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Pilot Trial of Advanced Fluidized Composting for High-Strength Industrial Waste Treatment

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ABSTRACT

Thermophilic aerobic treatment systems offer unique advantages for treatment of high strength organic waste streams. These systems combine the best features of conventional aerobic and anaerobic processes that include rapid biodegradation kinetics and low biological solids production, respectively. Application of these processes can result in substantial economic benefit by reducing residuals processing and disposal costs. The paper describes a six-month pilot-study conducted for a pharmaceutical manufacturing facility in Scotland. The major component of the high-strength wastestream is fermentation biomass that has almost sludge consistency. The pilot study covered several different and highly variable loading conditions. The paper will also discuss the process benefits along with design/application considerations for the full-scale system.

KEYWORDS

Aerobic liquid waste treatment, high-strength organic waste, industrial waste, thermophilic process, pilot study

INTRODUCTION

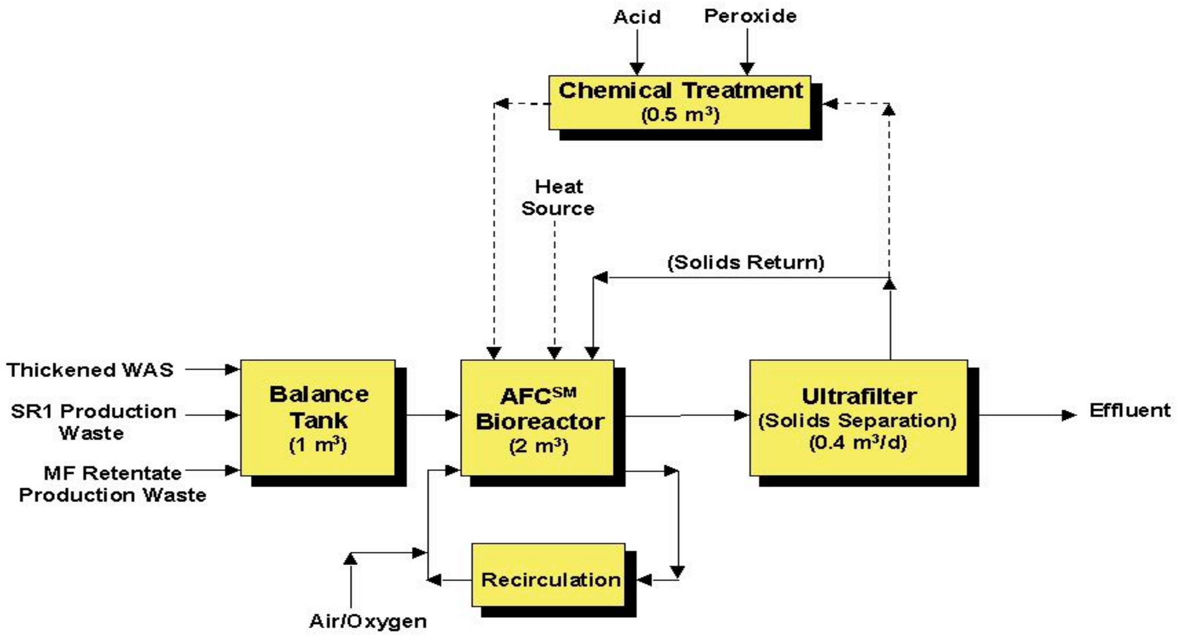
A pharmaceutical manufacturing facility in Scotland operates a two-stage activated sludge wastewater treatment plant (WWTP) to treat process wastewaters from two different types of manufacturing operations. The major source of the organic load to the WWTP is from the fermentation operation, with some minor contribution of the chemical plant and utility-type operation (such as solvent recovery). The fermentation operation generates a high-strength organic wastewater with high suspended solids concentration, that reflects almost sludge consistency. To unload the organic waste from the WWTP, the facility piloted Advanced Fluidized Composting (AFC^{SM}) for the treatment of the high-strength wastewater streams.

Overview of Thermophilic Aerobic Treatment

Thermophilic aerobic treatment is a promising process technology for treating high strength organic waste streams and sludges that result in a highly efficient rate of organic destruction with little or no generation of residual sludges commonly associated with most biological processes. The technology combines the advantage of low biomass yields and rapid kinetics associated with high temperature operation and stable process control of aerobic systems into one process flow scheme.

A flow schematic of the AFC^{SM} process as it was applied during the pharmaceutical manufacturing completely mixed, thermophilic (45 - 65 °C) reactor for treatment. For this pilot system, the bioreactor volume was too low and the surface area too high to allow the reactor to reach thermophilic temperature so electrical heaters were used to maintain thermophilic conditions throughout the testing period. Effluent from this reactor is sent to a solid separator (e.g., ultrafilter, dissolved air flotation, or other appropriate solid separation device). A portion of the separated solids is returned to the thermophilic reactor while the remaining solids go to a small chemical treatment unit prior to being sent back to the thermophilic reactor for further digestion and destruction.

Figure 1 - AFC^{SM} Process Pilot Flow Schematic



Note:
---- Designates Batch Process

Results from several bench-, pilot-, and full-scale systems have shown that the technology can effectively reduce organic residuals up to 90% with a potential to achieve 100% destruction. The high destruction efficiency is achievable because the high temperature characteristics of the thermophilic process facilitates the biodegradation of organic components that are more soluble at high temperature making it easier for the biomass to efficiently convert the soluble organics to carbon dioxide and water. Residual organics or organic solids resisting biodegradation are “softened” in the chemical treatment step and then converted to carbon dioxide and water upon re-entering the thermophilic reactor.

Thermophilic systems are rarely deliberately applied or considered as technology for liquid waste treatment. Mesophilic aerobic systems or anaerobic technology are usually applied instead. Thermophilic aerobic processes can offer substantial performance benefits over other biomass systems. Many aerobic thermophilic treatment systems evolved inadvertently in cases where mesophilic aerobic systems were designed without sufficient sensitivity to heat generation and accumulation issues. These “inadvertent thermophilic” systems were devised using retrofit approaches on existing mesophilic systems. In some cases, thermophilic operation (operating temperature approximately 38 °C and higher) was maintained while in other cases, operational modifications were implemented to facilitate a return to mesophilic operations (operating temperatures less than 38 °C).

AFC^{SM} was selected because there are several advantages of thermophilic systems over mesophilic aerobic or anaerobic systems. These include the following:

- *Lower waste sludge production* – Thermophilic aerobic systems have characteristically lower biomass yields, which results in lower sludge production. Some commercial systems are engineered, which virtually eliminate waste organic sludge production. One system in the United

States has been operating for two years and has treated 2,300 tonnes of COD with no excess sludge disposal.

- *Enhanced COD Removal* – Thermophilic aerobic units have been observed to realize higher levels of COD removal than mesophilic systems. The system discussed in this paper is fed influent COD concentrations of 30,000 mg/L and produces an effluent with a COD of approximately 20 mg/L. This is a COD removal efficiency of 99.9%.

- *High Loading Rate Capability* – Thermophilic aerobic systems can be engineered to have very high loading rates in comparison with mesophilic aerobic treatment systems. Loading rates of 14 kg COD/m^3/day have been demonstrated on fermentation broths resulting from pharmaceutical production activities.

- *Enhanced Biodegradability Capability* – Thermophilic aerobic systems have the biokinetic capability of aerobic systems and are much more kinetically robust then anaerobic systems.

Pilot Design and Trial Objectives

Experience has shown that aerobic thermophilic treatment systems present challenges for engineers and operators. Key design issues surrounding any high rate thermophilic aerobic application involve the aeration system, solids separation, and foam control.

- *Oxygen transfer* – Increased operating temperatures which lower dissolved oxygen saturation values and higher chemical oxygen demand (COD) loading necessitate an increased focus on the design of the oxygen transfer or aeration system. Typically, to meet the high oxygen transfer requirements of the process, aggressive aeration systems are specified (e.g., jet aeration) and reactor water depths are increased above conventional applications. Jet aeration was selected for the pilot, since the full-scale WWTP at the facility also utilizes jet aeration system. However, it should be noted that the reactor depth of 1.5 m was not optimal for effective oxygen transfer. Increased depth would facilitate better oxygen transfer efficiency.

- *Solids separation* – A thermophilic biomass can not be separated using gravity settling and biomass yields are very low (i.e., less than 0.05 kg per kg of COD removed), therefore the system requires more aggressive methods of solids separation. Field experience has shown that ultrafiltration, dissolved air flotation, and rotary drum thickeners are effective in providing high capture efficiency of the thermophilic biomass. Ultrafiltration (UF) was the choice for the pilot based upon existing full-scale experience of other AFC applications. Two UF systems were used during the pilot in order to evaluate the performance of both polymeric and ceramic membrane technologies.
- *Foaming* – Both high biomass concentration in the bioreactor (over 30,000 mg/L of suspended solids) and high temperature are conducive to foaming incidents. The high solids loading and subsequent destruction within the bioreactor results in accumulation of high levels of biological surfactants. Transitions to thermophilic operation (shifting microbial populations from mesophilic to thermophilic) or cycling between thermophilic and mesophilic operation also result in spurious foam production. Adding antifoam agents or designing mechanical foam breakers can control foaming. Antifoam was sporadically used for the pilot system. In addition, the chemical treatment step is also used for foam control. Regular chemical treatment of the reactor mixed-liquor breaks down the formed microbial detergents into a smaller, more-readily degradable form thus preventing the accumulation of such materials in the system. The chemical treatment process can be operated as either a continuous or batch operation. Batch operation was selected for this pilot trial. The facility decided to run a six-month pilot of the AFC^{SM} technology to:

  - confirm the applicability of the process to treat organic solids and other high-strength organic wastes produced at the facility in order to off-load the existing WWTP;
  - provide data for the regulatory agency in support of AFC^{SM} as a preferred technology for solids disposal;
  - provide sound engineering basis for developing full-scale design and accurate information on capital and operating costs;
  - confirm COD destruction

- quantify organic and inorganic sludge production
- evaluate ultrafiltration as a solids separation system; and
- test system performance under variable loading conditions, including “shock loading” (including both pH and temperature swings).

This paper will focus on the COD and suspended solids treatment performance as measured during the pilot trial and identify key design issues for process scale-up.

Pilot Waste Characteristics and Loading Conditions

The waste streams considered for the pilot trial were those that were high in both Chemical Oxygen Demand (COD) and suspended solids and low in volume. The combination of high COD and suspended solids typically rendered these streams hard to degrade in the existing WWTP by causing high reactor operating temperature, poor oxygen transfer efficiency, and subsequent filamentous bulking. Based upon the criteria above, three streams were selected: solvent recovery still bottoms (SR1), (micro) filtration retentate, (MF Retentate), and waste activated sludge (WAS) generated in the existing WWTP. The average, minimum, and maximum waste characteristics for each individual stream as measured throughout the pilot trial including the combined waste fed to the pilot are given in Table 1.

Table 1 – Pilot Waste Characteristics

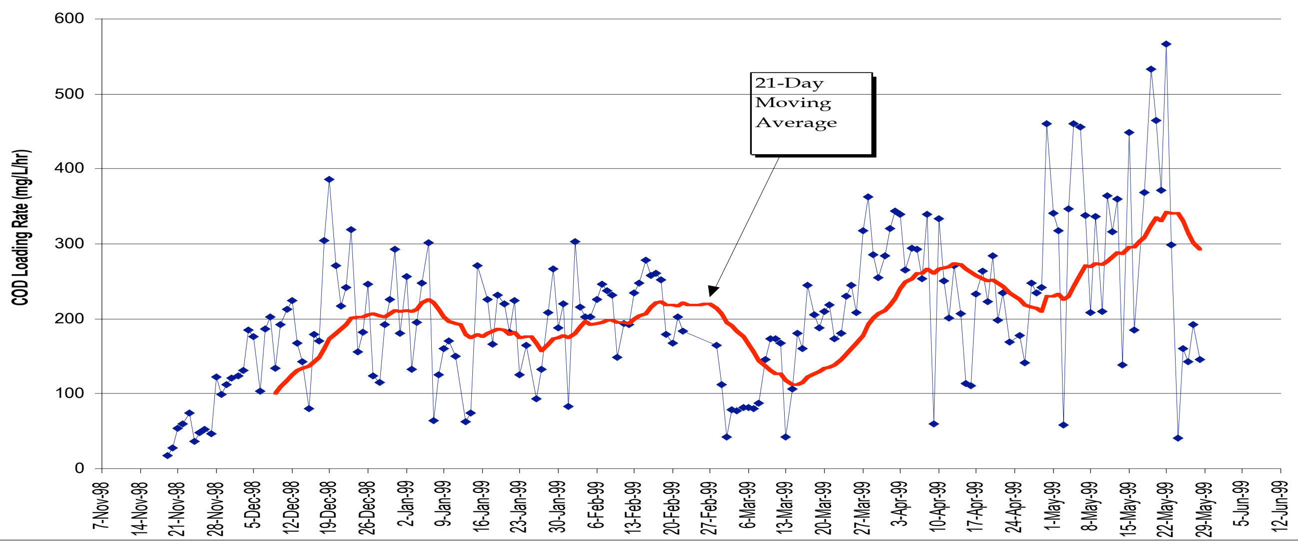
Characteristics	WAS	SR1	MF Retentate	Combined Feed
Flow (L/d)				
Avg	100	83	20	203
Min	-	-	-	31
Max	-	-	0	534
COD (mg/L)				
Avg	28,945	49,760	114,091	46,747
Min	4,900	10,300	36,500	14,320
Max	90,000	96,000	176,700	98,800
TSS (mg/L)				
Avg	19,790	12,429	40,318	15,045
Min	6,200	388	9,400	2,980
Max	57,714	25,133	70,120	45,000
VSS (mg/L)				
Avg	17,264	10,883	37,294	13,449
Min	5,333	324	8,400	2,820
Max	52,000	23,267	66,160	37,333
TDS (mg/L)				
Avg	7,843	38,242	56,859	29,873
Min	5,000	6,720	15,580	10,160
Max	28,200	100,680	98,960	70,620
TKN (mg/L)				
Avg	2,367	2,608	5,350	2,710
Min	283	297	953	754
Max	6,071	4,353	9,048	5,259
NH_3-N (mg/L)				
Avg	Not Measured	Not Measured	Not Measured	601
Min				269
Max				917
PO4 (mg/L)				
Avg	187	490	691	476
Min	18	108	171	161
Max	853	816	1,272	882
pH (S.U.)				
Avg	7.08	6.13	5.74	5.91
Min	6.62	5.73	5.47	4.66
Max	7.53	6.53	5.98	10.98

Consistent feed strength was a major problem during the pilot test due to the variable nature of the primary manufacturing operation. This in turn caused swings in the food-to-mass (F/M) ratios. Although this made it very difficult to balance out the loading rates, it was found to have little effect in the overall performance with respect to maintaining excellent COD and organic solids destruction rates.

One of the key parameters that determine the size of the full-scale AFC^{SM} reactor and the oxygen transfer system is COD loading rate/COD destruction rate. Since typical COD destruction rates exceed 90% of the COD loading rate, the COD loading rate is used to size both systems. Typical reactor COD loading rates for AFC^{SM} systems are 4.8 – 9.6 kg/m3/day when jet aeration operated on compressed air is used to transfer oxygen. However, when supplemental oxygen is added to the jet aeration system, reactor loading rates can exceed 14 kg/m3/day when no biokinetic inhibition exists with relation to the growth of the biomass on the target waste stream. The jet aeration utilized throughout this pilot was limited to 8.4 kg/m3/day oxygen transfer due primarily to limited reactor operating depth. Supplemental oxygen was added towards the end of the trial to determine the maximum loading rate on the system assuming no limit on oxygen transfer.

Figure 2 depicts the daily COD loading rate to the AFC^{SM} bioreactor throughout the pilot trial along with a 21-day moving average. As previously stated, the daily rate was highly variable due to the variability of the individual waste streams. The pilot biomass seed, taken from the first-stage of the existing WWTP which normally operates above 40 oC, acclimated very quickly to the target waste streams and achieved the 4.8 kg/m3/day COD loading rate within 30-days of operation. Loading rate was held at this level for 2 months to quantify COD and organic solids destruction prior to being increased to 8.4 kg/m3/day (maximum oxygen transfer capability of the pilot at thermophilic temperatures using air) and ultimately to a maximum of 14 kg/m3/day with the use of supplemental oxygen. COD loading rate changes throughout the trial were based on daily reactor COD, effluent COD, and reactor biomass oxygen uptake rate measurements. The average loading rate throughout the pilot trial was 5 kg/m3/day.

Figure 2 - AFC^{SM} Pilot Reactor COD Loading Rate



PILOT TRIAL COD AND SUSPENDED SOLIDS TREATMENT RESULTS

Figure 3 shows the COD treatment performance of the pilot over the six-month trial period. Included in Figure 3 is the cumulative COD fed to the pilot reactor, the cumulative COD contained in the AFC^{SM} reactor, the cumulative COD that was discharged in the pilot effluent, and the cumulative COD treated in the reactor. Review of the data presented in Figure 3 shows that the pilot was fed over 1,650 Kg COD with 110 Kg discharged into the effluent yielding a COD treatment performance COD In versus COD Out of 93.3%. Overall COD treatment performance including the COD accumulation in the reactor of 112 Kg was 86.6% demonstrating the ability of the system to handling extreme variations in COD loading (daily variations as high as 300%) whilst maintaining high COD removal rates with no solids wasting.

Figure 3 - AFC^{SM} Pilot Reactor COD Treatment Performance

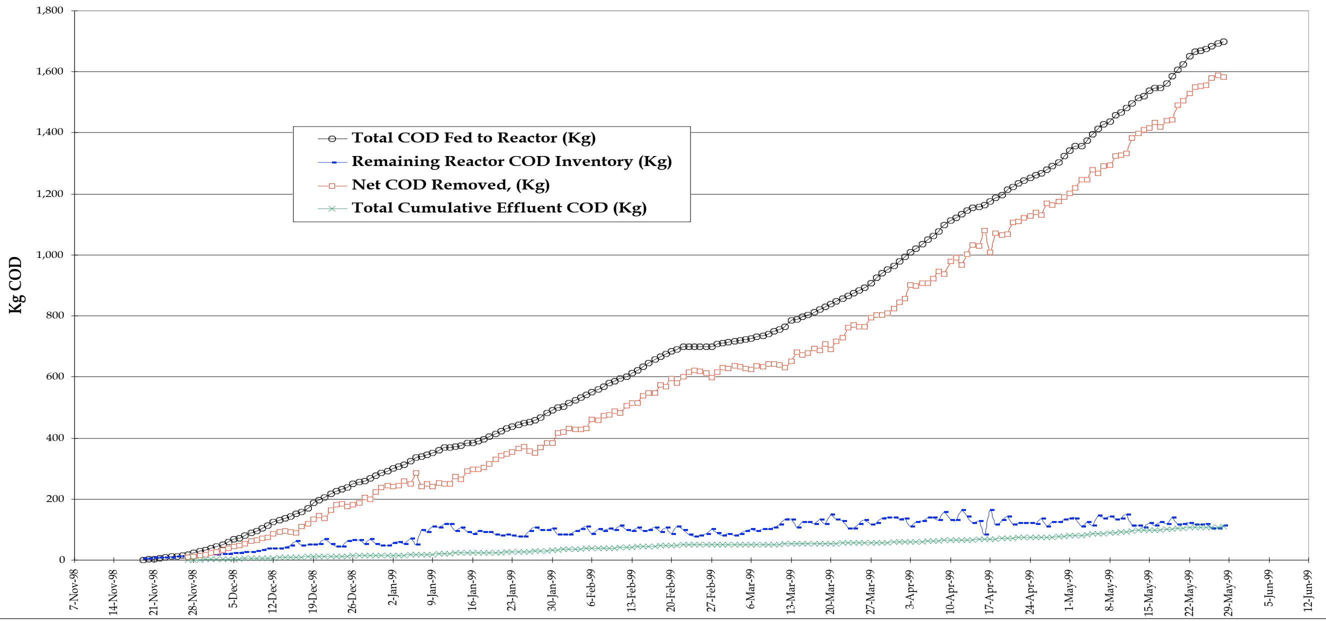
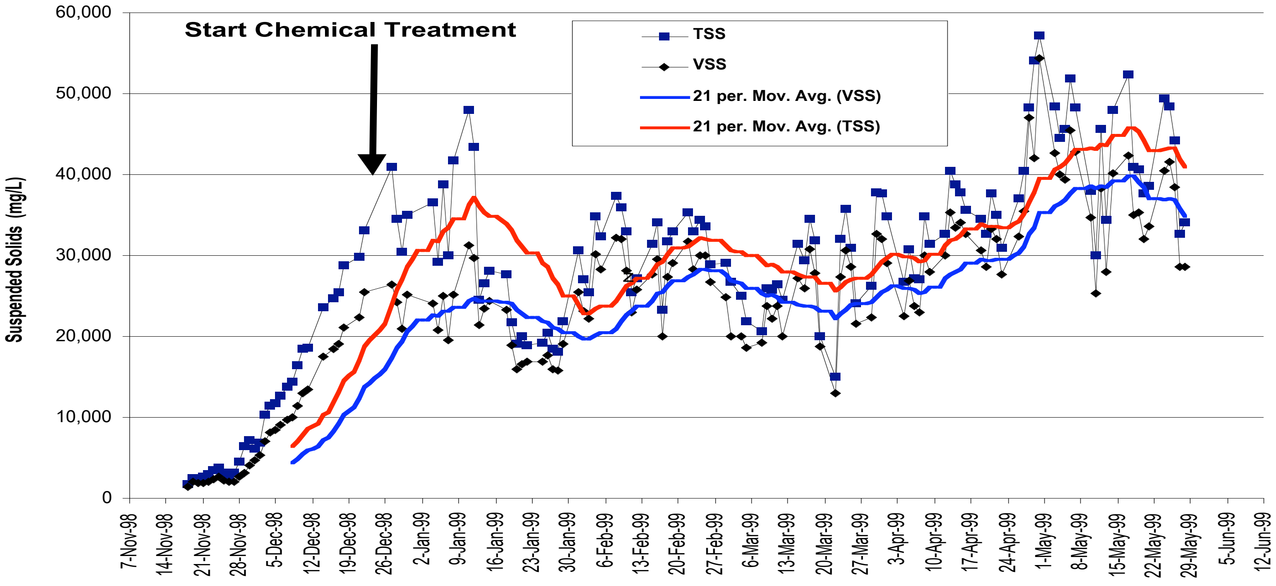


Figure 4 shows the daily total and volatile suspended solids levels (TSS and VSS, respectively) within the reactor over the six-month trial period along with the respective 21-day moving averages. These data show accumulation of TSS and VSS over the first month of pilot operation while the biomass is acclimating to the waste streams and thermophilic operating conditions. Also, the reactor was foaming quite heavily and required regular use of antifoam to keep the contents within the reactor.

Figure 4 - AFC^{SM} Pilot Plant Reactor TSS and VSS Levels



At the end of the first month, the chemical treatment process was initiated by batch treating a portion of the reactor solids being returned by the ultrafilter using hydrogen peroxide under low pH conditions. The goal of the chemical treatment step is to partially solubilize the excess suspended solids so they can be more easily biodegraded when returned to the bioreactor for treatment. The results of treating between 3% and 5% of the reactor mixed-liquor by volume essentially shutdown solids accumulation within the reactor and minimized foaming while the reactor was being loaded at 4.8 kg/m3/day COD. In addition, the difference between reactor TSS and VSS remained relatively constant throughout this testing period indicating that both organic and inorganic solids were be treated and removed from the system. Both organic and inorganic solids did accumulate during the last 1.5 months of pilot operations when the focus of the pilot changed to quantifying maximum COD loading while maintaining high COD treatment efficiency. During this period, chemical treatment was shutdown to allow the biomass to grow and acclimate to the higher COD loading conditions.

At the end of pilot testing when the reactor was shutdown and drained, a primarily inorganic solids material was found to have accumulated within the various nozzles on the reactor walls and within the suction of the ultrafilter system. The material was later identified as struvite (magnesium ammonium phosphate) which forms under conditions of low dissolved oxygen, neutral pH, and high levels of dissolved magnesium, ammonia, and phosphate. Accumulation of struvite within the existing WWTP had also been reported and since the building blocks for struvite are necessary additives in the production process, a procedure for preventing the accumulation in the full-scale AFC^{SM} system was required.

CONCLUSIONS/FULL-SCALE DESIGN IMPLICATIONS

The use of the AFC^{SM} process for treatment of high strength organic liquid and solid wastes generated at a pharmaceutical manufacturing facility in Scotland was successfully demonstrated via the six-month operation of an onsite pilot system. Average COD destruction across the treatment process was 93.3% with no excess solids disposal at COD loading rates ranging from 4.8 – 14 kg/m^3/day. Organic and inorganic solids were controlled via the low production of excess biomass in the thermophilic reactor and the use of a batch chemical treatment process to partially solubilise the excess solids and recalcitrant COD prior to transfer back to the thermophilic reactor for further biodegradation. Regular use of chemical treatment also minimized the production of biosurfactants that cause excessive foaming which is characteristic of conventional thermophilic treatment processes thus minimizing the need for antifoam addition for foam control. Some inorganic solids accumulation in the form of struvite was identified at the very end of the pilot trial and will have to be managed via monitoring/periodic blowdown to the existing WWTP as part of the full-scale system.

With regard to full-scale system design, the COD loading should not exceed 9.6 kg/m^3/day on air alone and a maximum of 14 kg/m^3/day using supplemental pure oxygen addition. Heat balance calculations verify the system will autothermally maintain greater than 50 ^{o}C operating temperature throughout the year using an un-insulate, coated-steel reactor operated at expected COD loading conditions. An adequately sized balance tank although not critical is recommended upfront of the AFC^{SM} process to minimize the variability in COD concentration and hydraulic flow of the incoming waste streams yielding a more stable overall process operation and more consistent COD/Solids treatment performance. Pilot ultrafilter performance yielded flux rates in the range of 25 LMH (litres per m^2 per hour) for both polymeric and ceramic membrane systems. Full-scale ultrafilter flux rates are expected to be 40 – 60 LMH based on minimization of struvite accumulation, elimination of silicon based antifoams (use of polyol-based antifoams), and experience onsite and at other full-scale AFC facilities operating at similar reactor mixed-liquor levels and temperatures. Primary operating requirements for the full-scale system are power estimated to be 39 kW/tonne COD Applied and peroxide usage for chemical treatment at 54 Kg peroxide per tonne COD Applied. The full-scale system will be automated and require no additional manpower to operate. System start-up is scheduled for third quarter 2002.

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