Design and Operation of Final Clarifiers

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The final or secondary clarifier is one of the most important unit processes and often determines the capacity of a treatment plant. The activated sludge system consists of two unit processes, the aeration basin and the final clarifier (Figure 1), which are inseparable, with the performance of one closely linked to that of the other. The failure to consider this interdependency has led to poor clarifier design and operation.

This article outlines factors that are central to the design and operation of clarifiers, as well as tools available to analyze and predict their behavior, based on a systems approach.

Types of Settling

The types of settling that occur in wastewater treatment are summarized in Table 1. Type III settling is the predominant mechanism in secondary clarifiers and governs design, although Types I, II, and IV settling may also occur to a limited extent.

Functions of a Clarifier

The final clarifier must perform two primary functions: clarification and thickening. Clarification is the separation of solids from the liquid stream to produce a clarified effluent with low effluent suspended solids (ESS) levels. Thickening is the conveyance of sludge particles to the bottom of the tank, resulting in a slightly concentrated underflow, or return activated sludge (RAS).

Clarification involves less than 2 percent of the solids that enter the clarifier. A rise in ESS is an indication of clarification failure. Thickening involves a relatively larger fraction of the solids (> 98 percent). Thickening failure results in a rise in sludge blanket depth. If the clarifier fails in either of these functions, the following would be encountered:

- Effluent TSS permit violations.
- Unintentional wasting of solids with the effluent leading to a reduction of solids retention time (SRT), which could potentially impact the biological process.

Clarifiers may also be used for temporary sludge storage during diurnal flow fluctuations. Long-term sludge storage in clarifiers should be avoided, since it results in a substantial portion of the biomass being held in the clarifier in a relatively inactive state, rather than in the aeration tank, where oxygen and substrate are available for the desired biological reactions to occur. Also, deep sludge blankets could potentially cause denitrification and secondary phosphorus release.

Design & Operational Criteria

The criteria commonly used in the design and operational assessment of final clarifiers are the overflow rate, the solids loading rate, and the weir loading rate. Of these, the overflow and solids loading rates are the most important and are discussed in the following paragraphs.

<u>Overflow Rate</u>

As the floc settles in a clarifier, the displaced water rises upward. The upward velocity of water is termed the overflow rate (OFR), with units of gpd/ft^2, and is determined by dividing flow (gpd) by the clarifier surface area (ft^2).

When a clarifier is operated at a specified OFR, all particles having settling velocities higher than the operating OFR will be removed, while particles with lower settling velocities will be carried over the effluent weir. By selecting a proper OFR, clarification is ensured. When the clarifier is not thickening limited (rising sludge blanket), its capacity may be increased by improving settleability.

<u>Solids Loading Rate</u>

The clarifier solids load rate (SLR) in lb/d/ft^2, represents the mass of solids applied

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Table 1
Types of Settling

Type of Settling	Description	Solids Concentration	Primary Mechanism in:
I. Non-flocculent	No particle flocculation. Particles are hydraulically supported & settle independently of each other.	Very low	Grit removal
II. Flocculent	Particles flocculate and settle as larger particles. They are hydraulically supported.	Low	Primary clarification
III. Zone	Flocculated particles settle together as a layer or zone and are hydraulically supported.	High	Final clarification
IV. Compression	Increased contact between particles, which are mechanically supported by particles below. As the layers compress, water is squeezed out.	Very high	Sludge thickening

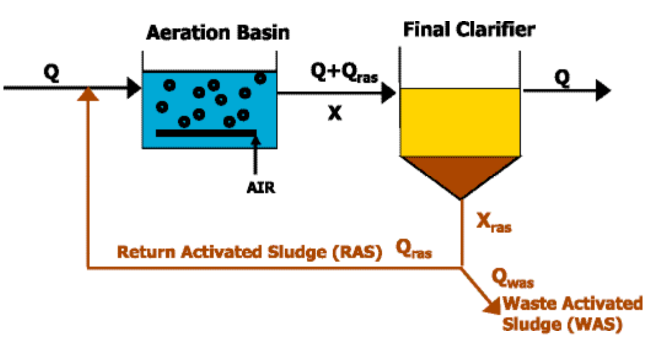

Figure 1: The Activated Sludge System

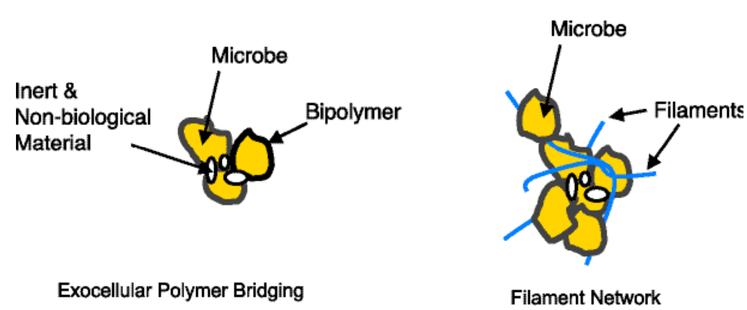

Figure 2: The Bioflocculation Mechanism

Table 2
Common Clarification Failures

Type of Failure	Common Symptoms	Potential Cause
Dispersed growth	Turbid effluent. No distinct solids-liquid interface	No exocellular bridging due to: Too many non-flocculating organisms or filaments Presence of surfactants & toxic compounds Very short SRT (during startup)
Viscous bulking (non-filamentous)	Poor settling and compaction. Sludge has jelly-like consistency. Foaming & scum formation. Rising sludge blanket	Excessive exocellular polymers due to nutrient deficiency.
Pin floc	Spherical floc. Good settling of larger floc but poor settling of smaller floc. Low SVI but turbid effluent.	Too few or no filaments.
Filamentous bulking	Large irregular floc. High SVI with clear supernatant Poor settling and compaction. Rising sludge blanket.	Excessive filaments due to: Long SRT, Low F:M, Low D.O., and Low pH Presence of sulfide and readily biodegradable substrate Nutrient deficiency

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per unit area per unit time. It is calculated as follows:

$$SLR = 8.34*(Q + Q_{ras})*X/A \qquad (1)$$

Where,

- Q = Influent flow, mgd
- Q_{ras} = RAS flow, mgd
- X = MLSS concentration, mg/L
- A = Clarifier surface area, ft^2

The maximum amount of solids that can be conveyed to the bottom of a clarifier is called the *limiting flux*. When SLR exceeds the limiting flux, a rising sludge blanket (thickening failure) is encountered.

Most design engineers prefer to keep the maximum solids loading rate in the range of 25 to 35 lb/d/ft^2. Higher rates of up to 50 lb/d/ft^2 have been encountered in plants with low SVIs, well-designed clarifiers, and effective solids removal. The state point analysis discussed below provides a means of establishing site-specific solids loading rate.

According to the International Water Association model (Figure 2), the clarifier solids concentration profile consists of four zones: a clear water zone (h_1), a separation zone (h_2), a sludge storage zone (h_3), and a thickening/sludge removal zone (h_4). When the SLR exceeds the limiting flux, the sludge storage zone (h_3) expands to accumulate the sludge and limits its conveyance to the bottom of the tank. The continued expansion of h_3 will result in the sludge interface reaching the effluent weir, causing a loss of solids (clarification failure).

During normal operation, the storage zone expands and contracts in response to the diurnal fluctuation of solids loading; therefore, sufficient clarifier depth should be provided to accommodate the routine expansion of the sludge blanket. If the applied solids flux is less than the limiting flux (underloaded condition), the sludge blanket would be composed of zones h_2 and h_4 only.

Factors that Impact Clarifier Performance

The clarification capacity is related to the rate at which the incoming solids can be separated and conveyed to the sludge collection mechanism at the bottom of the tank. Clarifier performance is primarily impacted by sludge settleability and MLSS concentration. Favorable hydrodynamic characteristics are also vital to clarifier performance.

MLSS Requirements

The aeration basin MLSS is one of the most important operating parameters, since it directly impacts clarifier SLR. The design MLSS is typically selected based on the solids inventory required to meet process objectives. Mixed-liquor concentrations significantly less than 1,000 mg/L do not settle well, while mixing and oxygen transfer may become limiting at MLSS above 6,000 mg/L.

For a given process requirement, a higher MLSS concentration would require a smaller biological reactor but a larger clarifier to accommodate the increased SLR. An optimized MLSS is one for which the total system (aeration basin plus clarifier) cost is a minimum.

Where feasible, implementing a step-feed configuration would allow greater solids inventory to be maintained for a given volume of the activated sludge basin without impacting the clarifier SLR.

Sludge Settleability

Like MLSS, sludge settleability has a profound impact on clarifier design and operation. The density differential between the aeration basin floc (which contains greater than 75 percent water) and the surrounding water is small; therefore, flocculation is necessary for effective solids separation in the clarifier.

Flocculation is the process by which particles aggregate into larger (up to 2 mm diameter) and heavier particles that settle readily. When this happens in biological systems, it is called bioflocculation.

According to Jenkins et al. (2004), bioflocculation involves two mechanisms. As shown in Figure 3, some microbes (floc formers) produce exocellular polymers that allow them to “stick” to each other to form a weak and relatively small floc that is susceptible to shearing. The second particle bonding mechanism involves filamentous organisms that form a reinforcing network, which strengthens the floc and allows it to grow into a larger particle.

As the floc grows, inert particles are incorporated. The presence of some inert material has been shown to promote good settling. As presented in Table 2, commonly encountered clarification problems can be explained by the degree of flocculation.

From an operational point of view, a proper balance between filamentous organisms and floc formers would ensure good settleability. Short filaments may not impact

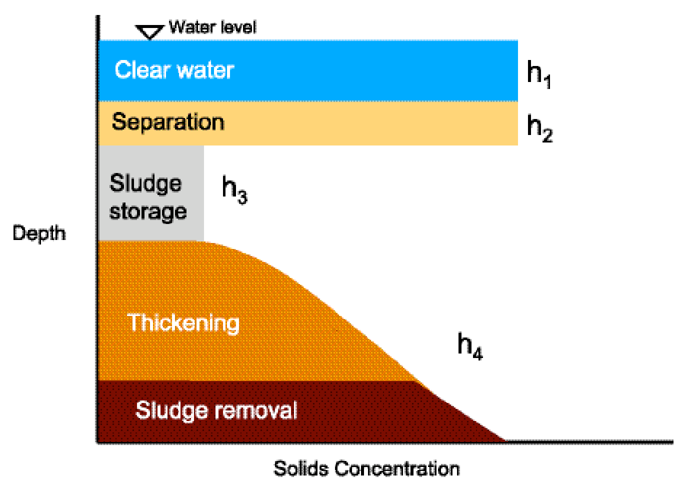

Figure 3: Depth-Solids Concentration Profile

Table 3
Strategies for Enhancing Sludge Settleability

Strategy	Explanation
Biological selectors (aerobic, anoxic, or anaerobic)	Promote the growth of floc-forming organisms by maintaining a high F:M ratio in the initial contact zone to achieve rapid soluble organic uptake. Selectors may be staged to improve kinetic selection.
RAS Chlorination	Selective elimination of filaments. Excess chlorine dose may reduce anaerobic phosphorus release and nitrification.
Elimination of conditions that favor filamentous growth	Change D.O., SRT, and F:M to create an optimum growth environment for floc formers.
Changing bioreactor flow configuration	Plug-flow or completely mixed tanks in series increase F:M.
Chemical addition (polymer, iron & aluminum salts)	Enhance flocculation of dispersed solids and control viscous bulking.
Add inert solids	Enhance settleability with weighting action of inert solids.

sludge settleability, even when present in significant numbers, as much as a smaller number of long and coiled filaments. Strategies commonly used for improving sludge settleability are presented in Table 3.

Sludge settleability impacts the operating RAS flow rate (Q_{ras}). A mass balance around the clarifier provides the following expression for Qras (mgd) in terms of influent flow (Q, mgd), MLSS (X, mg/L), and RAS solids (X_{ras}, mg/L):

$$Qras = (Q^*X) \div (X_{ras}-X) \qquad (2)$$

For example, as shown in Figure 4, a decrease in RAS solids concentration (X_{ras}) from 8,000 to 7,000 mg/L, due to decrease in settleability, will require an increase in Q_{ras} from 60 to 70 percent to transfer the same mass of solids to the activated sludge basin. Also, for a given change in settleability, the change in RAS rate is more dramatic as the operating MLSS increases.

Steady-state clarifier operation is rarely encountered in practice. Operating parameters fluctuate throughout the day. If the available RAS flow range is limited, the operator will not be able to maintain the desired MLSS as changes in settleability are encountered. In addition, if the actual RAS rate is less than the required rate, the resulting solids accumulation in the clarifier will cause the sludge blanket to propagate to the surface (thickening failure), resulting in loss of solids in the effluent (clarification failure). This illustrates the link between the performance of the clarifier and the aeration basin and the need for operational flexibility.

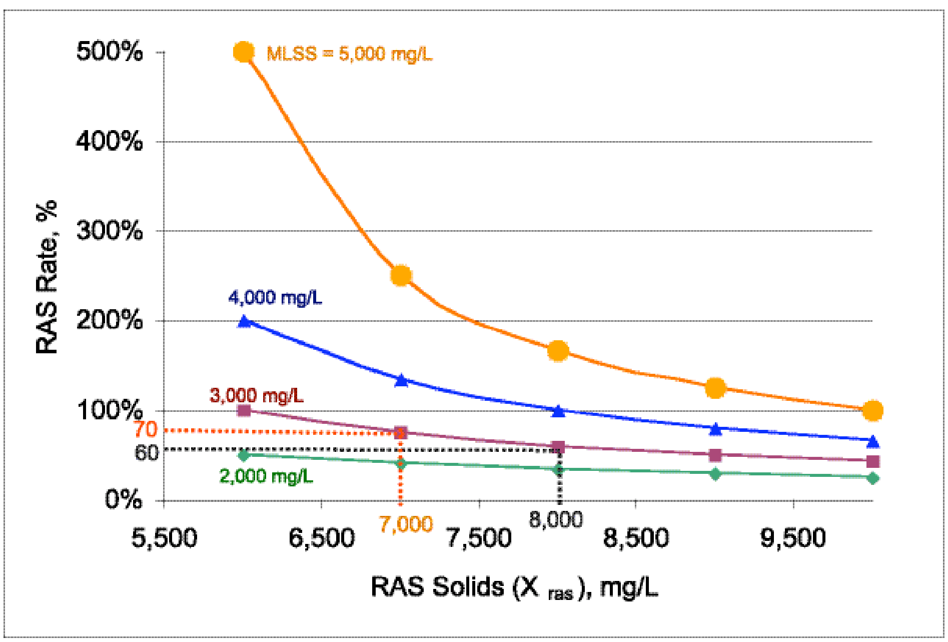

Figure 4: Impact of RAS Solids on RAS Rate

Sludge settleability may be measured by several methods, including the traditional (unstirred) Sludge Volume Index (SVI), Stirred SVI (SSVI), Dilute SVI (DSVI), and SSVI at 3,500 mg/L ($SSVI_{3.5}$). The Traditional SVI is the most commonly used method and is defined as the volume (mL) occupied by 1 g of the MLSS following 30 minutes of settling. Good and poor settleabilities are represented by SVI values of less than 100 mL/g and more than 175 mL/g, respectively.

Hydrodynamic Considerations

The solids capture efficiency is strongly impacted by hydrodynamic characteristics of the clarifier. Features that contribute to improved clarification include:

- Even flow splitting to allow the full capacity of all clarifiers to be realized. Poor performance of an overloaded clarifier generally can not be compensated by good performance of an underloaded clarifier.
- Energy dissipating inlets to achieve uniform distribution of flow and enhanced flocculation.
- Strategically placed internal baffles to minimize short circuiting and density currents.
- Deep flocculating center well to enhance flocculation.
- Deep tanks ($\geq$15 feet) to allow the sludge blanket to expand and contract in response to varying operating conditions without causing elevated ESS.
- Rapid sludge removal mechanism (e.g. hydraulic suction, Tow-Bro™ type).

Floc Shear

While it is important to encourage strong floc formation, it is equally important to preserve the integrity of the floc that is formed. Aeration systems should be designed to provide adequate air and mixing, while avoiding floc breakup.

In diffused aeration systems, air input higher than 90 scfm/1,000 ft^3 tank volume is likely to cause floc shear. Likewise in mechanical aeration systems, the typical volumetric power input should not exceed 3.5 HP/1,000 ft^3.

In addition, turbulence should be minimized in mixed-liquor conveyance systems. If pumping is required, proper pump selection is critical. A gently aerated clarifier feed channel or clarifiers with flocculating feed wells are likely to enhance floc formation.

State Point Analysis

Basic Concept

State Point Analysis (SPA) is a practical tool available to designers and operators to examine the behavior of the final clarifier under various operating scenarios. Since it is based on site-specific data, SPA can also be

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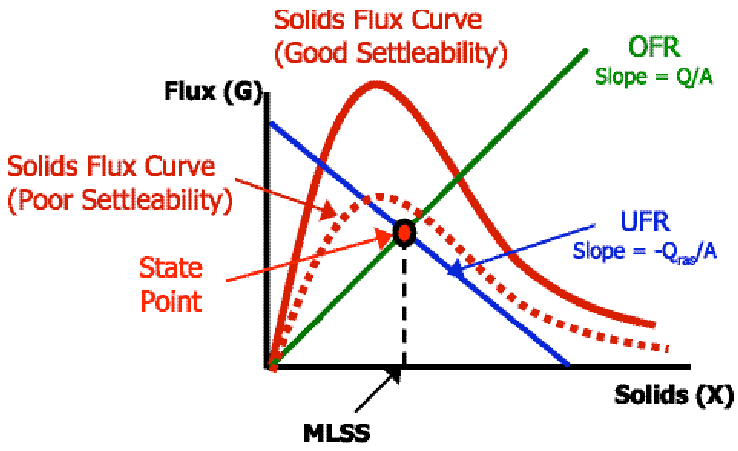

Figure 5: Elements of State Point Analysis

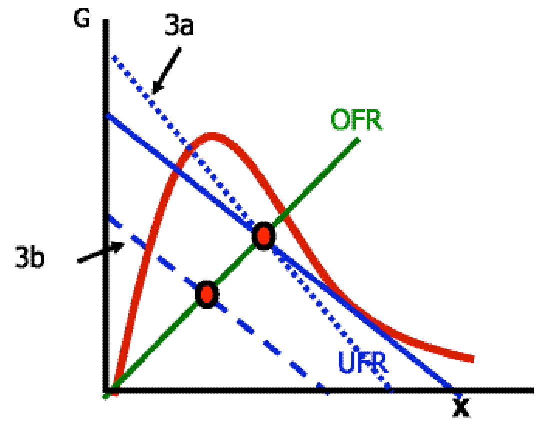

Figure 6: Critically Loaded - Thickening

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used to develop design criteria specific to a plant, thereby lowering design safety factors, optimizing clarifier size, and enhancing confidence in the design process.

SPA is an extension of the solids flux theory, which describes the movement of solids through a clarifier. As stated before, Type III settling is the predominant solids removal mechanism in final clarifiers. It involves settling of flocculated particles as a zone or blanket, with particles maintaining their position relative to each other. The zone settling velocity (ZSV) is a function of MLSS concentration (X) and is commonly expressed by the Vesilind equation:

$$ZSV = V_o e^{-kX} \qquad (3)$$

Where V_o and k are settling constants obtained from a series of settling tests. A good settling sludge is characterized by high Vo and low k. The solids flux (G), lb/ft²/d, is obtained by multiplying the zone settling velocity by the solids concentration.

$$G = (ZSV)\ X \qquad (4)$$

By combining equations (3) and (4), we obtain:

$$G = (X^*V_o)^*e^{-kX} \qquad (5)$$

By performing a series of settling tests at different MLSS concentrations, several combinations of X and G values can be generated. The solids flux curve is then developed by plotting G on the y-axis and the corresponding value of X on the x-axis.

The next step is to superimpose the two key operating parameters of a clarifier, the OFR and underflow rate (UFR). These are shown as straight lines with slopes determined as follows:

$$OFR = Q/A \qquad (6)$$
$$UFR = -Q_{ras}/A \qquad (7)$$

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Table 4
Interpretation of the State Point Analysis

State Point	UFR Line	Clarification	Thickening	Potential Corrective Action*
Within the flux curve. (Figure 5)	Below the descending limb of the flux curve.	Underloaded	Underloaded	None.
Within the flux curve. (Figure 6)	Tangential to the descending limb of the flux curve.	Underloaded	Critically loaded	3(a) Increase RAS rate. 3(b) Reduce feed solids by converting to step-feed or lowering MLSS.
Within the flux curve. (Figure 7)	Intersects the descending limb of the flux curve.	Underloaded	Overloaded	4(a) Control filaments to improve sludge settleability. 4(b) Reduce feed solids by converting to step-feed or lowering MLSS.
On the flux curve. (Figure 8)	Below the descending limb of the flux curve.	Critically loaded	Underloaded	5(a) Increase number of clarifiers to reduce rise rate.
Outside the flux curve. (Figure 9)	Intersects the descending limb of the flux curve.	Overloaded	Overloaded	6(a) Increase number of clarifiers to reduce rise rate.

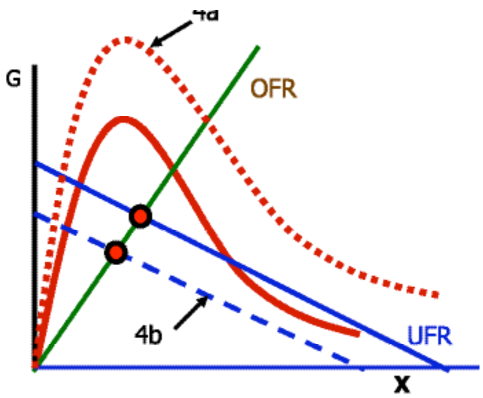

Figure 7: Overloaded - Thickening

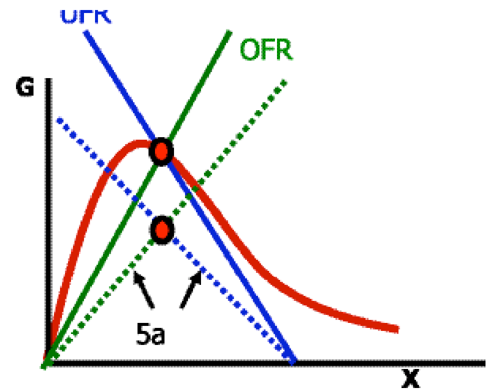

Figure 8: Critically Loaded - Clarification

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Where,

Q = Influent flow, gpd

Q_{ras} = RAS flow, gpd

A = Clarifier surface area, ft^2

The OFR line represents the upward velocity (positive slope) of the water flowing through the clarifier and is drawn from the origin with a slope of Q/A. The UFR represents the downward velocity (negative slope) of the solids due to sludge withdrawal. It is drawn with a negative slope of Q_{ras}/A, starting at the clarifier solids flux (G) on the y-axis, which is calculated using Equation 1:

$$G = SLR = 8.34*(Q + Qras)*X/A \qquad (8)$$

The various components of the SPA are shown in Figure 5. The point of intersection of the OFR and UFR lines is the State Point. The solids concentration (X-axis) at the State Point is the aeration basin MLSS concentration. The State Point represents the operating point of a clarifier. Because operating conditions are never constant, the State Point is dynamic in nature.

<u>Practical Application</u>

The SPA approach can be used by designers and operators to predict clarifier performance as follows:

- Clarification condition is predicted by the location of the State Point in relation to the solids flux curve. This analysis would allow site-specific OFR to be established. The different clarification conditions are:
  - Underloaded: State Point contained within the flux curve. Settling velocity > OFR. Low ESS.
  - Critically loaded: State Point on solids flux curve. Settling velocity = OFR. ESS close to permit limits. At this operating point, peak flows will likely result in high ESS.
  - Overloaded: State Point located outside the flux curve. Settling Velocity < OFR. Solids carryover resulting in high ESS.
- Thickening condition is predicted by the location of the UFR line in relation to the descending arm of the solids flux curve. This analysis would allow site-specific SLR to be established. The different thickening conditions are:
  - Underloaded: UFR line contained within the flux curve. SLR < Limiting Flux. No significant solids accumulation and no appreciable sludge blanket.
  - Critically loaded: UFR line is tangent to the descending arm of flux curve. SLR = Limiting flux. A sludge blanket is formed. This may be an acceptable operating point to cope with diurnal peak solids load. Continued growth of the sludge blanket should be avoided.
  - Overloaded: UFR line intersects the descending arm of flux curve. Significant solids accumulation and deep sludge blanket. Net transfer of solids from aeration basin to the clarifier. Continued propagation of the sludge blanket is likely to result in loss of solids in the effluent (clarification failure).

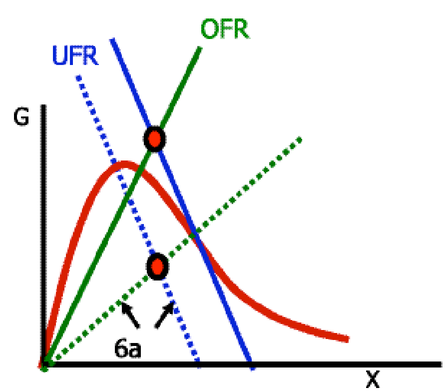

Figure 9: Overloaded – Clarification & Thickening

As illustrated in the Figure 5, a good settling sludge (low SVI) will have a greater area below the solids flux curve, relative to a poor settling sludge (high SVI). This implies that with a good settling sludge, the State Point will have greater freedom of movement within the solids flux curve and the clarifier will have a greater operating range.

A few examples of how SPA can be used to investigate and correct clarifier performance issues are summarized in Table 4. The potential solutions, denoted (a) and (b), are shown in dashed line in the respective figures.

Increasing the RAS flow is a quick way to transfer solids from the clarifier to the aeration basin to relieve thickening failure; however, this will also increase the solids loading rate to the clarifiers and may not be an effective long-term strategy.

Conclusion

This article reviews the many interrelated factors that impact clarifier performance and presents the State Point Analysis as a practical tool available to designers and operators for assessing clarifier behavior under various operating scenarios. The State Point approach also allows site-specific design criteria such as solids loading rate to be developed, based on the linked behavior of the activated sludge basin and the clarifier.

The engineer's goal should be to use good design practices in the design of final clarifiers; however, poor sludge settleability can curtail the operating range of even the best of clarifiers. Operators should strive to enhance settleability to the extent possible in order to ensure stable clarifier operation over a wide range of operating conditions.