High-rate Combined Solids Contacting and Thickening Minimize Footprint and Maximize Treatment

JERRY PHIPPS, USFilter, Ames, IA, and
GLEN SUNDSTROM, USFilter, Rockford, IL

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ABSTRACT

Waste production and footprint are important considerations in the design of any industrial water treatment plant. Many industrial water treatment facilities use lime softening to reduce hardness, suspended solids, silica and other potential foulants in their cooling water, boiler feed and other process water systems.

A recently developed package plant combines solids contact reaction and sludge thickening in a single tank. This design eliminates transfer pumps, interconnecting piping, valves and instruments while reducing overall footprint. The process, along with pilot-scale and full-scale results, will be discussed.

BACKGROUND

Solids contact clarifiers are commonly used for industrial water treatment. The clarifiers are used to treat surface waters, ground waters and wastewaters including cooling tower blowdown (CTBD). The chemistry can be adjusted to target solely suspended solids removal or both suspended and dissolved solids removal via lime softening.

Clarifiers are most commonly placed at the front of the treatment system to reduce contaminants such as suspended solids, dissolved solids, hardness, alkalinity, silica, iron and manganese. These contaminants could lead to scaling problems in the cooling and boiler feedwater systems.

Clarified water is often of high enough quality to use in the cooling water system without further treatment. The portion of the water used for boiler makeup or other process water typically requires further treatment such as filtration, reverse osmosis, and/or demineralization. However, the pre-treatment step makes the entire system more efficient by reducing solids loading to the downstream unit operations.

Solids contact clarifiers for lime softening service are normally sized for 0.85 – 1.5 gpm per square foot of overall footprint. With the amount of water typically required

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for cooling tower makeup and other uses, the solids contact clarifiers represent a significant portion of the treatment plant's overall footprint.

Typical solids contact clarifiers produce sludge containing approximately 3% dry solids by weight. Solids are usually further dewatered in a sludge thickener prior to being sent to a sludge press. The sludge thickener requires additional footprint as well as transfer pumps between the clarifier sludge sump and thickener, interconnecting piping and valves, and a supernatant return system to return clear overflow back to the front of the treatment plant. Eliminating a sludge thickener substantially decreases a treatment plant's installed cost.

Minimizing waste production and footprint were key factors in developing a treatment process that includes an integral sludge thickener in a compact arrangement. The process can be used to produce water for process water use, cooling tower makeup, sidestream and blowdown treatment, as well as for pre-treatment to high-purity boiler feed systems. Test results and full-scale results follow.

PILOT TEST UNIT DESIGN

With the above considerations, a design was developed to meet three primary objectives:

a) Enable higher rise rates to minimize footprint;
b) Produce thick sludge to eliminate a separate sludge thickener; and
c) Produce high-quality effluent of equal or better quality than is typically expected of a solids contact unit.

A pilot test unit was built to simulate full-scale operation, verify design parameters and meet the above objectives. Design was based on solids contacting theory. By recirculating solids within the unit, newly precipitated solids collide with and adhere to previously formed precipitates. As newly precipitated solids attach to existing floc particles, the floc particle size increases which in turn increases the particle terminal settling rate. Stokes Law, shown in Eq. (1), gives the terminal settling rate of a spherical particle at a low Reynolds number:

$$u_t = g d_p^2(\rho_p-\rho)/(18\mu) \quad \text{(Equation 1)}$$

where u_t = terminal settling velocity
g = acceleration of gravity
d_p = particle diameter
ρ_p = particle density
ρ = density of surrounding fluid
μ = fluid viscosity

Eq. (1) shows that at constant particle density, the settling velocity is proportional to the square of the particle diameter. If the particle diameter doubles, then the terminal settling velocity will increase by a factor of four. This, in turn, increases the maximum rise rate of the process and minimizes the required equipment footprint.

Many solids contact units provide either internal solids recirculation that is three to six times the inlet flow or external sludge recirculation at 5 - 10% of the inlet flow. To maximize solids contact and floc particle diameter, the design was developed with both internal and external solids recirculation. Internal solids recirculation was designed at 10 times the inlet flow with an external sludge recirculation pump sized for 10% of the inlet flow.

Maximizing chemical efficiency is yet another benefit of solids contacting. Previously formed precipitates act as catalysts for new precipitation reactions, while recirculated solids and sludge contain excess unreacted chemical. Recirculation ensures that unreacted chemical is used and reactions fully complete.[2]

Eq. (1) shows that particle density also significantly affects the settling velocity. In order to maximize particle density, a high shear impeller was incorporated into the design to constantly shear the floc as it recirculated. Continuously shearing and re-forming the floc particles supposedly releases entrained water and produces a denser, rapidly settling floc particle.

To ensure high-quality effluent at the highest rise rates possible, tube-settling modules were placed in the unit's settling zone. Settling tubes and/or plates have been used for many years to substantially increase the allowable upflow rate or reduce carryover at the same upflow rate.[3] Placing these devices at an incline increases the effective settling area. Rising particles contact the settlers' surface, which inhibits the particles' ability to continue rising[3]. Tube settlers, inclined at 60° from the horizontal, were used for this unit. The tubes' vertical depth was 21 inches, and the tube openings were on 2-inch centers to provide 6 sq ft of effective settling area per square foot of plan area. Historically, tube settlers of this configuration have increased upflow capacity by approximately 1 ½ - 2 times.

Figure 1 shows a flow diagram of the pilot unit. Chemicals and raw water are combined with recirculated sludge and enter the unit's center draft tube. An impeller within the draft tube provides additional recirculation, up to 10 times the inlet flow, while continuously shearing and re-forming the floc particles. The draft tube is surrounded by a cylindrical rotating reactor assembly that provides detention time for the recirculation process.

Treated water then flows upward through a channel connected to the reactor tank assembly. Water overflows from the upflow tube and turns downward into the outer settling zone. Heavy solids drop to the bottom of the tank while clarified water takes a sharp 180° turn into the effluent zone. The effluent zone is fitted with 60° tube settler modules that increase the effective settling area and allow for higher flow rates.

Sludge is compacted and thickened in the bottom of the tank before scraper arms move it towards a centrally located sump. Sludge from the sump is blown down periodically.

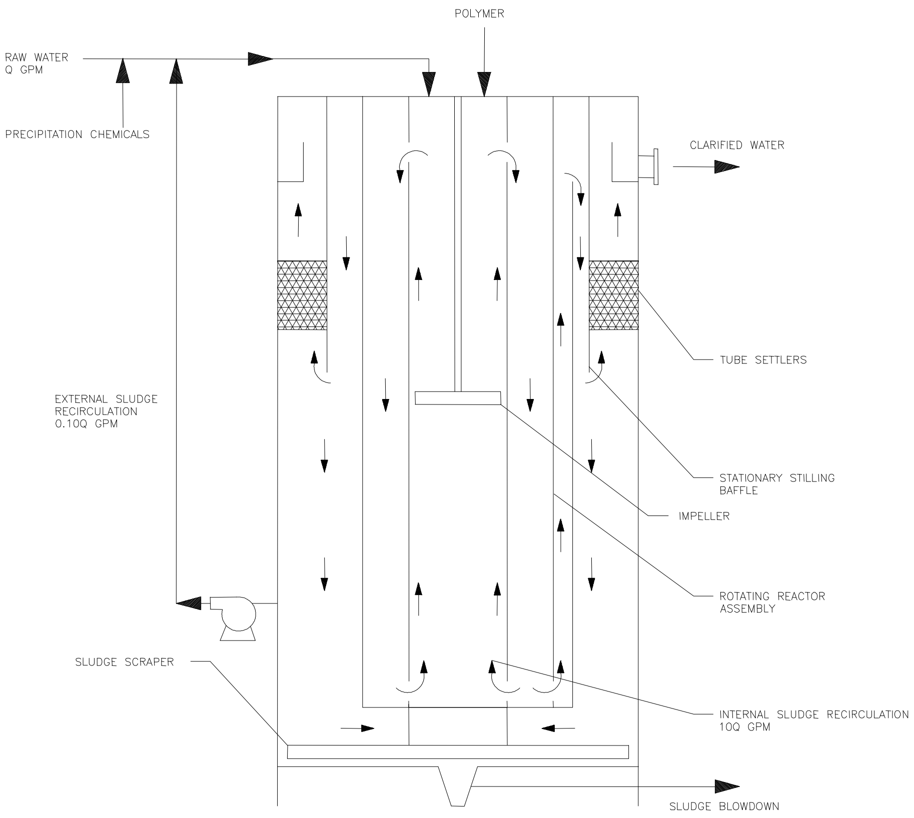

FIGURE 1: Pilot Plant Flow Diagram

Multiple pilot studies confirmed performance on different water supplies and applications. The pilot results are summarized below.

GROUND WATER SOFTENING TEST RESULTS

Initial testing occurred over a two-week period, utilizing an aerated ground water source from a Midwest water treatment plant. The study's primary objectives included verifying that the process would produce good quality effluent water at the design flow rate and determining what solids concentration could be expected in the sludge. Table 1 illustrates average raw water quality.

TABLE 1: Raw Ground Water Quality

Parameter	Concentrations
Temperature	52° F
pH	7.6
Hardness (Total)	360 mg/L as $CaCO_3$
Calcium	260 mg/L as $CaCO_3$
Magnesium	100 mg/L as $CaCO_3$
Alkalinity (Total)	260 mg/L as $CaCO_3$
Turbidity	47 NTU
Iron	5.2 mg/L
Manganese	0.4 mg/L

According to Table 1, the water was present at typical well water temperatures and contained high iron and manganese, high turbidity (likely due to insoluble iron), calcium bicarbonate hardness and magnesium non-carbonate hardness. Flow rates tested were between 100 - 160 gpm which equates to 2.0 - 3.2 gpm/sq ft of overall tank area and 5.5 – 8.8 gpm/sq ft of net settling area. Lime was added at approximately 250 mg/L to target the calcium bicarbonate hardness. A high molecular weight anionic polymer was dosed at 0.5 mg/L to improve solids densification and overall performance. The chemical reactions that took place when lime was dosed into water follow[4].

$$CO_2 + Ca(OH)_2 = CaCO_3 + H_2O \quad \text{(Equation 2)}$$

$$Ca(HCO_3)_2 + Ca(OH)_2 = 2CaCO_3 + 2H_2O \quad \text{(Equation 3)}$$

$$Mg(HCO_3)_2 + Ca(OH)_2 = CaCO_3 + MgCO_3 + 2H_2O \quad \text{(Equation 4)}$$

$$MgCO_3 + Ca(OH)_2 = CaCO_3 + Mg(OH)_2 \quad \text{(Equation 5)}$$

Equations 4 and 5 can be combined to create Equation 6.

$$Mg(HCO_3)_2 + 2Ca(OH)_2 = 2CaCO_3 + Mg(OH)_2 + 2H_2O \quad \text{(Equation 6)}$$

As seen in Eq. (3), bicarbonate alkalinity first combines with calcium to precipitate calcium carbonate. Calcium and magnesium removal depends on the amount of alkalinity in the water. Hardness removal is therefore limited by raw water alkalinity unless it is added, typically in the form of soda ash.

Based on the above raw water characteristics and chemical reactions, hardness removal was expected to consist mostly of calcium removal with limited magnesium reduction. As Eq. (2) and Eq. (3) were the primary reactions taking place, sludge should consist mostly of calcium carbonate.

In estimating the settling rate and sludge thickness, it is important to know which precipitates are present in which quantities. Experience shows that calcium carbonate sludge settles faster and thickens better than metal hydroxide sludges.

Average effluent quality and results are summarized in Table 2.

TABLE 2: Clarified Ground Water Quality

Parameter	**Concentrations**	**Percent Removal**
pH	9.9	n/a
Hardness (Total)	160 mg/L as $CaCO_3$	56%
Calcium	75 mg/L as $CaCO_3$	71%
Magnesium	85 mg/L as $CaCO_3$	15%
Alkalinity (Total)	55 mg/L as $CaCO_3$	79%
Turbidity	2 NTU	96%
Iron	0.3 mg/L	94%
Manganese	0.01 mg/L	98%

Hardness and alkalinity reduction paralleled theoretical predictions, as did good iron and manganese removal. Effluent turbidity typically remained below 2 NTU, which is commonly suitable for direct feed to a cooling tower.

Sludge was blown down periodically to remove accumulated solids from the unit. Sludge samples were routinely collected and found to contain on average between 30 - 50% dry solids by weight -- significantly higher sludge density than the 3% solids sludge typically observed with conventional lime softening equipment. The unit contained enough sludge storage volume to extend the time between blowdown events, which allowed the sludge to further compact and thicken.

The solids concentration achieved with this pilot study translates to lower waste volumes than conventional equipment. If the solids concentration is x times the typical concentration, then waste volume will be less than 1/xth the waste volume due to differences in specific gravity.

In review, the initial two-week pilot study on a ground water source confirmed that the primary performance requirements were met:

a) The unit performed well at rise rates up to 8.8 gpm/sq ft of net settling area, which equates to 3.2 gpm/sq ft of overall tank area. This is less than half the footprint required for conventional lime softening equipment, excluding thickening.

b) Sludge thickness was as thick as, or thicker than, expected from a separate sludge thickener. Sludge was determined to be thick enough to be directly fed into a sludge press for further dewatering.

c) Theoretical predictions of effluent quality proved accurate, with effluent suspended solids being low enough for typical cooling tower feedwater but without the need for further treatment such as filtration.

COOLING TOWER BLOWDOWN (CTBD) SOFTENING TEST RESULTS

The next pilot study was conducted on CTBD from a Midwest power plant. The study aimed to confirm performance and design parameters based on a more difficult application where interference might occur between the cooling water chemicals and the precipitation reactions. The water also contained very high concentrations of hardness with only moderate alkalinity, resulting in high amounts of metal hydroxide sludge.

The raw water contained high levels of silica and, as a result, the unit's ability to remove silica was also examined. Silica removal is often a concern for industrial water treatment plants because silica will limit the number of concentration cycles in boilers and cooling towers. It is also soluble in high-pressure steam, where it can potentially form very hard, irreversible scaling of condensers and turbine blades[2].

Soda ash was added to optimize hardness reduction, boost alkalinity in the water and precipitate remaining calcium and magnesium. The following chemical reactions take place when soda ash is dosed into water[2].

$$Ca(SO_4 \text{ or } Cl_2) + Na_2CO_3 = CaCO_3 + Na_2(SO_4 \text{ or } Cl_2) \quad \text{(Equation 7)}$$

$$Mg(SO_4 \text{ or } Cl_2) + Na_2CO_3 + Ca(OH)_2 = Mg(OH)_2 + CaCO_3 + Na_2(SO_4 \text{ or } Cl_2) \quad \text{(Equation 8)}$$

Table 3 summarizes raw CTBD quality. In general, the water was warm and very high in hardness, silica and suspended solids.

TABLE 3: Raw CTBD Quality

Parameter	Concentrations
Temperature	74-101° F
pH	8.2
Hardness (Total)	1422 mg/L as $CaCO_3$
Calcium	981 mg/L as $CaCO_3$
Magnesium	436 mg/L as $CaCO_3$
Alkalinity (Total)	296 mg/L as $CaCO_3$
Turbidity	100 NTU
Silica (Total)	162 mg/L as SiO_2

According to Table 3, the majority of calcium and all of magnesium were present as non-carbonate hardness. As shown in Eq. (7) and Eq. (8), high amounts of both lime and soda ash were required for removal. On average, lime was added at approximately 616 mg/L, and soda ash was added at 1,204 mg/L. Instead of adding a dry anionic polymer, an emulsion-type anionic polymer was dosed at a rate of 6.5 mg/L. Ferric chloride was added at a rate of 28 mg/L to improve effluent turbidity.

Flow rates tested were between 100 -165 gpm, which equates to 2.0 - 3.3 gpm/sq ft of overall tank area and 5.5 - 9.1 gpm/sq ft of net settling area. Results are presented in Table 4:

TABLE 4: Clarified CTBD Quality

Parameter	Concentrations	Percent Removal
pH	10.7	n/a
Hardness (Total)	100 mg/L as $CaCO_3$	93%
Calcium	36 mg/L as $CaCO_3$	96%
Magnesium	64 mg/L as $CaCO_3$	85%
Turbidity	5 NTU	95%
Silica (Total)	31 mg/L as SiO_2	81%

Results show that the unit performed well, even on this difficult application. Good hardness reduction was achieved, and turbidity once again came within acceptable industry requirements. Silica reduction was found to be above 80%. It should be noted that silica reduction is a function of both raw water magnesium content and temperature, with silica removal improving as these parameters increase[3]. Magnesium may need to be fed directly into the unit if water sources are deficient in the mineral.

Average sludge concentration was 29% dry solids by weight, similar to what was observed with the ground water testing. This showed the sludge collection and blowdown system could effectively remove large amounts of solids to maintain a steady state solids inventory. Sludge blowdown should be set to maintain a sludge concentration of 15 - 20% solids. This also increases the sludge's ability to flow and minimizes plugging. The lower sludge concentration is still thick enough to be sent directly to a filter press without requiring further thickening.

In summary, the second CTBD pilot study verified the primary performance requirements were met, even for such a difficult application.

a) The unit performed well at rise rates up to 7.1 gpm/sq ft of net settling area, which equates to 2.6 gpm/sq ft of overall tank area. This is approximately one-half the footprint required for conventional lime softening equipment on a similar application, excluding thickening.
b) Sludge concentration was as high as, or higher than, expected from a separate sludge thickener. Sludge was determined to be concentrated enough for direct feed to a sludge press for further dewatering.
c) Effluent quality lined up with theoretical predictions, with effluent suspended solids low enough for typical cooling tower feedwater without requiring further treatment such as filtration.

GROUND WATER SOFTENING FULL-SCALE RESULTS

A full-scale, 1.8-MGD unit was installed at a Midwest automobile plant. The unit, which started up in January 2005, was retrofitted into an existing basin to replace an old failing clarifier mechanism.

The facility takes untreated well water and softens it for potable and process water use. Clarified water flows through gravity filters where it is polished before use. A portion of this water is further treated for use as boiler feedwater. The existing sludge recirculation pumps that draw sludge from the bottom of the unit and recycle it back to the unit inlet were also re-used. Sludge is blown down periodically from the recirculation line.

Table 5 summarizes typical raw water quality. As the raw alkalinity exceeds the raw hardness level, all hardness is present as carbonate hardness and requires only lime for removal per Eq. (2), (3), and (6). The full-scale installation is very similar to the initial ground water softening pilot test. Lime is slaked, and an anionic polymer is added at approximately 0.5 ppm.

TABLE 5: Full-scale Ground Water Application Raw Water Quality

Parameter	Concentrations
Temperature	55° F
pH	7.3
Total Hardness	350 mg/L as $CaCO_3$
Calcium	160 mg/L as $CaCO_3$
Magnesium	190 mg/L as $CaCO_3$
M Alkalinity	360 mg/L as $CaCO_3$
CO_2	37 mg/L

Table 6 shows the operating results. The lime softening process removed calcium down to the lowest level possible[2]. Overall hardness lined up with results obtained from on-site jar testing. Effluent turbidity remained constant at 5 NTU, matching pilot study results.

A photo of the full-scale unit is shown in Figure 2.

TABLE 6: Full-scale Ground Water Application Clarified Quality

Parameter	Parameter	Percent Removal
pH	10.3	n/a
Total Hardness	60-80 mg/L as $CaCO_3$	80%
Calcium	35 mg/L as $CaCO_3$	78%
Magnesium	45 mg/L as $CaCO_3$	76%
M Alkalinity	90 mg/L as $CaCO_3$	75%
CO_2	0 mg/L	100%

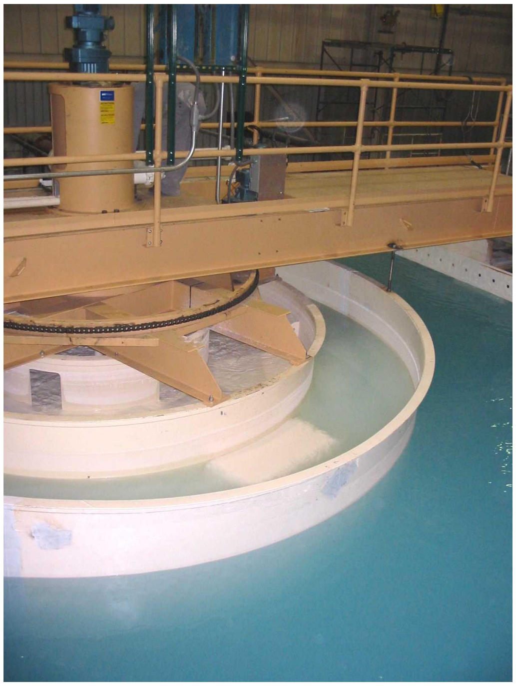

FIGURE 2: 1.8-MGD Unit in Operation

APPLICATION EXAMPLE

Figure 3 compares footprints for the combined clarifier-thickener and separate units. The right-hand side shows the actual equipment recently supplied for a 4,800-gpm lime softening application at a power plant. The plant uses two 50-ft diameter clarifiers, plus a 45-ft diameter sludge thickener. Overall footprint of the separate clarifiers and thickener is 110 ft by 105 ft, for a total of 11,550 sq ft including spacing between the tanks. The combined clarification-thickening unit has a footprint of 39 ft by 66 ft 4 in, or 2,587 sq ft. This is about 22% the size of the separate clarifiers and thickener.

The smaller footprint means lower foundation and basin costs. The single basin design eliminates interconnecting piping, valves, pumps and instruments between the clarifiers and thickener. This design also eliminates the thickener supernatant return system, which typically consists of an overflow tank with level controls and a pump to transfer water back to the front of the plant.

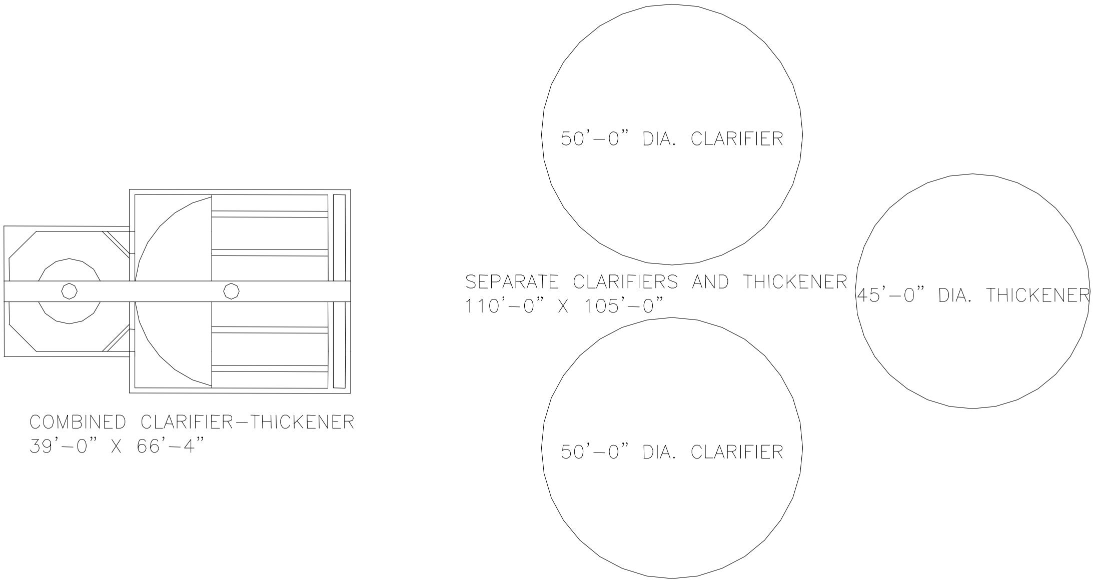

FIGURE 3: Footprint Comparison of Combined Vs. Separate Clarification and Thickening

CONCLUSIONS AND APPLICATION RECOMMENDATIONS

Pilot testing confirmed the design could successfully operate at high rise rates and produce thick sludge while maintaining high-quality effluent. Design performance has been proven in a full-scale, 1.8-MGD industrial application.

Unit footprint is between 2.0 - 3.2 gpm/sq ft of overall tank area. The higher rise rates are suitable for "easier" applications such as ground water softening, warm waters and primarily calcium carbonate precipitation. For more difficult applications such as cold waters, CTBD or sidestream treatment, or when high amounts of hydroxide sludge are produced, the rise rate will be closer to the lower end of this range to account for less rapidly settling particles. For applications such as CTBD, where sequestering agents and/or surfactants are present, jar testing is strongly recommended to define and optimize chemical feed requirements and operating parameters. The pilot unit is available, and further studies will likely be conducted by 2006.

Sludge concentration was between 15 - 20% dry solids by weight, although higher concentrations were achieved during pilot testing. The desired range was determined based on the sludge flow characteristics. Adjustments to sludge blowdown frequency and duration could control the sludge concentration.

Minimizing footprint and producing thick sludge reduces equipment footprint and eliminates the need for a separate thickener, resulting in a simplified installation and lower installed cost. The process is applicable to various installations including municipal drinking water and industrial applications.

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REFERENCES

1. Perry, R. and Green, D. (1997). "Perry's Chemical Engineers' Handbook, 7th Edition," pp. 6-51, McGraw-Hill.
2. Nordell, E. (1961). "Water Treatment for Industrial and Other Uses, 2nd Edition," pp. 496, 70, 494, 507, Reinhold Publishing Company.
3. Drew Chemical Corporation (1977). "Principles of Industrial Water Treatment, 1st Edition," pp. 18-19, 21, Drew Chemical Corporation.
4. American Water Works Association, American Society of Civil Engineers (1998). "Water Treatment Plant Design, 3rd Edition," pp. 284, McGraw-Hill.