THE "STICKMAN" WASTEWATER TREATMENT FACILITY - APPLYING BASIC FUNDAMENTALS TO THE DESIGN AND OPERATION OF PLANTS.

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ABSTRACT

This document explains the theory of operation for municipal water pollution control facilities using the "StickMan" analogy. By this approach, it is our intent to demonstrate to plant designers, plant operators and regulatory authorities, a means by which the operation of a biological waste water treatment facility can be understood in the simple terms of a human body. Optimization of the hydraulic (amount) and organic (quality) loading is key to the success of the facility.

UNDERSTANDING THE PROCESS

To understand how the introduction of physical/chemical pretreatment allows for improved operations efficiency and lower capital costs for industrial or domestic sewage treatment plants, it is first important to have a thorough understanding of the basics of a biological wastewater treatment facility. In the simplest terms, a biological wastewater treatment plant is nothing more than a farming operation. The waste entering the treatment plant can be categorized as particulate or insoluble wastes along with dissolved or soluble waste. The first portions of the treatment plant such as the screens, grit tanks and primary clarifiers are responsible for removing the particulate matter on the basis of its size and/or specific gravity. These pieces of equipment are designed to remove particulate matter that cannot or does not normally dissolve in the wastewater and thus would not be removed in subsequent biological treatment processes. In some older installations where extended aeration plants were installed, the primary clarifiers were deleted as it was felt that the biological treatments could adequately handle the higher strength waste associated with the particulate matter that was not removed in the primary clarifiers. This is only a correct assumption if the particulate matter can be dissolved in the wastewater, however as many operators will confirm, most of this insoluble matter merely floated on the surface of the tanks or ended up as unsightly deposits in the bottom of the facilities.

In the second stage or biological portion of the treatment plant the dissolved or soluble matter is consumed by the active biological microorganisms as a source of food to facilitate the biomass reproduction. Once the microorganisms have consumed the soluble matter and reproduced they are harvested from the system through the waste activated sludge and disposed of as a particulate component. This is nothing more than a standard farming operation where the crop is grown, harvested and removed from the fields.

It is also exactly the same as the feeding, growth and reproduction of the human body (alias the "Stickman") up to and including the deposition of waste byproducts from the biological system. As we all know there is an optimum amount of food to maintain a biological system, whether it be the human body or a treatment plant or a corn field, and an imbalance in that process can result in failure of the biological system.

In the simplest system, consider a lunchroom where six workers have ordered pizza and beer.

There is an optimum amount of pizza and a maximum amount of beer that the workers can consume in order to be able to return to their positions in an optimized condition. A lack of food will result in the workers having insufficient energy to complete their tasks, whereas over consumption of the food will leave the workers in an uncomfortable position also unable to properly execute their tasks. The beer provides a source of water and essential nutrients but in itself is also a toxin, thus a little bit causes no problem but an overconsumption can cause total failure of the system. All of these same rules apply to a biological wastewater treatment plant.

It is important therefore, that for a biological system to operate effectively, the amount of food entering the system that is to be consumed in the harvesting operation be matched to the amount of biomass or the number of microorganisms that are growing and consuming the food. In technical terms related to wastewater treatment operations, the mass of food relative to the mass of microorganisms is referred to as the F/M ratio and is expressed as kilograms of food entering the water pollution control plant (ie. BOD_5) divided by the kilograms of biomass or microorganisms in the tank (ie. mixed liquor volatile suspended solids-MLVSS). Different types of treatment plants operate at different F/M loadings. Depending on the purpose of the treatment plant and the expected effluent quality. Optimizing the F/M is an important means of designing and operating a water pollution control plant.

For any water pollution control plant the amount of food entering the plant is a function of the hydraulic load to the facility times the concentration of the organic matter or BOD_5 in the raw sewage. For a given population there is generally a constant amount of food or BOD_5, however the hydraulic flow to the treatment plant can vary depending on storm flow conditions, sewer infiltrations and spring run off. As a result is quite normal to find a relatively constant organic loading to a treatment plant but a very wide swing in the hydraulic loading to a treatment plant.

It is important therefore that consideration be given to both the organic loading rates to individual unit processes in a treatment plant as well as hydraulic loading rates. Since the food to the treatment plant is pre-set by the population of the community, plus any industrial loads from organic manufacturing facilities, the most logical way to control the F/M ratio is through the control of the microorganism level within the biological aeration tank. As in the farming example discussed earlier, this is achieved through the process of harvesting the microorganisms from the production facilities.

Since the mid 1970's the control of treatment plants by controlling the F/M ratio evolved into a new concept of controlling the treatment plant by controlling the "M" value of this ratio, achieved by controlling the harvesting the microorganisms.

The technical term associated with this is control of the SRT (solids retention time), which is a measure of the length of time that any one microorganism is held in the aeration tank or biological portion of the treatment plant. In simple terms the SRT is calculated as the total mass of microorganisms in the system divided by the total mass of organisms wasted on a per diem basis. For example, if there are a thousand pounds of microorganisms in the aeration tank and a hundred pounds are wasted every day, then the solids retention time in the facility is ten days. We have provided an in **Appendix One** a more technical outline of the relationship between the food to microorganism ratio (F/M) and the solids retention time (SRT) that demonstrates there is a direct relationship between the F/M and SRT numbers, thus although some operators insist on controlling plants on the F/M ratio, while others control the plant on the SRT ratio, they are in essence controlling the plant in the same process and merely measuring the end results by a different formula. Operating a treatment plant using the F/M method requires extensive analytical work and calculations. Whereas our example in the appendix shows operation on the basis of SRT can be carried out through the use of simple settling tests.

APPLICATION OF THE THEORY

The F/M ratio and the SRT numbers should clarify why it is important to operate a biological treatment system with the correct amount of food relative to the given amount of microorganisms in a system or alternatively adjusting the microorganism level to accommodate the provided amount of food in the raw sewage or primary effluent.

A treatment system that is out of the optimized range for the F/M or SRT will not operate properly and the effluent quality will deteriorate rapidly. As we explained in our example of the workers in the lunchroom, there is both a high and a low limit to the SRT or F/M values at which point the system will fail. There are many applications of this theory both to the operation of normal domestic sewage facilities and those wastewater treatment plants which are receiving complex industrial organic wastes. Through a process of bench or pilot scale tests, it is possible to determine the exact SRT value required for the decomposition of various waste streams to meet a given set of effluent guidelines.

Similarly operation of a full scale wastewater treatment plant can provide a clear indication of the optimum F/M or SRT numbers. Once this value is known it is then possible to make a determination as to the specific treatment processes that can be used at any one facility to obtain optimum effluent conditions.

Where this whole concept applies to conventional Water Pollution Control Plants is of most importance during periods of heavy rainfall, spring run, or dilute indistrial wastes off when there is a very dilute sewage entering the facility, particularly the biological components of the treatment plant. If it is now understood that there is an optimum food to microorganism ratio (F/M), then it should be understood that even though the concentration of the BOD_5 or food may have decreased during run off conditions, the total amount of BOD_5 entering the facility has remained the same. It therefore becomes clearly evident that it is practical to expand on the biological component of the wastewater treatment plant, merely to handle the increased hydraulic flow through the facility. It is of course important to provide for facilities which are controlled by hydraulic loading rates or surface loading rates such as the primary and secondary clarifiers to accommodate the increased hydraulic loading but it is not necessary to expand on the biological treatment components at the same time.

An alternative that has been used effectively to handle the increased hydraulic flow and decreased organic content during storm conditions has been to introduce a side stream treatment using physical/chemical methods to handle the peak flow such that the hydraulic loading to the biological treatment plant can be held constant, as determined by the maximum loading rate to the secondary clarifiers. There is of course some variation in the hydraulic loading that would be acceptable to the biological treatment plant which in most instances is set at two times the average dry weather flow as this is the maximum that is normally acceptable to the secondary clarifiers, if designed according to MOE standards.

For example, if a treatment plant was designed on an average day flow of 1 MIGD and the clarifiers had the capacity to handle 2 MIGD, but storm flows were approaching 4 MIGD then it can be seen that the treatment plant would have operating difficulties. In such an instance we would assume that the BOD_5 to the treatment plant might be 100 mg/l at 1 MIGD, would reduce to 50 mg/l at 2 MIGD and would be 25 mg/l at 4 MIGD. In all cases the total amount of food entering the biological portion of the treatment plant would be the same, therefore, the aeration tank or biological reactor should be the same size for each one of these conditions.

Increasing the size of the biological component merely to handle the storm water flows would results in underfeeding of the system resulting in rapid failure of the treatment plant eventually leading to washout of the treatment plant and total non-compliance with the effluent criteria.

As a means of properly handling such a condition, pilot and full scale treatability tests have shown that it is more appropriate to use physical/chemical storm water treatment tanks to handle the excess storm water flow during periods of high infiltration. For the example given above for the 1 MIGD treatment plant it may be appropriate to take up to 2 MIGD through the biological treatment component while providing for storm water treatment facilities to handle the additional 2 MIGD. As you can appreciate, the capital costs associated with the construction of the storm water treatment facilities is significantly less than the capital costs associated with a complex biological wastewater treatment component.

Although this is critical to the economic evaluations of the facilities, it is the technical requirements that are of the most importance. By this we mean that it is totally impractical to expand a biological treatment plant to handle wet weather conditions when in fact it is known before the expansion takes place that the treatment plant will not operate.

APPLICATION TO MUNICIPAL TREATMENT FACILITIES

Understanding all of the above makes it a simple matter to understand why many municipal Water Pollution Control Plants should not undergo a mere image expansion with a high capital cost but rather should give serious consideration to other alternatives such as the handling of the high infiltration flows by physical/chemical treatment methods or the pretreatment of industrial wastes prior to discharge.

There are of course other alternatives such as the installation of flow equalization facilities at the treatment works, or upstream in the collector system, that also can be considered during the economic evaluation of the construction program. In all cases it is a matter of balancing the food into the treatment plant to the microorganisms in the treatment works to ensure that effective and efficient treatment is maintained.

As most people are aware from the Class Environmental Assessment process (Class EA), there are two major points at which the evaluation of alternatives are provided for and these should be applied rigorously to the evaluation of the expansion for the Pollution Control Plant.

In the first instance, one must give consideration to the evaluation of the alternatives to the undertaking, namely what alternatives are in place for the facilities. Under this preliminary evaluation one can consider the "do nothing" approach whereby no treatment plant expansion is provided for and thus the community cannot grow, or alternatively a do nothing approach where no treatment plant changes are made the plant is overloaded, the effluent quality deteriorates and the loading to the receiving stream increases.

Other alternatives could be changing the receiving stream location to allow for a poor quality effluent from an overloaded treatment plant, adding expanded facilities to the municipal plant to allow for increased growth, or perhaps even building new treatment works at new locations. The second part of the alternatives evaluation relates more to the evaluation of alternative means to achieve the treatment goals decided upon in the first evaluation. At this stage in the Class EA one can then consider the alternatives of expanded mirror image plants, the implementation of flow equalization, collection and impoundment of storm waters, or the alternative of implementing combined physical/chemical and biological treatment. The Class EA process is nothing more than a common sense approach to evaluating all of these various alternatives. However, both economic and technical considerations must be made. The worst thing that can happen is to have the community elect for a total plant expansion, merely because they want to take advantage of funding available from the MOEE. This one point alone has been responsible for the failure of more water pollution control plants in south western and south eastern Ontario than in any other singular event throughout the 1960's and 1970's.

In one instance alone, for which detailed studies have been completed in the 1980's capital costs of $17,000,000 and annual operating costs of over $1,000,000 were expended merely to expand treatment facilities to consume government funds. As a result, the treatment facility failed to meet the effluent criteria and all of the expanded facilities had to be shut down in order to make the treatment plant facility operate effectively. The interest cost alone on the capital equipment was a staggering amount to pay for a series of now dormant tanks.

The evaluation of the treatment plants to determine the optimum conditions has numerous other positive side effects as well. For example, in a number of full scale optimization studies to evaluate future plant expansion requirements, it has been determined that there is residual capacity within the existing treatment works. Very often it is possible to achieve a re-rating of the treatment facilities through modifications of the operating conditions, or with only minor upgrade of the existing facilities.

In many instances the addition of facilities to adequately handle solids harvested from the biological portion of the plant is all that is required to allow for increased expansion of the facilities. In other instances the addition of more efficient aerators or primary storm tanks is all that is required. Actual site testing can be used to very quickly and accurately determine the specific conditions for any one facility.

The Pollutech organization has now some 25 years of experience in determination of the optimum conditions for water pollution control plant facilities, and as such we have numerous case studies that we can use to demonstrate the theory and concepts that we have outlined in this document.

APPENDIX ONE

CONTROL OF TREATMENT PLANTS BY F/M AND SRT

The F/M (food to microorganism ratio) can be calculated from this for any required MLSS or MLVSS (volatile) number, or conversely a required MLSS number can be calculated given to BOD load and the required F/M value.

F/M = [BOD (kg/day)] / [Aeration Volume (m3) x MLSS (mg/L) / 1000]

If you wanted to operate the plant at a higher loading rate you would decrease the MLSS (you have to take whatever load comes into the plant). Simply stated to increase the F/M from 0.03 to 0.06 you could cut the MLSS in half from 3500 mg/L to 1750 mg/L.

What many design engineers and operators fail to understand is that a biological treatment plant is a living system, just like the human body. There is an optimum amount of food required for a given mass of organisms, and conversely an optimum amount of microorganisms required to consume a given amount of food. Simply stated, you can not design for a given F/M but rather you have to find the correct F/M for a particular waste stream. This is the benefit achieved from lab or pilot scale testing, before the design of a treatment plant. The best demonstration to operators is to show how a human body operates when fed incorrectly. Too much food, you get too fat and can't manoeuvre properly. Too little food and you don't have enough energy to do anything. A human body has an optimal F/M just like a treatment plant.

In order to study and possibly correct the treatment plant operation it is essential to find the optimum MLSS levels for the facility. In many cases the plant operators are not wasting the right amount of sludge and thus the MLSS levels are increasing substantially. The treatment plant, if considered like a farming or harvesting operation, is based on the need to convert soluble BOD to an insoluble cell mass, which is then harvested. If you don't harvest, the facility gets overgrown and fails. In the treatment plant, if the cells (MLSS) are not harvested, the level of the MLSS will continue to increase until the plant "burps" and the solids self waste and pour over the clarifier weir. If the clarifiers are operating with a high sludge blanket and once in a while they "burp" and the plant loses a great mass of the MLSS in the effluent. This is usually identifiable from good effluent solids and the massive changes in the MLSS levels.

To demonstrate how the operators can manage the facility, I refer you to the simple schematic of a typical treatment plant as shown in Figure 2. The whole plant can be operated on the basis of the 30 minute settling test (SV) or the calculated value of the Sludge Volume Index (SVI).

The SV is the settled volume in a 1 litre cylinder after 30 minutes, whereas the SVI is a calculated number for the SV related to the MLSS. Selecting a typical data point, let us assume the SV is given as 96, meaning there were 960 mls of sludge and 40 mls of clear supernatant after 30 minutes settling. At the given MLSS value of 2450 mg/L the SVI is calculated:

SVI = 960 mls x 1000 / 2450 mg/L = 391

If the settling of the sludge improved at the same MLSS the SVI number would change accordingly:

SV (mls)	MLSS (mg/L)	SVI
200	2450	82
400	2450	163
600	2450	245
800	2450	326
1000	2450	408

As a "rule of thumb" a well operating plant would have an SVI of less than 100 which in this case means the SV should be somewhere between 200 and 400 mls after 30 minutes. As an approximation, a plant can be operated with an SV of 300 (30%) as a starting point. It should be stressed that the SVI is not a meaningful number if the value is over 100. We seldom use this calculated measurement because it does not assist an operator in optimizing the plant but rather confuses the issue. It is best to look at the SV alone.

The settling test (SV) is an important measure for the treatment plant operator as it can be used to control the treatment plant without the need for daily suspended solids measurements. Consider a simple schematic of a treatment plant with an aeration tank and a clarifier as depicted in Figure 2.

In this schematic the flow between tanks are the "Q" values and the solids are represented by "S".

The following are the keys:

Qi = influent flow

Si = influent solids, assume these are zero (0)

Vm = aeration tank volume

Sm = aeration tank solids (MLSS)

Qr = recycle flow from bottom of clarifier

Qw = waste sludge flow off recycle line

Sr = solids concentration in recycle or waste flow

Qe = effluent flow (influent minus waste flow)

Se = effluent solids, can also assume zero

The plant operator can conduct a 30 minute settling test in a 1 litre graduated cylinder. The MLSS (Sm) is placed in the cylinder and is allowed to settle. After 30 minutes it may have settled to 30 percent (300 mls). From this the operator can calculate the amount of solids in the recycle stream, relative to the amount of solids in the aeration tank, based on this concentration factor:

$$Sr = [Sm] / [SV / 1000] = [Sm \times 1000 / SV]$$

For example, if the MLSS was 2500 mg/L and the SV test showed settling to 300 mls, the Sr (return sludge concentration) is likely in the order of 8333 mg/L.

The relationship between the Sr and the Sm does not need to be calculated unless the operator wants to confirm that the test is accurate. The important role for this relationship is that it allows the plant operator to calculate what the sludge return rate should be based on the settling test results. To understand this it is important to understand a simplified mass balance of the treatment plant.

Referring to Figure 2, the amount of solids entering the aeration tank is the amount in the influent (QiSi) plus the amount entering by the recycle stream (QrSr). The mass of solids leaving the aeration tank is (Qi+Qr)Sm. The value for QiSi, for example, is the volume of sewage times the solids concentration:

$$QiSi = [7701 \text{ m3} \times 250 \text{ mg/L} \times 1000 \text{ L/m3}] / [1000 \text{ mg/gm} \times 1000 \text{ gm/kg}]$$

It is not necessary to calculate all these numbers, unless the operator is controlling the plant operation by very precise means. Rather, we can make simple assumptions to show how the settling test can be used to calculate the sludge return rate required to operate the facility.

The mass balance formula for the aeration tank is:

$$QiSi + QrSr = (Qi+Qr)Sm$$

If we assume the solids in the influent is negligible as compared to the solids in the recycle stream and the aeration tank, then the value for Si is 0 and the formula simplifies to:

$$QrSr = (Qi+Qr)Sm$$

From the settling test, as described above, the value for Sr is given as:

$$Sr = Sm \times 1000 / SV$$

The mass balance formula is then substituted to give:

$$[Qr \times Sm \times 1000 / SV] = (Qi+Qr)Sm$$

$$Qr = (Qi+Qr) \times Sm \times SV / (Sm \times 1000) = (Qi+Qr) \times SV / 1000$$

$$[Qr / (Qi+Qr)] = [SV/1000]$$

To calculate the sludge recycle flow the process can be simplified to set the recycle flow as a percentage of the influent flow. For this then one can set the influent flow (Qi) to a value of 1. In a settling test that gave an SV of 300 mls, the recycle rate can be calculated as:

[Qr / 1+Qr)] = (300/1000)

[Qr / (1+Qr)] = 0.3

Qr = 0.3(1+Qr)

Qr = 0.3 + 0.3Qr

Qr - 0.3Qr = 0.3

0.7Qr = 0.3

Qr = 0.3/0.7 = 0.43

Therefore the return rate would be set at 43 percent of the plant flow. The simplified version of this formula, that can easily be used by a plant operator is as follows: (SV is a decimal value)

Qr = [SV / (1-SV)] x Qi

Qr = (0.3 / 0.7) x Qi

Qr = 0.43 x Qi

Where this formula is very valuable and critical to the evaluation of this plant is where the sludge settles poorly, either due to filamentous growth or high solids concentrations (Sm or MLSS). If an operator was to conduct a settling test to determine the recycle rate using the above formula, the range of results could be as follows:

SV	Qr (as calculated)
200	0.25
400	0.67
600	1.5
800	4.0
900	9.0
950	19.0
990	99.0
999	999.0
999.9	9999.0

What this table clearly shows is that the recycle of sludge, to keep the plant operating, becomes increasingly more difficult as the SV value increases. A normal plant might be designed to handle up to 150 percent sludge recycle, so for this example if the SV exceeds 600 there is no way this plant can operate. It will eventually wash out. The closer the SV value approaches 1000, which is what is happening, the recycle rate approaches infinity. The plant must have an SV of 500 or less or it just won't be able to operate.

The operators must harvest the sludge from the plant as it grows or the plant is doomed for failure. Not only must the plant waste the amount of solids the account for the influent solids (QiSi) but they must also account for the mass of solids grown from the BOD in the influent. Simple approximations can be made to estimate the amount of solids wasted, or alternatively the plant can be operated on the basis of a preset SRT (Solids Retention Time). It is much easier to operate a plant at a set SRT than the try and judge the amount of solids to waste each day to hold the MLSS constant. It must also be understood that the SRT is directly related to the F/M ratio and therefore controlling one automatically controls the other. Modern day plants are generally controlled by the SRT.

The SRT value is calculated as the mass of solids in the aeration tank (VmSm) divided by the mass of solids wasted each day (QwSr):

SRT = (Vm x Sm) / QwSr

Therefore, the amount of solids to be wasted to operate at a 10 day SRT can easily be calculated:

QwSr = (Vm x Sm) / SRT

Qw = (Vm x Sm) / (SRT x Sr)

From the previous analysis of the mass balance we know that there is a direct relationship between the solids in the recycle (Sr) and the solids in the aeration tank (Sm) based on the settling test results:

[Sm / Sr] = [Sv / 1000]

For example, with a settling test result (Sv) of 300 the concentration of the solids in the aeration tank (Sm) relative to those in the recycle (Sr) would be 0.3 or 30 percent. The flow for the recycle (Qw) can then be calculated easily:

Qw = (Vm / SRT) x (Sm / SRT)

Qw = (Vm /SRT) x 0.3

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