to maintain excess dissolved oxygen (DO) at all times, giving it an advantage of eventually having better effluent quality.

FIGURE 6. Typical diffused aeration-activated sludge aeration tank illustrating the long, narrow aeration tank. The Lake Tahoe wastewater treatment plant is shown.

Oxygen transfer is essential for the proper operation of activated sludge systems. Yet, it was not until the 1960s that many field measurements were made on the oxygen transfer characteristics of aeration tanks. Equipment manufacturers made claims for the oxygen transfer rates of their equipment, but design engineers never verified that the equipment met those transfer rates in the field after the plant was put into operation. Part of the problem lay in the lack of an acceptable test to verify oxygen transfer. Because of the difficulties with an aerated lagoon system in Kansas City, it was recognized that the design engineer had to take responsibility for writing specifications for aeration equipment that required field testing

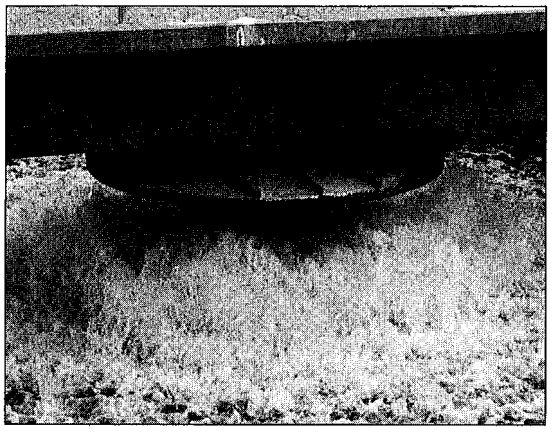

FIGURE 7. A surface mechanical aerator currently used for activated sludge at Lawrence, KS.

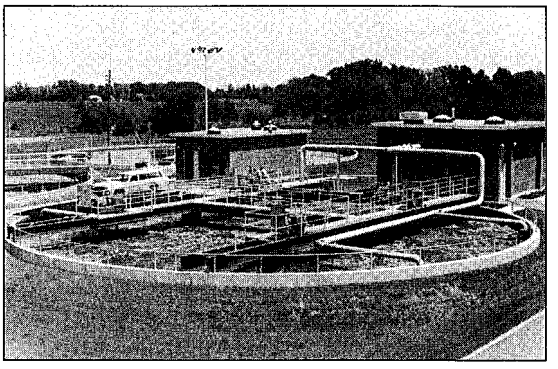

FIGURE 8. Typical aeration tanks with four turbine type aerators. The Grand Island, NE, plant is shown.

to demonstrate oxygen transfer characteristics. The Grand Island, NE, wastewater treatment plant was the first plant that had comprehensive testing specifications for aeration equipment.[19] Since 1964, consulting engineers have specified field testing of aeration equipment with the accumulation of considerable data on oxygen transfer for different aeration equipment.[34]

Recently, a new procedure was developed for evaluating diffused aeration equipment in conventional activated sludge systems having long, narrow aeration tanks.[35] This procedure consists of taking DO and oxygen uptake measurements at regular intervals down the aeration tank. By plotting these data, it is possible to determine the point when the system shifts from being oxygen limiting to having excess oxygen. The DO data remains low as long as DO is limiting and shows a sudden rise when the system has excess DO. The oxygen uptake rate at the point of change in DO is a measure of the oxygen transfer of the aeration equipment. It is possible to check that data from the remaining data with excess DO. Data from several different treatment plants have shown that most conventional activated sludge plants operate under partial oxygen deficient conditions. The net result of partial oxygen deficiencies is less endogenous respiration in the aeration tank and more excess sludge to remove from the system. The effluent quality is acceptable as long as excess oxygen occurs before the end of the aeration tank.

Based on general relationships, field data indicated the following oxygen transfer for different aeration equipment:

- 10-15 mg/L/hr for coarse bubble aeration in a conventional aeration tank
- 20-30 mg/L/hr for fine bubble aeration in a conventional aeration tank
- 40-60 mg/L/hr for fine bubble aeration over the entire bottom of an aeration tank
- 20-30 mg/L/hr for a high-speed surface aerator
- 40-60 mg/L/hr for a slow-speed surface aerator (see Figure 7)
- 60-70 mg/L/hr for both mechanical and diffused turbine aeration (see Figure 8)
- 100-130 mg/L/hr for pure oxygen

These values are for aeration equipment in normal tank volumes. Increasing the tank volume will decrease the rate of oxygen transfer; while decreasing the tank volume will increase the oxygen transfer rate. Aeration equipment must be tested in the actual aeration tank. The only valid testing technique for aeration equipment today is the clean water test. Dirty water, or mixed liquor, testing has too many variables to be used for aeration equipment certification. However, dirty water testing is useful for evaluating general oxygen transfer under operating

conditions.

Since adequate oxygen is essential for the efficient operation of activated sludge plants, adequate oxygen must be present in the aeration tank. A simple test for adequate oxygen is nitrification. If there is adequate oxygen in activated sludge systems, there should be some nitrites or nitrates in the mixed liquor. Without adequate oxygen, many activated sludge systems produce filamentous bacteria with poor settling characteristics. Filamentous bacteria are as capable of metabolizing organics as dispersed bacteria, but they are normally not as efficient. Under oxygen limiting conditions, mixing is generally not very turbulent, allowing the floc particles to remain relatively large. The filamentous bacteria project from the floc and project a larger surface for metabolism than the bacteria in the large floc particle. The net result is that low turbulence favors filamentous bacteria, not because of oxygen limitations, but because of more favorable competition for the oxygen and the food. As mixed liquor suspended solids concentrations increase, the amount of turbulence for good oxygen transfer and proper growth of non-filamentous bacteria must also be increased. Too often this fact has not been recognized by design engineers or plant operators.

Solids Separation

An important part of the activated sludge process is the separation of mixed liquor suspended solids (MLSS) from the final effluent by gravity. A portion of the separated suspended solids are returned to the aeration tank to provide sufficient living microbes for rapid metabolism and to provide sufficient flocculent solids to ensure rapid flocculation and separation in the secondary sedimentation tank. The system requires daily wasting of suspended solids by direct wasting or loss in the effluent. Since loss of suspended solids in the effluent is not desirable, wasting of excess sludge must equal the amount of sludge produced each day.

In laboratory activated sludge systems fed a soluble organic substrate, the MLSS will be composed of active microbial mass, dead cell mass and inorganics. As indicated previously, the active microbial mass is a function of the metabolized organics and the number of times the microbes are recycled through the system. The dead cell mass is a function of the active mass in the MLSS and the length of time the microbes are retained under aeration since the dead cell mass is created by endogenous respiration of the living mass. The inorganics are incorporated in the microbes, both living and dead, to about ten percent of the microbial suspended solids and accumulate as the solids retention time (SRT) increases.

In field activated sludge systems, the wastewater contains suspended as well as soluble solids. Biodegradable suspended solids in the wastewater are metabolized in the same manner as the soluble organics, but the non-biodegradable suspended solids (both organic and inorganic) simply accumulate in the MLSS every time the MLSS is recycled through the system. Thus, these inert suspended solids become a major part of the MLSS and, eventually, control the operation of the activated sludge system.

Due to the effects of the active fraction of the MLSS, efforts are made to return the settled solids back to the aeration tank as quickly as possible. Hydraulic sludge collectors have been designed to collect settled sludge over the entire bottom of the secondary settling tank rather than using conventional sludge scraping equipment and center drawoff. Hydraulic sludge collection equipment has been viewed as removing settled solids faster than conventional sludge collection equipment. Hydraulic sludge collection equipment has become standard at the present time.

The surface overflow rate (SOR) controls the removal of particles by gravity sedimentation. T.R. Camp's concepts for activated sludge sedimentation tanks indicated that he favored rectangular tanks over circular tanks because of their hydraulic stability.[36] He pointed out that the design engineer should use density currents to advantage in solids separation and in designing secondary sedimentation tanks.

Norvell Anderson examined both rectangular and circular sedimentation tanks and

felt that density currents were very important in both tanks.[37] The MLSS entered the secondary tank and dropped to the top of the sludge blanket and moved across the tank bottom to the outer wall and up to the effluent weir. As a result of his studies, Anderson recommended that the effluent weir be placed at 1/4 to 1/3 of the radius from the outer wall so that the rising suspended solids would have an opportunity to settle. Design engineers have found that specification requires too complex a structure for economical construction, but they have placed a double-sided weir box as far out as practical.

In 1963 K.L. Murphy made an excellent dye study of a model sedimentation tank and agreed with Anderson's ideas about weir location.[38] In spite of these innovations, secondary sedimentation tanks often failed to provide good solids separation and produced poor effluent quality. Effluent from a well-operating activated sludge system should have little soluble BOD5 (3-5 mg/L) with the suspended solids determining the effluent BOD5 quality.

Part of the problem with secondary sedimentation tanks resulted from the high MLSS recommended by some engineers. It was believed that the soluble effluent BOD5 was related to the MLSS concentration and the time of aeration. By increasing the MLSS it was thought that the soluble effluent BOD5 would be decreased. Examination of basic metabolism indicated that the soluble effluent BOD5 was a function of the BOD5 loading rate as long as an excess microbial mass existed in the aeration tank. It made no difference what the MLSS concentration was as long as it was above the minimum level for the specific system. Often, the ability to flocculate and settle was more the controlling factor than active microbial mass. Pflantz demonstrated that the effluent suspended solids depended upon the MLSS transported within the system.[39] Thus, the high MLSS concept tended to create more problems than solve them.

One problem with secondary sedimentation tanks in Minnesota led to a critical evaluation of the primary design criteria for secondary sedimentation tanks. It was found that SOR is not valid in activated sludge separation since secondary sedimentation tanks do not operate with uniform flow patterns to produce separation based on particle size. Incoming MLSS dropped to the bottom of the sedimentation tank and moved rapidly across to the outside wall and up to the effluent weir. The impact of the rising current at the wall was most evident in the afternoon when maximum flows arrived at the treatment plant. Increasing the rate of return sludge to move the settled solids out of the sedimentation tank and back to the aeration tank to handle the increased organic load simply increased the hydraulic problem and the loss of suspended solids in the effluent. Thus, basic design concepts and basic operating concepts combined to defeat treatment plant efficiency.

Examination of the hydraulic sludge collection system indicated that uniform solids collection could be obtained only when a high rate of return sludge flow was maintained to keep the return sludge concentration low enough for uniform flow. Most plants operated with 6000-8000 mg/L return activated sludge (RAS) concentrations. The high RAS flow rates combined with the normal maximum flow rates to blow suspended solids out in the effluent. The collection of solids at the outer wall created a strong fluid flow outward that produced a rising momentum force which helped carry solids out of the tank. Instead of improving solids removal, the hydraulic sludge collection system was part of the problem. Reexamination of Anderson's data indicated that the MLSS were removed as the solids entered the sedimentation tank under the centerwell. Data gathered by Katz and Geinopolos on hydraulic sludge collectors showed that the sludge was removed on entering the sedimentation tank.[40] Comparison of operating data with conventional sludge collection equipment showed that conventional sludge collectors produced thicker RAS concentrations, necessitating lower sludge return rates and lower density currents. For activated sludge systems maintaining the same MLSS concentrations, conventional sludge collection

systems demonstrated better results than hydraulic sludge collection systems. Although hydraulic sludge collectors sounded like such a good idea, design engineers never made the necessary evaluation to show their value or lack thereof.

This lack of sound design criteria for secondary sedimentation tanks still leaves the problem up in the air. Few engineers even recognize that a problem exists. It most certainly does exist and it must be solved in order to obtain the maximum from activated sludge systems. Efforts have been made to modify the inlets to improve the hydraulic characteristics of secondary sedimentation tanks, but the results have been negative. The simplest solution to date has been to reduce MLSS to a relatively low level (1000-2000 mg/L), and to construct a baffle around the periphery of the tank under a single edge effluent weir to deflect the rising flow back to the center of the tank. As reported by Stukenberg, this design has produced positive results (see Figure 9).[41]

Design Criteria

Sound basic concepts translate into sound basic design criteria. For activated sludge systems, the fact that the oxygen transfer characteristics in the aeration tank control the entire process has been considered a secondary factor. Without adequate oxygen, microbes simply cannot metabolize organic matter completely. With an excess of oxygen, carbon can be metabolized to better than 99% and nitrogen can be metabolized to any desired extent beyond that required for carbon metabolism. Aeration equipment is required to keep MLSS in suspension and to mix organics with the microbes and oxygen. Tank configuration and aerator spacing affect the mixing patterns within the aeration tank and affect the oxygen transfer rates.

Oxygen is transferred to the water at a specific point at a specified rate and is mixed with unoxygenated water as the liquid moves around the tank. The DO in the liquid is reduced by dilution with unoxygenated water and by microbial metabolism. A DO profile around the aeration tank can be very helpful in evaluating hydraulic flow patterns.

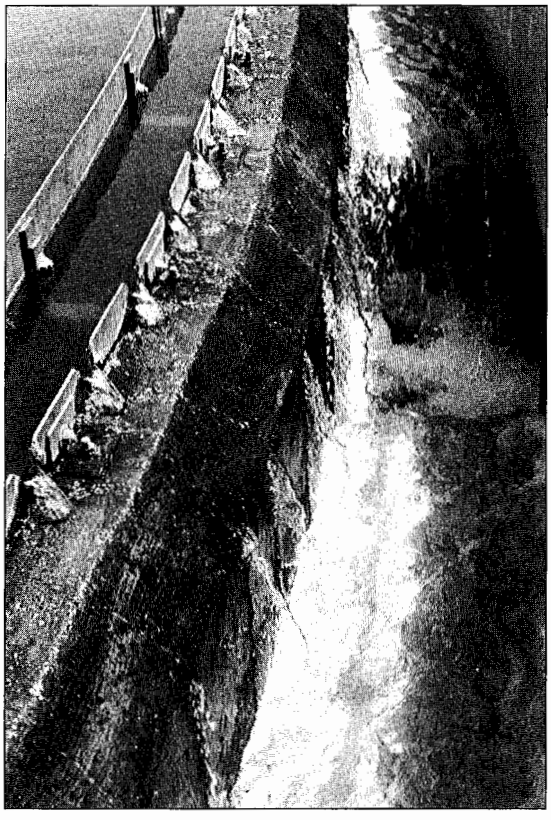

FIGURE 9. Final effluent from the activated sludge plant in Grand Island, NE, showing the clarity of effluent exhibited by the visibility of the submerged brackets for the scum baffle.

The organic loading rate determines the effluent quality as long as adequate oxygen is available for metabolism. Normally, the rate of oxygen transfer limits the organic load on the aeration tank. The organic loading rate is related to the total organic load in the wastewater applied to the aeration tank and the time for aeration. It is possible to take wastewater having any organic concentration and produce a satisfactory effluent by keeping the organic loading rate relatively low. A low soluble effluent BOD5 cannot be produced at a high organic loading rate. The soluble effluent BOD5 will generally be slightly less than one-tenth the BOD5 loading rate under aerobic conditions. If activated sludge has a one to one ratio of BOD5 loading rate to oxygen demand rate, the maximum loading rate for aerobic conditions should be less

than 60 mg/L BOD5/hr. With an average loading rate of half the maximum rate, the design rate would only be 30 mg/L BOD5/hr. Few activated sludge plants have been designed at such a low loading rate in recent years. This simply means that most activated sludge plants are operating under partial oxygen deficiencies for part of the day. A 24-hour composite sample permits the plant to meet Environmental Protection Agency (EPA) effluent citeria of 30 mg/L BOD5 and 30 mg/L suspended solids. The BOD5 leakage during partial oxygen deficiency is small and is diluted by the normal effluent quality produced with adequate oxygen.

It is possible to achieve a reasonable effluent BOD5 under overloaded conditions, but more excess activated sludge will be produced than under completely aerobic conditions. The effluent from activated sludge systems is made up of soluble, unmetabolized organics and excess suspended solids not removed from the final clarifier. In the aeration tank the oxygen demand is generated by the synthesis reaction and the endogenous respiration reaction. The synthesis reaction rate is normally about five to ten times the endogenous respiration rate. Under oxygen deficient conditions the major portion of the oxygen is used for synthesis with less oxygen being used for endogenous respiration. With a limited overload, organic matter is removed in almost the same manner as excess DO. Normally, activated sludge systems produce soluble effluent BOD5 values of 1 to 2 mg/L. With limited oxygen the soluble BOD5 can rise to 10 to 15 mg/L, still a reasonable value. If the final clarifier removes the activated sludge to around 10 to 20 mg/L under both cases, the total effluent BOD5 will rise from the 7 to 10 mg/L range to the 20 to 30 mg/L range, still meeting EPA effluent criteria. Since there is less endogenous respiration under the oxygen limiting conditions than under excess oxygen conditions, there will be less oxidation of microbial solids produced. The net effect will be more suspended solids to be wasted from the system.

Another key component in activated sludge design is the microbial mass in the aeration tank. The microbes must be greater than required for the organic load. Since microbes are maintained at high concentrations through recirculation, most activated sludge systems have many times more microbes than needed. To handle 60 mg/L BOD5/hr, only 120 mg/L active microbial mass would be needed. The synthesis reaction would produce 49 mg/L volatile suspended solids (VSS)/hr while endogenous respiration would use only 3 mg/L O_2/hr for this microbial mass. Needless to say, 120 mg/L microbial mass would not produce a good settling sludge with a highly clarified effluent. The MLSS must be increased by recycling settled sludge. The return activated sludge will bring back inert suspended solids, dead cell mass and active microbial mass. Each recirculation increases all fractions. Normal activated sludge systems require 800-1000 mg/L MLSS for good flocculation and solids separation. The return of active microbial mass increases the potential for endogenous respiration without any increase in the active mass produced by metabolism. At a 60 mg/L BOD5 loading rate, the oxygen demand rate for synthesis should be approximately 34 mg/L/hr, with 26 mg/L/hr for endogenous respiration. At 20°C with a 0.02 endogenous respiration rate, 0.022 mg/L/hr O_2/mg/L active microbial mass, the active mass should be about 1180 mg/L, 10 times that required to metabolize the BOD5 in wastewater. If the wastewater had a significant amount of inert suspended solids, the MLSS would be much greater than the 1180 mg/L. The inert suspended solids in the wastewater normally determine the active microbial mass fraction in the MLSS. Some inert inorganic suspended solids should be in the wastewater to provide some mass to help the rate of sedimentation of the floc. However, too great an amount of inert solids can result in filling the tank with MLSS and have the net effect of little benefit for the treatment process.

The RAS is critical for maintaining the desired MLSS under aeration. Good activated sludge will settle and thicken to 10,000 mg/L. The RAS flow should not be any greater than needed to maintain the desired MLSS concen-

trations in the aeration tank. If the MLSS is around 2000 mg/L, the RAS flow will be about 25% of the wastewater flow with a sufficient settling sludge. Sound design criteria should provide flexibility between 10 and 50% wastewater flow rates for the RAS flow rates. In recent years the RAS flow rates have been closer to 100% or more of the wastewater flow rate, too high for beneficial control.

Wasting excess activated sludge is essential. The daily increase in suspended solids must be removed from the system each day, if the system is to continue to function properly. The excess suspended solids must either be wasted or discharged in the effluent. If the goal is a high quality effluent, then the majority of the excess activated sludge must be removed by wasting. Waste activated sludge (WAS) is removed from the RAS to minimize the quantities of solids removed. Normally, the WAS flow rate will be less than five percent of the wastewater flow. Removing more WAS will lower the MLSS; removing less WAS will permit the MLSS level to rise. Accurate and timely WAS measurements are important in monitoring this process.

Operational Evaluation

Design engineers must not only understand the basis of design, but should also understand how to evaluate treatment plant operations. Operational data are predominantly collected on a grab sample or composite sample basis. Some of the data will have only historical value, such as BOD5 data. Flow and suspended solids measurements are of paramount importance since the treatment process is essentially a solids handling process. DO data and oxygen uptake data can aid in evaluating activated sludge, but these data must be properly collected to be of real value. Alkalinity and nitrogen data can also be useful.

Failure to recognize the basic concepts of the activated sludge process has resulted in improper operation of most plants. There has been a tendency to overanalyze and overcontrol the activated sludge process, resulting in poor effluent quality. The problem lies in the fact that aeration and sedimentation tanks are coupled systems that permit temporary imbalances, resulting in improper data collection and evaluation. The net result is a cyclical, and unsuccessful, attempt to adjust the system for uniform operation. This is especially true when the rates of return sludge are adjusted several times a day in the attempt to meet the variations in incoming loads. Wasting sludge without regard to organic loading rates and synthesis reactions will produce widely fluctuating results.

A recommended operational technique is to set the return sludge rates at the average desired rates and not vary the return sludge rates with the load. There are more than enough microbes in the system to stabilize the organics. At low flow conditions excess sludge will be removed from the secondary sedimentation tanks and transported to the aeration tanks. The aeration tanks will then show an increase in MLSS. As the excess load comes into the aeration tank, the extra MLSS will handle it easily. The sedimentation tank will then have the capacity to absorb the increase in MLSS displaced from the aeration tank without blowing solids out into the effluent. By wasting a constant flow fraction from the RAS, the system will automatically rise and fall as the load changes. Slight adjustments in WAS can be made every few days or weekly to keep the MLSS within the desired concentrations. Microcomputer analyses for daily mass balances of suspended solids throughout the system can help the operator maintain tight control of the system with a minimum of effort and variation.

Anaerobic Treatment

Anaerobic treatment of organic wastes has been recognized as a means of waste treatment for a longer period of time than aerobic treatment. However, anaerobic treatment had developed an initial negative reputation. Anaerobic metabolism results in the production of obnoxious compounds that can be considered undesirable. Yet, septic tanks can provide excellent stabilization of settled solids. Imhoff in Germany developed a two-story

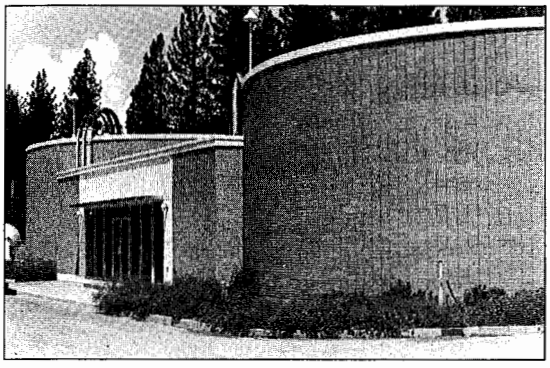

FIGURE 10. Typical anaerobic digestion tanks for domestic sewage sludges. The Lake Tahoe wastewater treatment plant is shown.

tank that allowed the sewage solids to separate and undergo separate digestion. Gas produced by digestion was initially allowed to escape through scum vents to the atmosphere. When it was recognized that the gas produced by anaerobic digestion could be burned, efforts were made to collect it.

Anaerobic Digestion

The technology for separate anaerobic digestion of sewage sludge was slow to develop. The first tanks were open tanks that were not mixed or heated. Scum formed on the liquid surface and acted as the top of the tank. The settled solids digested slowly and were relatively stable when removed from the digestion tank. The solids dewatered easily on the soil and did not produce obnoxious odors or attract flies. In addition, the stability of the sludge after digestion made it very attractive for subsequent use.

Research on anaerobic digestion began during the 1920s with studies on changes in the chemical characteristics of sewage sludge over time. Acid production occurs first, followed by the metabolization of the acids with the accompanied production of methane and carbon dioxide. After the methane production slows, the sludge is considered stable. Acid fermentation had been studied before, but the acid metabolism intrigued Buswell. Together with S.L. Neave, Buswell examined how the bacteria in sewage sludge metabolized acetic acid and propionic acid to methane and carbon dioxide.[42] Later, Buswell and Boruff studied the metabolism of more complex organic compounds such as cellulose, casein, peptone and stearic acid.[43] Research on anaerobic digestion moved ahead slowly until the 1950s when Stadtman and Barker used radiotracers to show the metabolism of some fatty acids and alcohols.[44,45]

In the 1950s anaerobic digesters were heated with hot water to about 85°F to increase the rate of metabolism. It was believed that the normal gasification process was adequate to achieve the mixing necessary for digestion. The digester had three major layers: a grease layer at the top, an actively digesting layer in the middle, and a well-digested layer at the bottom. Digesters required a long retention time (20-30 days) for stabilization. It had been noted that acid production was the most critical operating parameter. Excessive organic loading rates could result in rapid acid production and a drop in pH with the accompanied cessation of methane production. Alkalinity had to be added and a fresh microbial seed was necessary to get the system back into good operation. Buswell indicated that volatile acids were toxic if their concentrations exceeded 2000 mg/L. This was the most critical operating parameter that needed to be controlled.

The major step forward in anaerobic digestion came with P.F. Morgan's research on catalytic reduction (see Figure 10).[46] Morgan found that continuous gas recirculation increased organic loading by a factor of 10, and reduced the retention time to only 7-8 days. He indicated that the recirculation of gas created an increased rate of reaction. W.N. Torpey also experimented with increased rate of digestion.[47]

Biochemical Studies

Morgan and Torpey's work helped stimulate interest in anaerobic digestion as research was progressing on activated sludge. At M.I.T., C.N. Sawyer examined the problems associated with high-rate anaerobic digestion in the laboratory. One concern was volatile acid toxicity. An early study had indicated that volatile acids above 2000 mg/L were not toxic, but the cations associated with the

volatile acids could be toxic at high concentrations.[48] Additional research eventually showed that volatile acids *per se* were not toxic.[49] When volatile acids reached 2000 mg/L, the pH suddenly dropped as the buffer was all used up. The toxicity was the result of low pH and not the volatile acids. It was possible to have metabolism at 20,000 mg/L volatile acids as long as the volatile acids were neutralized and the pH was above 6.5. At high volatile acids, the toxicity was caused by high concentrations of soluble cations. Monovalent cations were more soluble and toxic than divalent cations.

These early studies at M.I.T initiated further research that took over 25 years to complete. The studies on volatile acids showed that adequate digestion proceeded for several weeks and then began to slow as the original seed sludge was displaced from the digester. Sufficient microbial digestion could be regained only by adding an amount of sewage sludge. Sewage sludge contained something the microbes required. Dried sewage sludge yielded the same results as liquid sludge. Efforts to locate the critical material were not successful. Iron and cobalt were two important materials required for adequate digestion, but something else was missing. In the later 1970s, mass spectroscopy studies of methane enzymes indicated the presence of nickel in one of the enzymes. This appeared to be the missing key that was needed to make anaerobic metabolism of pure organics a stable process. Schonheit, Moll and Thauer found that a methane bacteria that metabolized hydrogen and carbon dioxide to methane needed minute amounts of nickel, cobalt and molybdenum.[50] Just 0.009 mg of Ni was needed per g of cell mass produced; 0.0012 mg of Co per g of cell mass; and 0.0018 mg of Mo per g of cell mass. This study stimulated interest in determining the role these trace metals played in anaerobic digestion. Murray and van den Berg, and Speece *et al.* have shown that nickel is essential for maximum rates of anaerobic metabolism.[51,52]

The value of nickel in anaerobic digestion was accidentally observed and ignored as early as 1941. In addition, a published study in 1947 by Wischmeyer and Chapman confirmed the 1941 results.[53] Laboratory research on the anaerobic digestion of sewage sludge with varying amounts of nickel ammonium sulfate and nickel sulfate added to domestic wastewater to simulate plating wastes indicated that, at low concentrations of nickel, the rate of gas production was greater than the rate of gas production in the control digester. As the concentration of nickel increased, the nickel became toxic, and both the rate and the total gas production dropped below that of the control digester. Since nickel was not considered to be an essential trace element, but rather a toxic metal, the results of this research study passed without notice.

Current research at the University of Kansas is examining the role of several different trace metals in the metabolism of butyric acid. Not only are iron, nickel, cobalt and molybdenum being examined, but also zinc, copper and manganese. Butyric acid was chosen as the substrate since it is soluble and requires beta oxidation to be broken down to acetic acid before the acetic acid can be split to methane and carbon dioxide. The hydrogen atoms removed during beta oxidation were used to reduce carbon dioxide to methane and water. The net result is a mixed microbial population with different energy levels of metabolism. It will be interesting to see how the rate of metabolism is affected by the different trace metals.

Soluble Organics

P.L. McCarty and J.C. Young developed the anaerobic rock filter to treat strong, soluble organic wastes. The anaerobic filter appeared to be a effective system for treating certain types of industrial wastes. Over the next decade a large number of laboratory studies were made to demonstrate the ability of the rock filter to treat specific industrial wastes.

It was not until the energy shortage in the early 1970s that interest in anaerobic treatment shifted to the treatment of organic solubles. A few treatment plants appeared in Europe for treating sugar processing wastewater. In 1980 the Bacardi Corporation of Puerto Rico constructed the largest anaerobic

filter for treating industrial wastes. This plant had a 125 ft diameter plastic media, downflow type anaerobic filter with 30 ft diameter depth in a 42 ft deep tank. Since the Bacardi plant went into operation in 1982, it has operated without major problems and has successfully survived annual shutdowns for plant maintenance. Over half of the energy needs of the manufacturing plant are met by recycling the gas produced by the anaerobic metabolism of the rum distillery wastewater. The success of this large scale treatment system and others in recent years has clearly demonstrated the potential for anaerobic filters with energy recovery for plant operations.

Basic Concepts

Basic concepts of anaerobic digestion have developed slower than the basic concepts for aerobic systems. This is not surprising since the anaerobic systems have been more difficult to operate and require longer operating periods to obtain basic data. It is possible to use the basic concepts from early studies on aerobic reactions to provide similar relationships for anaerobic reactions. The basic metabolic reaction is the synthesis reaction. Organic metabolism is directed towards the production of microbial cell mass. The early studies at M.I.T. had indicated that 1/3 of the organics metabolized were oxidized to convert the remaining 2/3 of the organics to cell mass. The microbial protoplasm is a complex mass of hundreds of different organic compounds that have a relatively fixed chemical composition when introduced to an excess of nutrients. It has been found that 0.48 g of VSS are produced from each g of COD metabolized. Each g of cell mass produced requires 4.7 Kcal of energy in the protoplasm, with 2.3 Kcal of energy required to manufacture the protoplasm. These relationships hold for anaerobic microbes as well as for aerobic microbes. The amount of organic matter converted to cell mass will be exactly the same for anaerobic microbes as for aerobic microbes. The difference lies in the energy yields from the energy metabolism reactions. The aerobic reactions yield more energy than the anaerobic reactions. The net result is that less organics are oxidized aerobically and more organics are converted to cell mass than in anaerobic reactions.

Of the many different anaerobic reactions, there are two fundamental reactions that supply energy for the microbes. The first major reaction is the splitting of glucose to acetic acid. This reaction produces 71 Kcal for each molecule of glucose converted to acetic acid (0.37 Kcal/g COD). Approximately 6.2 g COD as glucose would have to be metabolized for energy for each g of cell mass. That one g of cell mass contains 1.4 g COD, requiring a total of 7.6 g COD from the glucose. Restated, the cell mass yield for one g COD metabolized as glucose should be 0.13 g. The second reaction results in the splitting of acetic acid to form methane and carbon dioxide. This reaction only yields 0.16 Kcal/g COD. The energy reaction for the acetic acid split requires 14.4 g COD/g of cell mass. The 1.4 g COD/g of cell mass for protoplasm and the 14.4 g COD/g of cell mass for energy gives a total COD requirement/g of cell mass of 15.8 g. For each gram of acetic acid metabolized, the cell mass yield is 0.063 g VSS. By combining the two reactions to give an overall synthesis for the metabolism of glucose to methane and carbon dioxide, approximately 0.18 g VSS is produced per one g COD glucose metabolized. Approximately 260 ml methane is also produced. The COD in the metabolized organics are simply transformed into the COD of the cell mass and the COD of the methane gas. If other end products are produced by anaerobic reactions, a portion of the COD may be tied up in those end products. The methane reaction is the most important anaerobic reaction since the low solubility of methane in water permits methane to be captured as a gas and used as an energy source. It is important to recognize that the energy in the original organic waste materials will be converted to microbial cell mass and methane. The methane is easily trapped as a gas, but the cell mass suspended solids pose the ultimate separation problem.

The early studies on bacterial flocculation at M.I.T. demonstrated that, under aerobic conditions, flocculation occurred

when all of the organic matter was metabolized. If these concepts hold true, it should be possible to obtain flocculation under anaerobic conditions when all the organic matter has been metabolized. Recent studies at the University of Kansas have demonstrated that anaerobic flocculation occurs under the same environmental conditions as aerobic flocculation. The addition of excess iron salts also can assist natural flocculation by artificially concentrating the dispersed bacteria, thus permitting complete metabolism rather than the loss of active, dispersed bacteria.

Complete metabolism under anaerobic conditions approaches the same degree of metabolism as under aerobic conditions, reaching 98 to 99%. The important parameter is microbial retention and rate of metabolism. Since the ability of the microbes to obtain sufficient energy for synthesis is the controlling factor, the rate of organic processing will ultimately limit the organic load and the extent of metabolism.

Future Studies

Anaerobic treatment offers the advantages of less excess microbial solids for ultimate disposal, and energy for easy reuse in the form of methane. It also offers the potential for high treatment efficiencies. However, few systems have demonstrated the full potential of anaerobic systems. There is still much research needed to define the critical factors affecting both the design and operation of anaerobic treatment plants. Anaerobic systems are harder to start than aerobic systems and require more skill in maintaining efficient operation. Yet, the fundamental concepts of anaerobic systems are the same as aerobic systems. The understanding that has been generated by studying aerobic treatment systems over the years can be utilized to shorten the time and effort required to develop sound anaerobic systems. The chemical characteristics of microbes in anaerobic systems are the same as in aerobic systems. The mechanisms for processing the organics for energy and synthesis are also the same. Only the electron transfer process and the ultimate electron acceptor are different. While anaerobic treatment can provide a high degree of treatment, aerobic treatment after anaerobic treatment can be used for a high quality effluent.

The future of biological treatment looks very bright. The design and operation of wastewater treatment systems are firmly established on sound basic concepts of microbiology and biochemistry, coupled with good engineering. There is no reason to doubt that efficient and economical plants will be provided as needed to meet the challenges of the future. Reusing and recycling water, nutrients and microbial solids will ensure the sufficiency of these valuable resources for the benefit of everyone whatever the demands of the future might be.

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