Biological Solids Reduction Using the Cannibal Process

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ABSTRACT: A laboratory study of the Cannibal process was undertaken to determine if the Cannibal system would generate less sludge compared with a conventional activated sludge system. Side-by-side sequencing batch reactors were operated—one using the Cannibal configuration and the other as conventional activated sludge. It was found that the Cannibal process generated 60% less solids than the conventional activated sludge system, without any negative effect on the effluent quality or the settling characteristics of the activated sludge. The oxygen uptake rate for the centrate from the Cannibal bioreactor showed that readily biodegradable organic matter was released from the recycled biomass in the Cannibal bioreactor. It is proposed that the mechanism for reduced solids from the Cannibal system is that, in the Cannibal bioreactor, iron is reduced, releasing iron-bound organic material into solution. When the Cannibal biomass is recirculated back to the aeration basin, the released organic material is rapidly degraded. *Water Environ. Res.,* **79,** 2380 (2007).

KEYWORDS: sludge, biosolids, activated sludge, solids reduction, digestion.

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Introduction

The activated sludge process is widely used for wastewater treatment because of its high organic matter removal efficiency. However, it remains a costly process to operate, in large part, because of the expense associated with excess sludge disposal. Operational and technological approaches to reduce the solids generation are of interest, but many of these have proven to be costly or negatively affect the effluent quality of the process. High sludge age processes have been used to reduce solids, but this may result in poorly settling pinpoint flocs (Bisogni and Lawrence, 1971) and excessive aeration costs (Grady et al., 1999). The treatment of the activated sludge recycle stream with a variety of chemical (ozone, acid, or base) or physical (sonication or mechanical shear) processes has been used, with mixed results (Stensel and Strand, 2004). The performance of these processes has been highly variable, costly, and sometimes results in poorer sludge dewatering.

A process to minimize activated sludge production has been developed, which incorporates a sidestream anaerobic bioreactor to a portion of the sludge recycle stream. The flow scheme for this process, called the Cannibal process, is shown in Figure 1. Although reports from field operations indicate that the process reduces the sludge mass by 60 to 70%, no side-by-side studies have been conducted under controlled conditions to fully evaluate the process or describe the mechanisms that might account for the reduction in the mass of sludge generated. This study was undertaken to

(1) Determine if the Cannibal process is capable of reducing sludge generation,
(2) Quantify the amount of solids reduction,
(3) Determine the effect of the Cannibal system on the effluent characteristics and sludge settling properties of the system, and
(4) Determine the mechanisms that account for the mass loss.

This study was conducted primarily as a laboratory study to eliminate the variability in wastewater flow and concentration normally associated with field operations. However, some field data were obtained and used to better understand the mechanisms that account for solids reduction by the Cannibal process.

Materials and Methods

Laboratory System. For the laboratory studies, two operational phases were used. In the first phase, laboratory reactors were run side-by-side, as shown in Figure 2. The Cannibal and control systems were operated as sequencing batch reactors (SBRs). Sludge was not wasted from the Cannibal reactor, except for one time, on day 9, and it was wasted directly from the mixed liquor at the end of the react step. For the control system, concentrated biomass was removed from the settled mixed liquor during the settling phase and wasted to an aerobic reactor (aerobic digester), with the same detention time as the anaerobic Cannibal bioreactor. Sludge from the anaerobic Cannibal bioreactor was returned to the main reactor, while sludge from the control aerobic bioreactor was wasted. The volume in the react tank in phase 1 was 4 L, and the feed was 2 L/d. The sidestream Cannibal and aerobic bioreactors each had a 10-day hydraulic retention time (HRT) and were fed 50 mL/d of settled sludge. The SBRs were operated at 4 cycles/day, with a react time of 5 hours and a settle time of 40 minutes.

For the second phase, a third SBR system was added, and no sludge was wasted from the additional system. The third SBR was added to evaluate the effect of a high solids retention time (SRT) on solids loss. It was observed, in the phase I operation, that the SRT for the Cannibal system was approximately double that of the control system. Therefore, the third system was added to compare the solids loss in a high SRT system with the solids loss in the Cannibal system, to demonstrate that the solids loss in the Cannibal was not the result of the high SRT. Rather, the high SRT was the result of the Cannibal operation. The other control reactor was operated in the same manner as in the first phase, with sludge passing through an aerobic digester before wastage.

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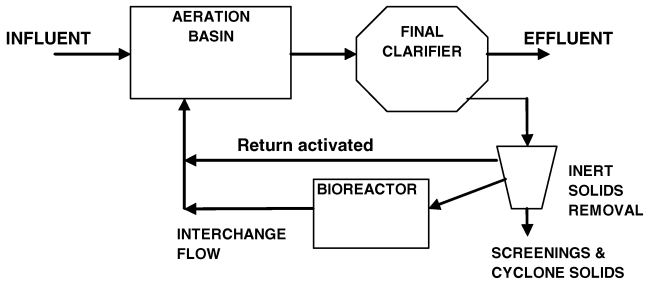

Figure 1—Flow scheme for the Cannibal process.

The feed rate was doubled to 4 L/d, and the HRT was reduced from 2 days to 1 day. The volume of settled sludge fed to the Cannibal and control bioreactors was initially the same as in phase 1 (50 mL), but, as solids built up, the flow to both the aerobic digester and the Cannibal reactor was doubled to 100 mL/d. In phase II, allythiourea (5 mg/L) was added to the feed, beginning on day 12, to eliminate nitrification.

A soluble synthetic feed with a chemical oxygen demand (COD) of 400 mg/L was used. The feed composition is shown in Table 1. The influent to the SBR reactors was fed to both systems from a single tank. Feed was prepared every other day.

Field System. A full-scale Cannibal system was operated to treat wastewater from a municipal facility at Byron, Illinois. Sludge samples from this facility were obtained by Siemens (Waukesha, Wisconsin) personnel and shipped overnight to Virginia Tech (Blacksburg, Virginia), in a cooler with cold packs to slow biological activity. Protein and polysaccharide concentration in solution from various locations in the plant were measured.

Analysis. Total solids, total suspended solids (TSS), total volatile solids, volatile suspended solids (VSS), and soluble COD were measured according to *Standard Methods* (APHA et al., 1995). The protein concentration was determined by the Hartree (1972) modification of the Lowry et al. (1951) method, using bovine serum albumin as the standard. Polysaccharide was measured by the Dubois et al. (1956) method, using glucose as the standard. The pH was measured using an Accumet 910 pH meter (Fisher Scientific, Pittsburgh, Pennsylvania). Dissolved cations and anions were measured using a Dionex ion chromatograph (Dionex, Sunnyvale, California). Methane sulfonic acid (30 mM) was used as the eluant at a flowrate of 1.0 mL/min.

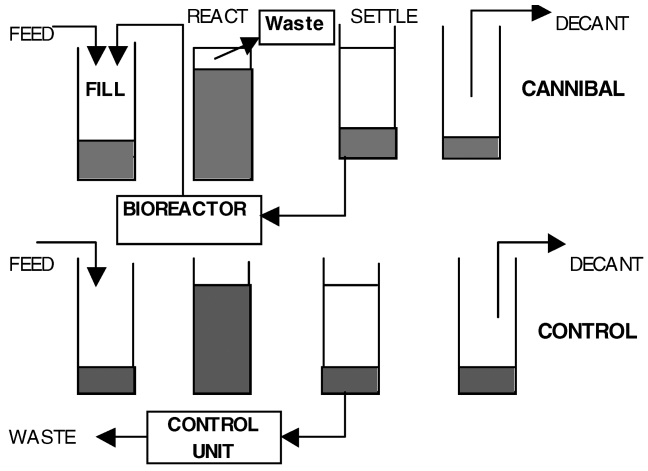

Figure 2—Laboratory operation for the phase I Cannibal and control systems.

Table 1—Medium composition and trace element.

Medium composition	Concentration	Trace element solution	Concentration
BactoPeptone	300 mg COD/L	Citric acid	2.73 g/L
CH_3COONa	100 mg COD/L	Hippuric acid	2 g/L
NH_4Cl	57 mg/L	$Na_3NTA \cdot H_2O$	0.36 g/L
NH_4HCO_3	60 mg/L	$Na_3EDTA \cdot 4H_2O$	1.5 g/L
KH_2PO_4	44 mg/L	$FeCl_3 \cdot 6H_2O$	1.5 g/L
$KHSO_4$	34 mg/L	H_3BO_3	0.25 g/L
$NaHCO_3$	394 mg/L	$ZnSO_4 \cdot 7H_2O$	0.15 g/L
$CaCl_2 \cdot 2H_2O$	220 mg/L	$MnCl_2 \cdot 4H_2O$	0.12 g/L
$MgSO_4 \cdot 7H_2O$	150 mg/L	$CuSO_4 \cdot 5H_2O$	0.06 g/L
$FeCl_3$	20 mg/L	KI	0.03 g/L
$Al_2(SO_4)_3 18H_2O$	20 mg/L	$Na_2MoO_4 \cdot 2H_2O$	0.03 g/L
Allylthiourea	1.4 mg/L	$CoCl_2 \cdot 6H_2O$	0.03 g/L
Trace element solution	2 mL/L	$NiCl_2 \cdot 6H_2O$	0.03 g/L
		$Na_2WO_4 \cdot 2H_2O$	0.03 g/L

* The concentration of $FeCl_3$ and $Al_2(SO_4)_3 18H_2O$ was changed from 10 to 20 mg/L on day 28 in phase I.

Some samples from various locations in the Byron, Illinois, Cannibal plant were subjected to size separation, to determine the molecular weight distribution of the soluble protein and polysaccharides. For this experiment, an aliquot of centrate was individually filtered through 1.5- and 0.45-μm, 30 000- and 1000-Dalton filters. Ultrafiltration was performed at 414 kPa (60 psi) through Amicon YM30 (30 kDa) and YM 1 (1 kDa) partly hydrophilic membranes (Amicon, Beverly, Massachusetts).

Oxygen Uptake Rate. At the end of phases I and II, the sludge in the bioreactors was centrifuged using a Beckman J2-HS centrifuge operated at 9000 × g for 30 minutes at ambient temperature (25°C) (Beckman Coulter, Fullerton, California). The centrate was decanted and added to activated sludge from the SBR, and the oxygen uptake rate was measured using a dissolved oxygen meter (YSI Model 57, Yellow Springs, Ohio). Oxygen uptake tests were conducted using 200 mL mixed liquor, 50 mL centrate, and enough tap water to fill a 300-mL biochemical oxygen demand bottle.

Observed Yield. The observed yield was determined over a given range of operation as the VSS increase/COD used, using all the data over the range of operation for which the yield was calculated.

Results and Discussion

Comparison of the Cannibal System with Conventional Activated Sludge Systems. In the first phase of testing, a side-by side comparison of the Cannibal system with conventional activated sludge systems was made, by measuring the effluent COD and suspended solids and the biomass wasted, while trying to maintain the mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) at a constant concentration. The MLSS and MLVSS for both systems are shown in Figure 3. It can be seen, from the data in Figure 3, that the MLSS and MLVSS varied somewhat; however, by day 35, lower variability in MLSS and MLVSS was observed. On day 10, solids

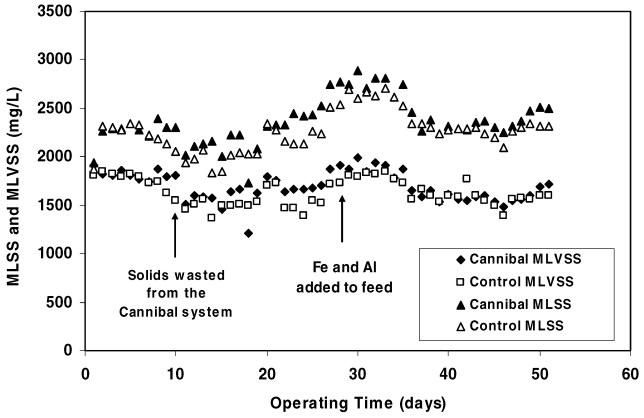

Figure 3—MLSS and MLVSS for the Cannibal and control systems (phase I).

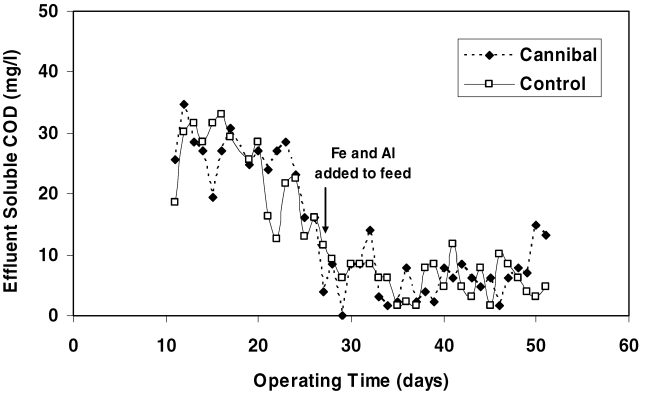

Figure 5—Effluent soluble COD for the Cannibal and control systems.

were intentionally wasted from the Cannibal system, because they were higher than those in the control, and, on day 28, additional iron (Fe) and aluminum (Al) were added to the feed, as noted in Table 1.

After day 9, no solids were wasted intentionally from the Cannibal system. The solids that were lost were effluent solids and solids removed because of sampling. For the control system, in addition to solids in the effluent and solids removed for measurement, solids were wasted daily from the aeration basin to the aerobic digester and then from the aerobic digester, to maintain the MLSS and MLVSS constant.

The additional iron and aluminum to the feed resulted in lower effluent suspended solids concentrations, as can be seen in Figure 4. The effluent suspended solids were similar for both systems and, after an initial acclimation period, remained at approximately 20 mg/L. In Figure 5, the effluent soluble COD for both systems is shown. As with the suspended solids, from approximately day 30 to the end of the study phase, the effluent soluble COD remained low in both systems.

The cumulative solids wasted over time are shown in Figure 6. As can be seen in Figure 6, from day 23 until the end of the study, the Cannibal system generated much less solids than the control. The accumulated solids for the Cannibal system over that period was approximately 40% as much solids as for the control. The observed yield (gram VSS/gram COD) for the control, which included an aerobic digester, was 0.28, and that for the Cannibal system was 0.11.

In Figure 7, the SRT for the two activated sludge systems is shown. The SRT for both systems was high, but the SRT for the Cannibal system was higher than that for the control system. Once steady-state was established (day 35), as evidenced by a low variability in MLSS and effluent TSS, the Cannibal system operated at an SRT of approximately 80 days, while the conventional system operated at an SRT of approximately 30 days. The SRT was calculated by dividing the mass of solids in the system (MLSS) by the average daily solids loss. Unlike most activated sludge processes, the Cannibal system SRT cannot be used as a design or operational parameter, because the system will attain an SRT that reflects the very low wastage and very low yields in these systems. Operationally, the control will be through maintaining a desirable MLSS or MLVSS or food-to-microorganism ratio.

These results are supported by the research of Saby et al. (2003), who found that recycling settled activated through an anoxic tank resulted in reduced biological solids generation, and the amount of reduction was dependent on the oxidation–reduction potential (ORP). Even at an ORP of +100mv, solids were reduced compared with an aerated control, but were not as low as for an ORP of −250mv.

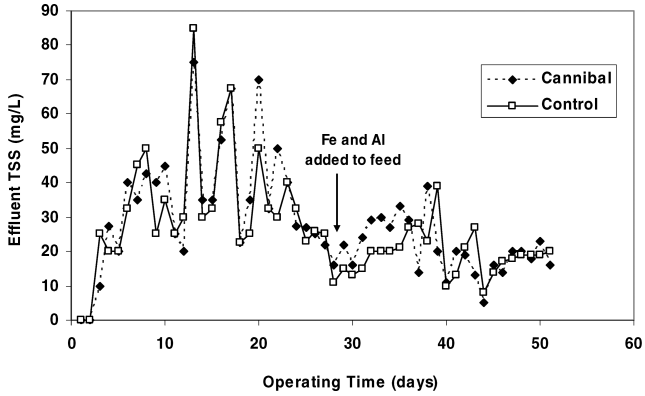

Figure 4—Effluent TSS from the Cannibal and control systems.

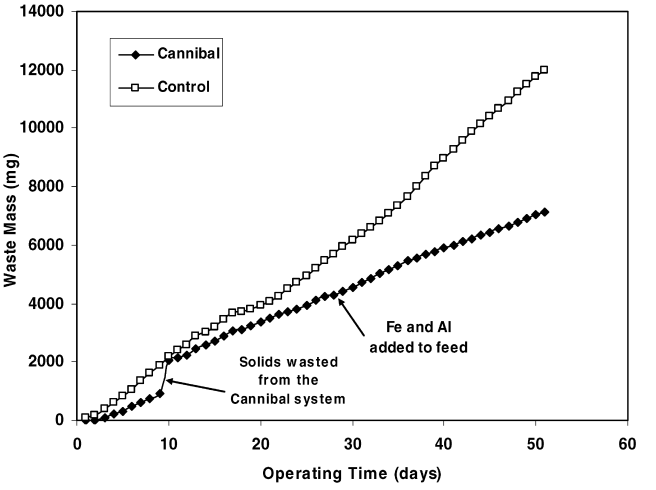

Figure 6—Cumulative solids wastage from the Cannibal and control systems (phase I).

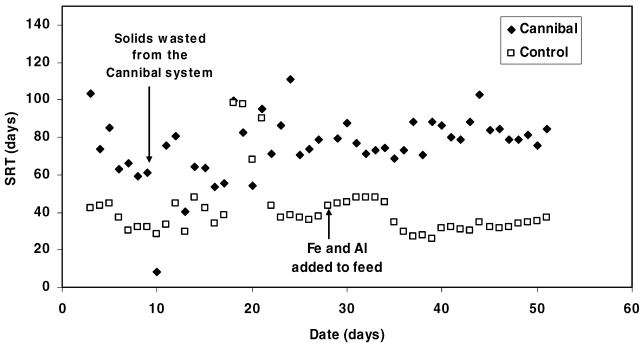

Figure 7—SRT for the Cannibal and control systems (phase I).

Mechanism for Solids Destruction. Exocellular polymeric substances (EPS) are a major part of the floc structure in activated sludge. Exocellular polymeric substances in activated sludge flocs constitute a matrix, in which bacteria and other particles are embedded. Jorand et al. (1995) described the complexity of the activated sludge floc structure using staining and the analysis of polymers released from sonicated sludges and found that the main polymers released from the activated sludge flocs were proteins, polysaccharides, and DNA. Frølund et al. (1996) found the components of activated sludge flocs to be protein (46 to 52% of total volatile solids), humic compounds (18 to 23% of total volatile solids), and carbohydrate (17% of total volatile solids) using the cation exchange resin extraction technique.

Therefore, if solids are to be reduced in the Cannibal system, it is likely that degradation of EPS will be important. The data in Figure 6 clearly show that the Cannibal system reduces biological solids generation compared with a control or nonCannibal system. The question that needs to be answered is: what is the mechanism?

Park et al. (2006) proposed that a primary mechanism for the degradation of waste activated sludge under anaerobic conditions was reduction of iron, coupled with the release of iron-associated organic matter, primarily protein, that are then easily degraded. The same mechanism was thought to apply to the Cannibal system. That is, when thickened sludge is cycled to the anaerobic bioreactor, iron is reduced, and organic matter is released or solubilized. When the sludge and solubilized organic matter are returned to the aerobic

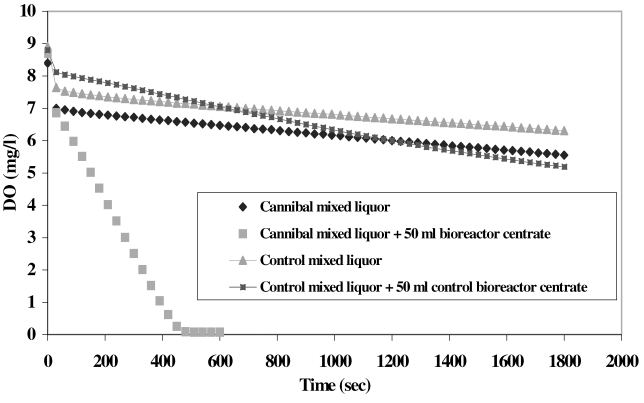

Figure 8—Oxygen uptake for centrate from Cannibal and control bioreactors (DO = dissolved oxygen).

Table 2—Protein and polysaccharides in the activated sludge reactor and bioreactors.

	Protein (mg/L)	Polysaccharide (mg/L)	Ca^{+2} (mg/L)	Mg^{+2} (mg/L)
Cannibal	10.8	4.5	79.5	17.0
Cannibal bioreactor (anaerobic)	81.0	10.8	82.3	33.1
Control	12.6	3.2	88.6	18.1
Conventional bioreactor (aerobic)	10.7	30.4	321.4	61.6

bioreactor (activated sludge aeration basin), it is degraded rapidly, before it can be recoagulated by the iron in the sludge. To determine if this concept is valid, sludge from both the anaerobic and aerobic bioreactors was collected and centrifuged; the centrate was fed to batch reactors containing mixed liquor from the aeration basins; and the oxygen uptake rate was then measured.

The results of the oxygen uptake tests are shown in Figure 8. It can be seen that the oxygen uptake rate for centrate from the Cannibal system was much higher than for the control system. This shows that the bioreactor in the Cannibal system contains readily biodegradable material that can be readily oxidized in the activated sludge reactor. In addition, the soluble protein and polysaccharide concentrations in the Cannibal bioreactor were 81 and 10.8 mg/L, respectively, and 10.7 and 30.4 mg/L, respectively, in the control bioreactor (Table 2). This is consistent with the digestion mechanisms suggested by Novak et al. (2003), who proposed that anaerobic conditions result in the release of iron-associated proteins that can then be degraded, and, under aerobic conditions, calcium- and magnesium-associated polysaccharides are released. The data shown in Table 2 indicate the release of protein in the anaerobic (Cannibal) bioreactor and release of calcium, magnesium, and polysaccharide in the aerobic bioreactor, which functions much like an aerobic digester.

It also appears that no special ''Cannibal organism'' is needed to reduce solids in the Cannibal system. The loss of solids in the Cannibal system compared with the control was initiated immediately after the system began operating, using sludge from a conventional activated sludge system (see Figure 6), and improved when iron was added to the wastewater feed. In phase I, a period of approximately 30 days was required to reach a steady-state operation, with regard to solids loss and effluent stability. It may be that the 30-day period to achieve steady-state was the result of the establishment of an active iron-reducing organism population; however, this was not investigated as part of this study. It also appears that the EPS that was released from the floc and degraded was replaced or regenerated in the aeration basin, because the supply of degradable organic matter was never exhausted in the Cannibal bioreactor, and flocculation was not negatively affected. Urbain et al. (1993) noted that EPS is necessary for flocculation in the activated sludge system; thus, if the EPS was consumed, flocculation would be expected to deteriorate. The mixed liquor settling characteristics, as indicated by the sludge volume index, were excellent, with values for both systems of approximately 60 mL/g over the study period.

Phase 2. In the second phase of the study, three reactors were operated—two in a manner similar to the first phase and another that had no wastage. The reason for this phase of the study was to

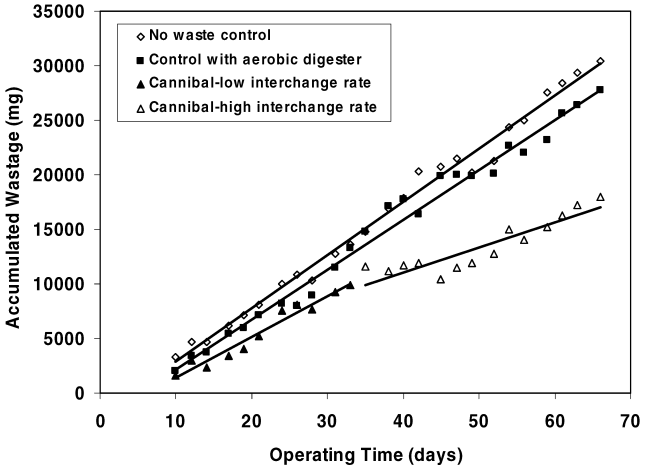

Figure 9—Cumulative solids for the Cannibal system at two interchange rates—a control with no wastage and a control with an aerobic bioreactor.

compare solids accumulation without any wastage, to better separate the effect of the Cannibal operation from the solids reduction that would occur from a high SRT system without the Cannibal operation. The feed volume was also doubled to reduce the HRT to 1 day and generate a higher level of biomass in the systems.

As can be seen in Figure 9, more solids accumulated in the no-waste system and in the control compared with the Cannibal system; however, the differences were not great. On day 33, the interchange rate (the rate of solids passed through the Cannibal bioreactor, expressed as percent per day of the biomass in the activated sludge reactor) was increased from approximately 4 to 7%. As can be seen in Figure 9, the increased interchange rate resulted in a decrease in the solids generation for the Cannibal system. Determination of the solids accumulation was made, by adding the increase in solids in the reactor to the solids lost in the effluent and solids collected for testing.

The lower solids amount generated for the Cannibal system is reflected in the observed yield data shown in Figure 10. It can be seen that the yields varied from a high of 0.26 mgVSS/mg COD for the control system to 0.11 mgVSS/mg COD for the Cannibal system at the higher interchange rate. At the lower interchange rate, the yield was 0.15 mgVSS/mg COD, which is still less than the

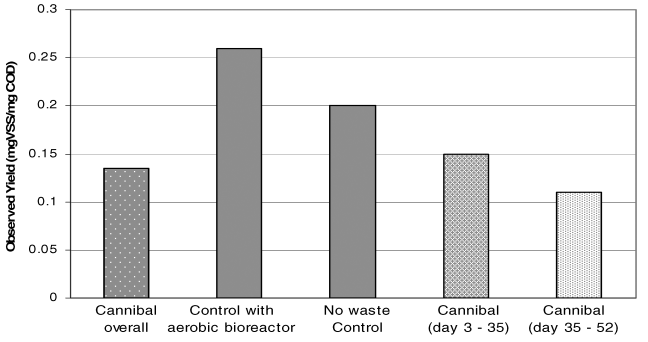

Figure 10—Observed yield for the Cannibal system and two control systems.

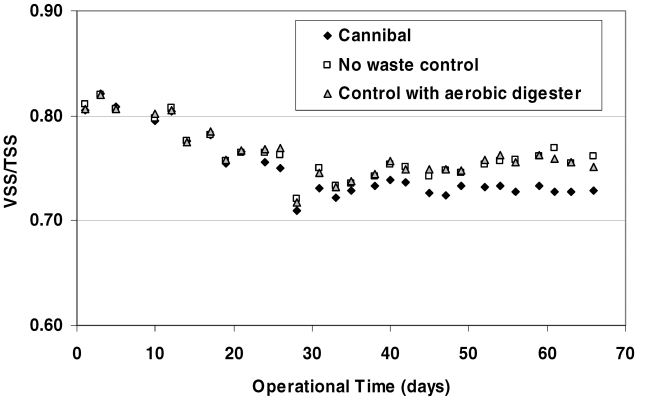

Figure 11—VSS/TSS in the mixed liquor from the various reactors.

control. As expected, the interchange rate is an important consideration in the design of the Cannibal system.

Because of the lack of wastage in the Cannibal system, coupled with the low yield for this system, it was expected that the volatile fraction in the Cannibal system would be lower than for the other systems. It can be seen, from the data in Figure 11, that the sludge in the Cannibal system had a volatile fraction of approximately 0.72, while the two control systems had a volatile fraction of approximately 0.76. The lower volatile fraction supports the loss of VSS that is seen for this system and might also indicate that iron accumulates in the sludge.

The phase II data show that the reduction of solids in the Cannibal system compared with the control is not the result of high SRT of the Cannibal system. Although the high SRT system without the Cannibal reactor generated lower solids than did the conventional system, there was still additional solids reduction in the Cannibal system. The operation of the Cannibal system leads to the high SRT, because sludge wastage is minimal. The effluent suspended solids for the three operational conditions are shown in Figure 12. It can be seen that the effluent suspended solids are similar, until day 40, when the suspended solids for the no-waste conventional system and the no-waste system with the aerobic bioreactor begin to increase. By day 40, the solids in the activated sludge reactors exceeded 6000 mg/L, and additional solids began to be lost in the effluent.

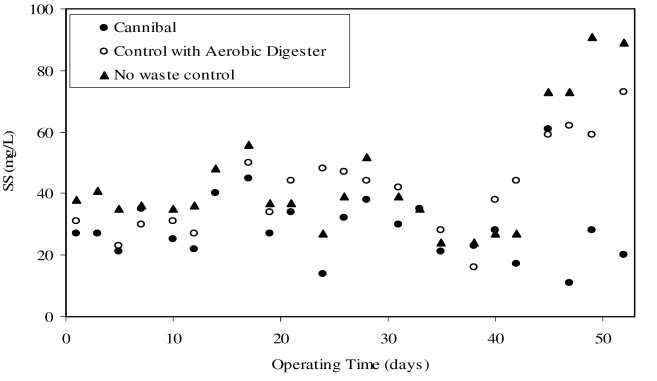

Figure 12—Effluent suspended solids (SS) over time from the three systems.

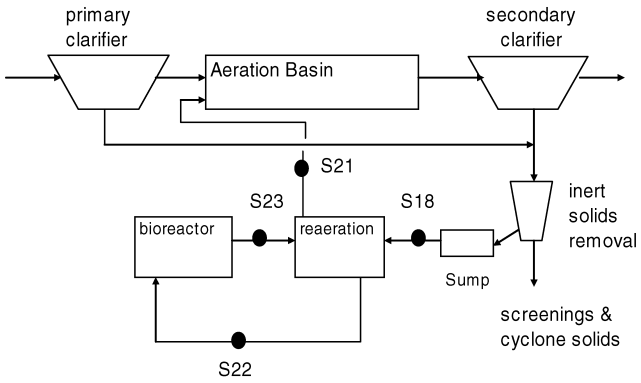

Figure 13—Schematic Diagram for the Byron, Illinois, wastewater treatment plant.

Field Data. Some field data were collected, primarily to measure the protein and polysaccharides across the system, to determine if the EPS release mechanism seen in the laboratory reactor could also be seen in field data. The plant investigated was the Byron, Illinois, wastewater treatment plant, which operated with a Cannibal system, as shown in Figure 13. Protein and polysaccharide data are shown in Tables 3 and 4, where 30k and 1k refer to protein and polysaccharides passing the 30 kDa and 1 kDa ultrafilter sizes.

The primary comparison is between location S18 and S23—the feed to the bioreactor and the discharge from the bioreactor, respectively. It can be seen that the protein content rises for the sludge from the anaerobic bioreactor. More importantly, the fraction of protein that passes a 1k Dalton molecular weight ultrafilter increases from 1.28 mg/L for location S18 to 4.48 mg/L at location S23. The fraction less than 1k can be considered readily degradable, so it is clear that the effect of the anaerobic bioreactor is to generate soluble biodegradable protein. Polysaccharides also increase, but the increase is much less than protein. Data for location S21 also shows that the protein that is released in the anaerobic bioreactor is readily degraded in an aerobic environment. These data support the observation, from the laboratory data, that the mechanism for solids reduction by the Cannibal process is the release of organic matter in the anaerobic (or Cannibal) bioreactor, and this material is then biodegraded under aerobic conditions.

Conclusions

Side-by-side SBR activated sludge systems with and without a Cannibal bioreactor were operated in the laboratory using a synthetic feed, to compare the solids generation for the two systems. The SBR system that was operated in the Cannibal configuration (the return sludge was retained in an anaerobic bioreactor for 10 days) resulted in a significant reduction in the generation of waste activated sludge. A reduction in solids of approximately 60% was seen for the specific operation compared with a side-by-side control system with an aerobic digester.

Table 3—Protein data by molecular size at four locations at the Byron, Illinois, plant.

	Protein (mg/L)			
Location	**1k**	**30k**	**0.45 μm**	**1.5 μm**
S 18	1.28	5.08	5.72	7.61
S 21	1.61	5.43	6.07	7.24
S 22	1.64	5.02	7.20	7.25
S 23	4.48	9.32	12.38	15.24

Table 4—Polysaccharide data by molecular size at four locations at the Byron, Illinois, plant.

	Polysaccharides (mg/L)			
Location	**1k**	**30k**	**0.45 μm**	**1.5 μm**
S 18	1.08	2.39	4.03	4.77
S 21	1.61	3.29	4.60	4.77
S 22	1.29	3.66	5.67	6.41
S 23	1.78	4.15	7.10	7.88

The mechanism for the additional solids loss appears to result from solubilization of organic matter in the Cannibal bioreactor that is then degraded when the bioreactor sludge and solubilized organic matter is returned to the aeration basin. This was demonstrated by comparing the oxygen uptake of centrate from the Cannibal and nonCannibal systems. The centrate from the Cannibal bioreactor had a very high oxygen uptake rate compared with the nonCannibal system, indicating the presence of readily degradable organic material.

No deterioration in performance was found for the Cannibal operation, as evidenced by the effluent soluble COD, effluent suspended solids, and settling characteristics of the mixed liquor.

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