Sixty-five-year old final clarifier performance rivals that of modern designs
James L. Barnard, Thomas E. Kunetz and Joseph P. Sobanski

ABSTRACT
The Stickney plant of the Metropolitan Wastewater Reclamation District of Greater Chicago (MWRDGC), one of the largest wastewater treatment plants in the world, treats an average dry weather flow of 22 m³/s and a sustained wet weather flow of 52 m³/s that can peak to 63 m³/s. Most of the inner city of Chicago has combined sewers, and in order to reduce pollution through combined sewer overflows (CSO), the 175 km Tunnel and Reservoir Plan (TARP) tunnels, up to 9.1 m in diameter, were constructed to receive and convey CSO to a reservoir from where it will be pumped to the Stickney treatment plant. Pumping back storm flows will result in sustained wet weather flows over periods of weeks. Much of the success of the plant will depend on the ability of 96 circular final clarifiers to produce an effluent of acceptable quality. The nitrifying activated sludge plant is arranged in a plug-flow configuration, and some denitrification takes place as a result of the high oxygen demand in the first pass of the four-pass aeration basins that have a length to width ratio of 18:1. The SVI of the mixed liquor varies between 60 and 80 ml/g. The final clarifiers, which were designed by the District’s design office in 1938, have functioned for more than 65 years without major changes and are still producing very high-quality effluent. This paper will discuss the design and operation of these final clarifiers and compare the design with more modern design practices.

Key words | final clarifiers, flocculation, gravity currents, inlet structures

BACKGROUND
The circular final clarifiers of the Stickney plant were designed around 1938, at a time when there was little understanding of the hydraulic issues dictating the behavior of clarifiers. The result is testimony to the true engineering genius of those designers. Gravity currents, the waterfall effect of the heavier influent mixed liquor, the upwelling near the peripheral wall, the need for baffling the influent, and the placement of the effluent channels were investigated and researched. Most of these terms that we regularly use today to describe the hydraulics inside these tanks were defined at that period when a number of large plants were designed in the United States that incorporated circular clarifiers (Anderson 1941, 1945) and rectangular clarifiers, (Gould 1943). In the absence of computer modeling, many of the studies were made on full-scale tanks using dye tests and ingenious floats (drogues) to detect the currents; some of these technologies are still in use today. The Stickney final clarifiers do not comply with many of the now generally accepted norms for inlet design, yet they produce effluent of outstanding quality with a total suspended solids concentration consistently in single digits. In a recent study state point analyses (SAP) and computerized fluid dynamics (CFD) were used to better understand the reasons for their excellent performance.

INLET STRUCTURES
It is generally accepted that there is a need for accelerating the flow of mixed liquor upon entering the tank and then impact the mixed liquor on either a solid surface or have
two streams impacting on one another, to destroy the momentum and create turbulence for flocculation. Examples of these are the WesTech design, shown on Figure 1, which involved the mixed liquor passing through slots in the vertical feed pipe into an energy dissipating inlet structure (EDI) or a tub at velocities as high as 0.75 m/s, and then exiting tangentially through outlets near the surface until it impinges on the skirt of the stilling well, imparting a rotating motion to the liquid in the stilling well. The turbulence caused by the rotation in the stilling well distributes the flow evenly, avoiding density currents and promoting flocculation in the mixed liquor. At high flows the momentum of rotation of the mixed liquor can carry over into the main clarifier and disturb the hydraulic patterns (Haug et al. 1999). Shaw et al. (2005) proposed placement of fins inside the stilling well skirt to counteract the rotational forces during high flows.

The need for the tub was questioned by Narayanan et al. (2002), who found that one out of five such final clarifiers at the Laguna Sub-regional Water Reclamation Facility (LSWRP) in Santa Rosa, California, performed consistently better than the other four. Inspection revealed that the excellent performance was the result of accidental omission of the bottom of one of the EDIs. The mixed liquor exiting the central feed pipe through slots in the pipe impinged onto the wall of the EDI and was deflected to the sides and in turn impinged on the currents from the other outlets, or it was deflected downward. Computational Fluid Dynamics (CFD) studies confirmed the superiority of the bottomless EDI over those with bottoms, indicating that “currently accepted design methods for EDI’s may not provide the most optimal solids removal performance during peak flow conditions” Narayanan et al. (2002).

Studies in Los Angeles (Haug et al. 1999) showed that the WesTech design functioned well at lower loads, but imparted a rotational velocity on the mixed liquor that carried over into the main body of the clarifier, limiting the loading rate on the final clarifiers to about 2 m³/m².h or the overflow rate to 2 m/h. They sought to improve upon this by using jets impacting on one another as shown on Figure 2 and called this the LA-EDI. They found that they could operate with surface overflow rates (SOR) or upflow velocities up to 2.7 m/h, and even as high as 3 m/h, without failure. The impacting of the jets destroyed their momentum and promoted flocculation without imparting rotational velocities.

All final clarifiers of the Stickney plant have a diameter of 38.5 m and a sidewater depth of 4.11 m, and the floors slope to a depth of 5.13 m in the center of the clarifiers. The double-sided effluent launder is suspended on cantilevers inside the peripheral wall. The inlet structures evolved with every extension of the plant. The original inlet consisted of a 1.07 m square feed conduit under the clarifier, with a cross sectional area of 1.14 m², that transitioned to a pipe, turns to a vertical position at the clarifier bottom, and continues upward in the shape of an inverted cone increasing in diameter to 1530 mm, with a surface area of 2.3 m² at a height of 3.15 m from the bottom (Figure 3). At the sustained wet weather flow, the upflow velocity of the clarifiers is 1.98 m/h. The sludge recycle rate varies from 30% to 50% of the influent and the MLSS concentration is...
between 2 and 2.5 kg/m³. The sludge loading rate varies from 5 to 6 kg/m².h. The clarifiers are of a simple design, with no flocculation well and no sophisticated baffles. In later designs the feed was further slowed down by enlarging the feed conduit to a square section with 1.22 m sides and a surface area of 1.49 m² and the top of the cone-shaped outlet having a diameter of 1.83 m and a cross sectional area of 3.35 m².

The designers sought to reduce the upflow velocity in the inlet pipe to around 300 mm/s to just prevent settling in the pipe. While not described in the paper (Anderson 1945) it seems that the designers were aware of the turbulence that would result from the expansion of the flow in the cone shaped vertical conduit and although flocculation was not discussed, this arrangement must have resulted in good flocculation.

In his paper and notes Anderson (1941, 1945) described the design and the goals of keeping the inlet velocities very low. They experimented with a number of options for baffling the inflow such as closing the bottom of the feed well and having side outlets but concluded that the process performed best with the inlet structure as designed.

**Computerized fluid dynamics (CFD)**

A CFD program was set up to evaluate the performance of the clarifiers at sustained wet weather flows of 52 m³/s to demonstrate worst case conditions, at the present depth of the inlet well skirt at 1.2 m below the liquid surface. The dimensions of the original inlet structures were used on the basis that slowing down the influent, as was done in the later designs, would further improve the performance. The following assumptions were made.

- The flow is distributed equally among all final clarifiers and 90 out of 96 of the clarifiers are in service.
- The mixed liquor solids concentration was 2,700 mg/L
- Diameter of each clarifier is 38.5 m
- Inlet pipe diameter is 0.91 m
- Sustained maximum flow to each tank is 0.53 m³/s
- Constant return activated sludge flow rate is 0.21 m³/s
- Inlet pipe flares open to diameter of 1.63 m
- The center of the in-board launder is located 4.27 m from perimeter wall
- SVI is 50 to 60 ml/g

The velocity profiles on Figure 4 show the effect of the expansion of the inlet pipe to reduce the momentum. The

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**Table 1** Velocities through final clarifiers

<table>
<thead>
<tr>
<th></th>
<th>Influent m³/s</th>
<th>RAS m³/s</th>
<th>Velocity (m/s)</th>
<th>Feed pipe Support SOR (m/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average flow</td>
<td>30</td>
<td>18</td>
<td>0.25</td>
<td>0.06</td>
</tr>
<tr>
<td>Sustained peak flow</td>
<td>52</td>
<td>18</td>
<td>0.42</td>
<td>0.09</td>
</tr>
<tr>
<td>Instantaneous flow</td>
<td>63</td>
<td>18</td>
<td>0.43</td>
<td>0.10</td>
</tr>
</tbody>
</table>

1 m³/h = 600 gpd/ft²
1 m³/s = 22.8 mgd

Table 1 describes the velocities through final clarifiers at different flow conditions.
spectrum of colors in this analysis ranges from red for velocities around 0.4 m/s to deep blue for velocities approaching 0. While this may not be clear in a black and white printout, the red color as in the inlet pipe, shows deep black, the transition (0.1 to 0.2 m/s) is light while the blue in the bulk of the clarifier is again a dark shade. This distribution is not ideal in that the influent momentum tends to be discharged to one side of the tank, creating an asymmetrical pattern. However, this seemed to have very little impact on the performance of the clarifier, as indicated by the deep blue region with very quiescent flow in the bulk of the clarifier. It appears that the momentum of the influent carries the mixed liquor to the top of the basin and that it is deflected downward by the skirt, and deflected towards the centre by the backflow of clear liquid which helps to break up the density current and in effect forms a flocculation zone, with little of the energy transferred to the lower part of the clarifier. Considering that in this example the SVI is low and the flow is high, the result is very good since a low SVI tends to encourage gravity currents.

This configuration results inevitably in gravity currents as would be the case with any modern design which includes a flocculation well. The gravity currents were determined by Anderson (1941) by the use of drogues. However, at overflow rates exceeding 2 m/h the modeling shows a very low velocity gradient in most of the tank but especially near the effluent channel.

For comparison, a CFD analysis of a WestTech design is shown on Figure 5. The color scale in the two figures differ in that on Figure 4 the highest point on the red scale represents 0.4 m/s while on Figure 5 it is 1.12 m/s. On Figure 5 the velocity of 0.4 m/s falls within the interchange between blue and green. When taking this into account, the Chicago inlet structure appears to perform better than the inlet structure shown on Figure 1.

Placement of the effluent launder

Studies by Gould (1943), Anderson (1945) revealed the need for dealing with the upwelling caused by gravity currents near the perimeter wall of circular clarifiers or near the end wall of rectangular tanks. Anderson concluded that the best position for the launder would be as close to the inlet as possible, making use of the return flow on the surface of the tank. However, the structural challenges and small weir length led to a compromise whereby the launders were placed so that their centers were 4.27 m from the perimeter wall. This arrangement was tested at full-scale, and existing tanks were modified and all new tanks constructed in this way. The placement of the launder is shown on Figure 6. Effluent total suspended solids (TSS) concentrations for May 2007 were plotted on Figure 7 for batteries A, B, C and D. The performance of the plant to date, as can be seen from the plots, is a tribute to the genius of the early designers. A number of high flow events were selected and listed in Table 2 to illustrate the performance of the plant at high flows and high overflow rates.
Crosby (1980) later proposed a baffle on the perimeter wall to deflect the gravity current away from a perimeter launder. This design proved to be superior to using in-board launders set too close to the perimeter wall. However, the positioning the launder as shown in Figure 6 is still widely practiced. Parker et al. (1995) stated that there has not been sufficient research to determine whether the Crosby baffle is an improvement on the Anderson (1945) finding. The effluent total suspended solids (TSS) concentrations, shown on Figure 7 for the month of May 2004, are evidence of the validity of the Anderson placement. The data on Figure 7 and in Table 2 was selected since it represented a period of high rainfall and high flows.

Table 2 | TSS Concentration in Stickney plant during high flows

<table>
<thead>
<tr>
<th>May 2004</th>
<th>Total suspended solids in batteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow m³/s</td>
<td>A</td>
</tr>
<tr>
<td>-----------</td>
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</tr>
<tr>
<td>13</td>
<td>44.2</td>
</tr>
<tr>
<td>14</td>
<td>53.7</td>
</tr>
<tr>
<td>15</td>
<td>49.3</td>
</tr>
<tr>
<td>22</td>
<td>52.2</td>
</tr>
<tr>
<td>23</td>
<td>46.7</td>
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<tr>
<td>24</td>
<td>40.3</td>
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<tr>
<td>25</td>
<td>41.4</td>
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<tr>
<td>30</td>
<td>54.4</td>
</tr>
<tr>
<td>31</td>
<td>64.2</td>
</tr>
<tr>
<td>Average for May</td>
<td>35.7</td>
</tr>
</tbody>
</table>

The Stickney activated sludge plant is an extreme plug-flow plant producing very good overall SVI's ranging from 50 to 85 ml/g. At a flow of 52 m³/s the feed pipe velocity of 0.9 m/s is reduced to 0.45 m/s as a result of the conical shape of the vertical inlet pipe. The energy destruction through turbulence caused by the conical inlet can be translated into a velocity gradient $G$ of 15 s⁻¹, which is normally considered insufficient for flocculation. While the asymmetrical flow pattern causes some streaming, the mixed liquor is discharged from the inlet pipe in a vertical direction which creates a circular motion in the vertical plane. Because of the large surface area of the outlet of the feed pipe, the bridge support offers little resistance to the flow and no opportunity for breakup of the floc as might happen in a more traditional EDI used in the USA. The concept is similar to that proposed by Barnard (Ekama et al. 1997, page 182) for low velocity mixing in the stilling well and diffusion through side outlets. Anderson (1945) tried a number of baffled systems for this inlet and none performed better than the original design. The very low SVI of 50 ml/g is normally a cause of strong density currents and several authors have noted the strong correlation between low SVI and high effluent suspended solids concentration (Parker 1983; Mulbarger et al. 1985; Parker & Stenquist 1986; Parker et al. 1995). This would indicate a need for energy dissipation and good flocculation. The combination of low SVI's and very low effluent suspended solids indicates excellent flocculation in the inlet structure of the Stickney plant while minimizing density currents.
Ekama & Marais (2000) determined from side-by-side CFD studies, State Point Analyses and full-scale testing of two differently designed clarifiers, that there is a good correlation between the performance predicted by a State Point Analysis (SPA) and the performance of a clarifier designed with good energy dissipation and flocculation, when a safety factor of 0.85 is applied to compensate for the less than perfect conditions even in well designed final clarifiers. Once all the settling parameters for the Stickney clarifiers were set, the SPA with an 85% safety factor was used to predict the critical flow, surface overflow rate, and solids loading rate with changing SVI at critically loaded conditions. This analysis was performed for MLSS concentrations of 2,700, 3,000 and 3,500 mg/L. The settling flux curve with a peak flow of 52 m³/s and a RAS return of 27 m³/s and MLSS of 3,000 mg/L showed that the Stickney clarifiers are critically loaded. at an SVI of 120 mL/g.

CONCLUSIONS

There are several final clarifier inlet structures that are designed to keep the velocities in the stilling well low and to make use of the vertical discharge of the mixed liquor to ensure gentle mixing and flocculation. The design of the final clarifiers of the Stickney plant of the MWRDGC has been described in many publications as an example of how not to design inlet structures, yet the exceptional performance of these clarifiers warrants a closer examination of the pioneering work done by the designers. By discharging the mixed liquor vertically, avoiding any restrictions that may accelerate the flow and break up the floc, and reducing the inlet velocity with a unique vertical cone-shaped structure that caused some turbulence in the vertical direction, excellent flocculation was achieved and quiescent conditions were created in the main body of the clarifier, which resulted in very low effluent suspended solids concentrations even at sustained surface overflow rates exceeding 2 m/h. The future operation of the plant will require performance at a flow rate of 52 m³/s for prolonged periods resulting from the collection and storage and pumping back of combined sewer overflows. Improving the inlet structures of the existing final clarifiers were considered in this study, but it was concluded that little improvement in performance would be achieved.

The results of these early studies of launder placement by the original plant designers still hold true today and it is not yet clear whether the less expensive option of the Crosby baffle, while at least equal in performance to the clarifiers at the MWRDGC plants, actually improves effluent quality. The Crosby baffles attached to an outboard launder maybe less expensive and side-by-side studies of these two types of weir placement is warranted.

REFERENCES


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