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Anaerobic Digestion of Cellulosic Wastes: Pilot Plant Studies

D. D. Lee
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ANAEROBIC DIGESTION OF CELLULOSIC WASTES: PILOT PLANT STUDIES

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ABSTRACT

Anaerobic digestion is a potentially attractive technology for volume reduction of low-level radioactive cellulosic wastes. A substantial fraction of the waste is converted to off-gas, and a relatively small volume of biologically stabilized sludge is produced. Process development work has been completed using a 75-L digester to verify rates and conversions obtained at the bench scale. Start-up and operating procedures have been developed, and effluent was generated for characterization and disposal studies.

Three runs lasting 36, 90, and 423 d were made using batch and batch-fed conditions. Solids solubilization rates and gas production rates were approximately double the target values of 0.6 g of cellulose per L of reactor volume per d and 0.5 L of off-gas per L of reactor per d. Greater than 80% destruction of solids was obtained. Preliminary effluent characterization and disposal studies were completed. A simple dynamic process model has been constructed to aid in process design and for use in process monitoring and control of a large-scale digester.

1. INTRODUCTION

Disposal of solid low-level radioactive waste is an increasing problem for the nuclear industry. The Oak Ridge National Laboratory (ORNL) generates about 2300 m^3 of low-level waste each year, of which ~350 m^3 is cellulosic and readily amenable to biological degradation. This waste is currently placed in trenches in the burial grounds after a portion has been compacted. In the trenches, it is subject to natural biological decomposition, which leads to instability and subsidence in the burial grounds. One alternative disposal technology is incineration; however, this approach suffers from substantial off-gas cleanup requirements and poor economics in the case of small incinerators to handle relatively small volumes of material.

Another alternative is the anaerobic digestion of the cellulosic fraction of the solids. Anaerobic digestion offers the attractive potential to reduce the volume of wastes by converting a substantial fraction of the solids to methane (CH_4) and carbon dioxide (CO_2) and producing a biologically stabilized sludge that is better suited for burial than is the original waste. The anaerobic digestion process is similar to that for a residential septic tank and the stabilization of sludge as practiced in the municipal wastewater treatment industry. The major biochemical reactions are illustrated in Fig. 1. Feasibility studies, a preliminary process design, and a cost estimate have been carried out for implementation of an anaerobic digestion plant to treat actual wastes at ORNL.[1–3]

The initial feasibility study[1] explored the rates and extent of microbial digestion of blotter paper, cloth, sanitary napkins, and pine sawdust in shake flasks, batch stirred reactors, and fed-batch stirred reactors. The stirred reactors had working volumes of 0.6 and 4.0 L; the shake flasks had 0.1-L working volumes. The stirred reactors were operated at 1% w/v solids concentration and gave cellulose degradation rates of 0.1 to 1.2 g of cellulose per L of reactor volume per d (g/L•d) and gas rates of 0.3 to 1.1 L/L•d. From these results, a cellulose degradation rate of 0.6 g/L•d and a gas production rate of 0.5 L/L•d were chosen for a preliminary conservative process design.

ORNL WS 34671

$$\text{CELLULOSE} \xrightarrow[\text{CELLULOSE HYDROLYZERS}]{} \text{SUGAR} + CO_2 + \text{CELLS}$$

$$\text{SUGAR} \xrightarrow[\text{ACETOGENS}]{} \text{ACETIC ACID} + CO_2 + \text{CELLS}$$

$$\text{ACETIC ACID} \xrightarrow[\text{METHANOGENS}]{} CO_2 + CH_4 + \text{CELLS}$$

Fig. 1. Major biochemical conversion steps in the anaerobic digestion of cellulose.

The preliminary process design and the cost estimate[2] were based on anaerobic digestion of a wet-pulped cellulosic materials mixture that is batch-fed to the digester. A 94.5-m^3 (25,000-gal) digester would be needed to treat the ORNL waste at a solids concentration of 1 to 2%. The flowsheet for the process (Fig. 2) includes separation of the solids remaining after digestion from the water, which will be treated in the ORNL low-level waste evaporator system. The solids can be mixed with a cement grout for landfill. It appears that a total volume reduction of ~80 to 90% will be possible with this process.

Process development work was initiated to provide scale-up data and operating experience for the design and operation of the full-scale digester at ORNL. The experimental work was carried out in 1-, 14-, and 75-L digesters using a feed material that simulated the cellulosic materials found in the ORNL low-level radioactive waste. Goals of this work included the development of dependable start-up techniques for the digester, determination of the viability of the proposed batch feeding method, and determination of digester operating conditions. The latter included consideration of solids concentration, pH, alkalinity, liquid recycle, supplemental municipal anaerobic sludge, long-term operating stability and solids destruction, and the need for supplementation with a mineral and vitamin solution. The early results were reported in ref. 3. Two runs were conducted in the 75-L digester to determine the most reliable start-up methods. These tests resulted in a standard start-up technique that uses low concentrations of cellulose plus supplemental methanol to decrease the length of time required for stable operation.

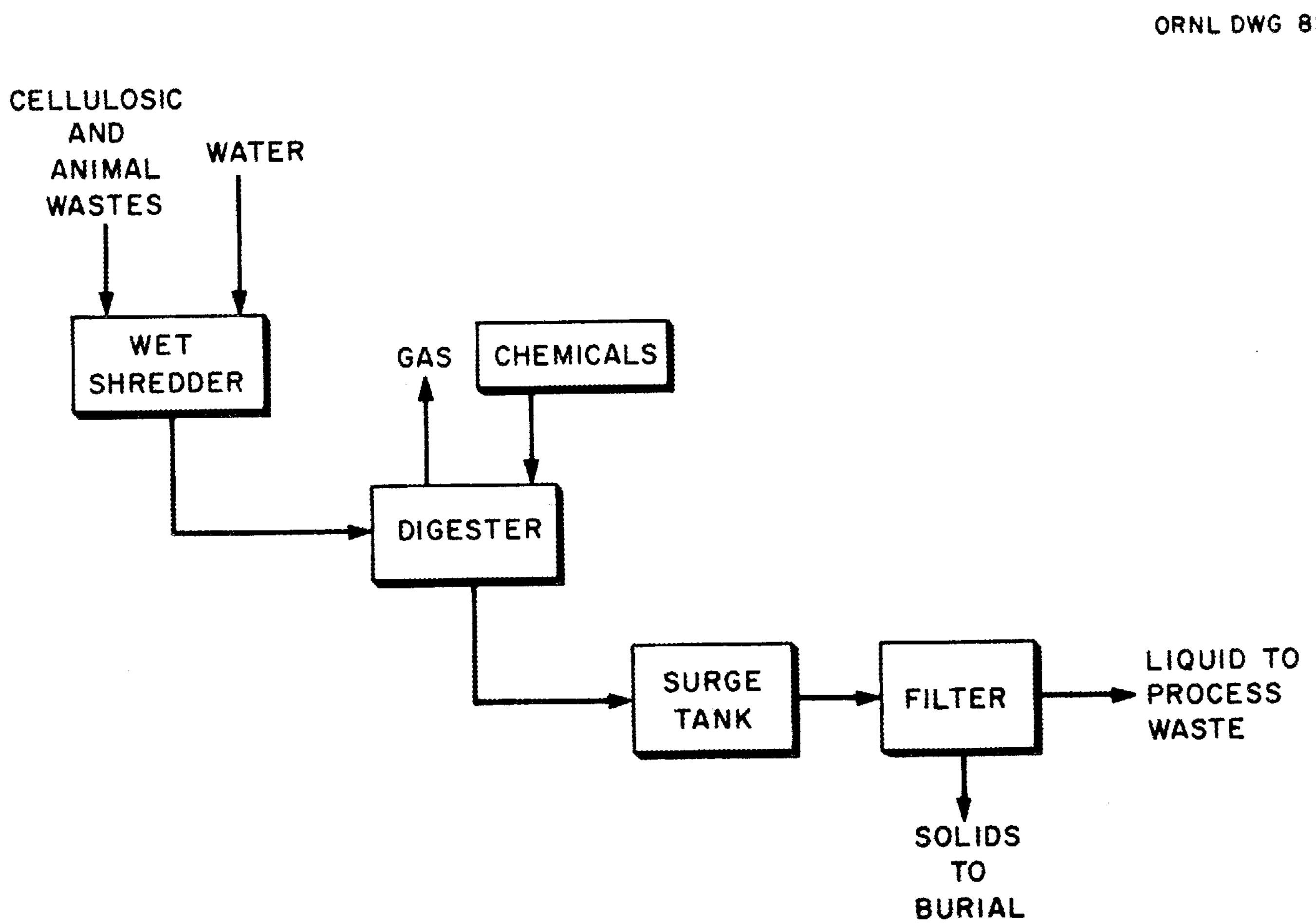

Fig. 2. Process flowsheet for anaerobic digestion of low-level cellulosic waste.

This final report discusses the third run with the 75-L digester, which lasted for 423 d. A mathematical model of the digestion process, which included the batch feeding schedule, was developed for use in guiding process development work and eventual process control. This dynamic model is described in ref. 3. Verification of the model with experimental data is presented in this report.

2. EXPERIMENTAL PROCEDURES

2.1 SUBSTRATES, NUTRIENTS, AND INOCULUM

The digesters were operated on simulated (nonradioactive) low-level solid waste composed of 90% blotter paper, 7% cotton/polyester (35/65) labcoats, and 3% sanitary napkins. The feed which was shipped to American Delphi, Inc., Westminster, California, for wet-shredding, was returned to ORNL as a ~10% slurry of ~1-cm particle size, and stored at 4°C. When a digester required feeding, an appropriate amount of feed was measured and added to the digester. Several samples were analyzed for solids content, and the average value of 9.72 wt % volatile solids was used to determine the amount of slurry added to the digester. The nutrients for the digester operation have been described previously.[3]

The inocula used to seed the digesters, and also added to the digesters occasionally to increase gas rates during some upset conditions, were obtained from several sources. The digesters were initially seeded using sludge from the bottom supernatant sample point of the anaerobic digester at the Oak Ridge West End Sewage Treatment Plant (ORWESTP). If possible, a portion of the sludge was added to the digester the same day as obtained, while the remainder was stored (for a maximum of 2 weeks) at 4°C for later addition. Other sludge was obtained from the ANFLOW digester at the Love's Creek treatment plant in Knoxville, Tennessee, and from the Kuwahee Treatment Plant, also in Knoxville.

2.2 ANALYTICAL PROCEDURES

The samples of digester contents, seed sludge, and feed were analyzed for total and volatile suspended solids (TSS and VSS), alkalinity, pH, and filtered and unfiltered chemical oxygen demand (COD) using Hach COD vials according to Standard Methods.[4] Total volatile acids (TVA) and several individual volatile acids (acetic, propionic, isobutyric, butyric, isovaleric, and valeric) were analyzed using a Varian 3700 gas chromatograph with a 3.2-mm-diam, 2-m-long column containing 60/80 Carbopak/0.3% Carbowax 20 M/0.1% H_3PO_4 at 120°C with a helium carrier and a flame ionization detector. Gas production was measured with a wet-test meter. Gas compositions were measured on a Sigma II gas chromatograph with a Poropak-Q column.

2.3 ANAEROBIC DIGESTER PILOT PLANT

2.3.1 Description of the 75-L Digester

The 75-L digester is a standard industrial fermenter with associated instrumentation and piping that was purchased from the New Brunswick Scientific Company as a unit (Fig. 3). Its working volume is ~65 L. The reaction vessel is made of 316 stainless steel, jacketed for temperature control, and equipped with pH control and agitation speed adjustment. It was modified for operation as an anaerobic digester by removing the gas sparger and the internal baffles. The three turbine impellers on the agitator shaft were replaced by a single 17.8-cm propeller-type agitator (Lightnin A310, Mixing Equipment Co.), which provided improved pumping

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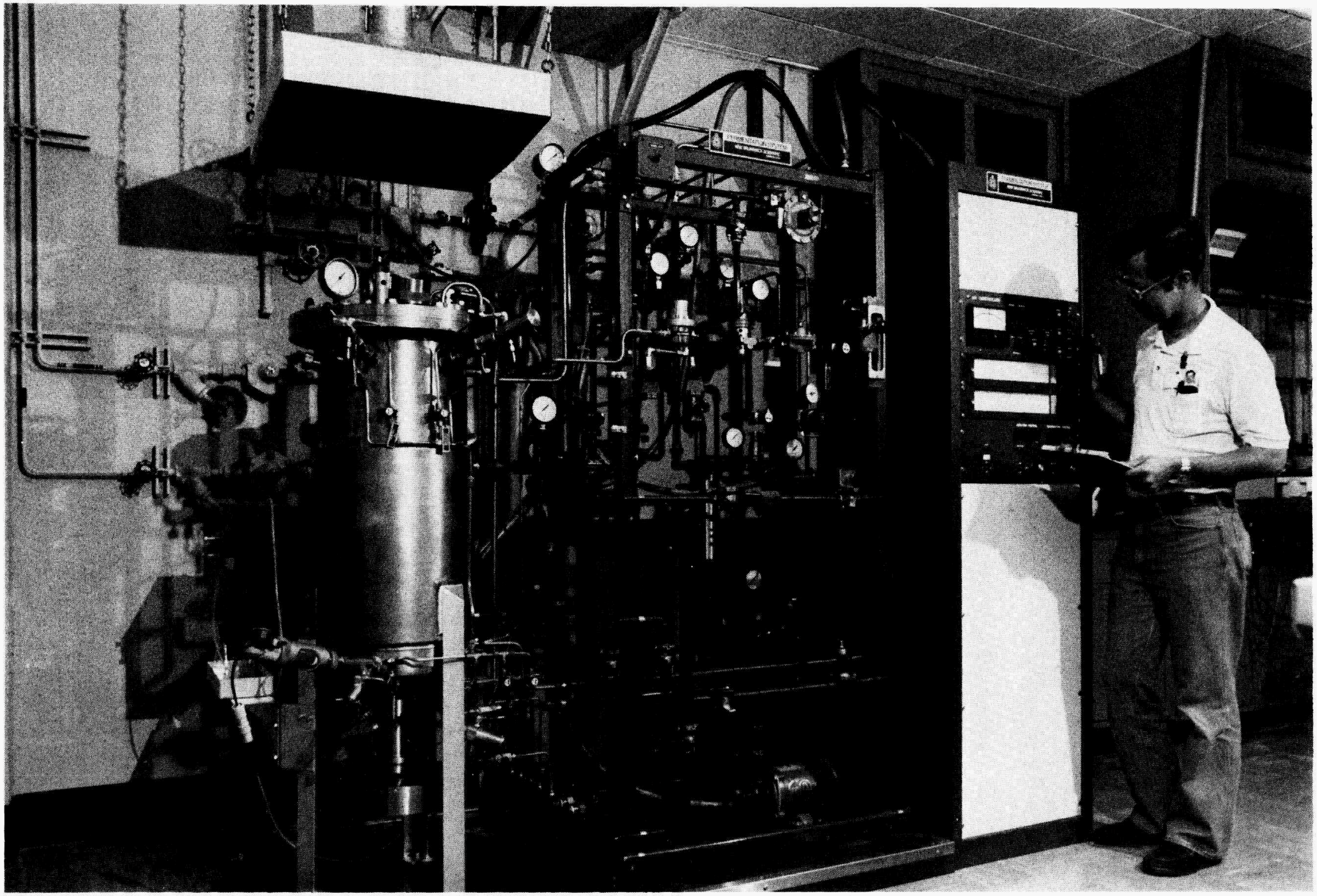

Fig. 3. The 75-L pilot plant digester.

action to suspend the larger particulates with less violent mixing action. An additional sampling system was added to the digester to obtain more uniform samples of the contents. The sampler consisted of a top-entering 1.27-cm-OD stainless steel tube that could be raised or lowered to any vertical position to obtain a sample of the digester contents. The sampler was operated by pressurizing the digester with nitrogen and then opening the sample valve.

2.3.2 Operating Procedures

The third run of the digester was initiated by adding a seed culture to the feed mixture of 0.1% cellulose, methanol, and nutrients. The seed sludge, which was obtained from the ORWESTP, was added in order to obtain a 3 vol % sludge concentration in the digester. The start-up period and the operation of the digester through the first six months are described in ref. 3.

The digester contents were sampled daily during the week, and the quantity of gas produced was recorded daily. The sampling procedure for the digester included taking two 200-mL samples, which were analyzed separately for TSS and VSS, and averaging the results. The remaining analyses (COD on filtered and unfiltered samples, individual volatile acids and TVA, and pH and alkalinity) were performed on a pooled sample. The volume of sample removed, the volume and content of the material fed to the digester (if any), and the time of sampling and feeding were recorded.

The digester was operated in the batch-fed mode; that is, the volume of feed to be added was calculated, and then the same volume of material was withdrawn from the digester and replaced by fresh feed. The fresh feed often included nutrient solutions and, in the early part of the run, additional sludge. The usual feed mixture contained about 200 g (dry wt) of cellulose material in a total volume of 4.0 L (see ref. 3). The feeding schedule varied according to the type of experiment and ranged from no feedings for a period of ≤2 weeks to feeding daily for several weeks. Usually, the digester was fed twice weekly. In addition, the cellulose content was varied from less than 200 g to 500 g per feeding, with one feeding of 1500 g of cellulose. For several months, when simulated waste was not available, Solka-Floc (a commercial powdered cellulose formulation) was used as the cellulose feed material.

During much of the operation with Solka-Floc, the digester was operated to simulate recycle of supernatant from a settling step in a large system. All of the extra digester effluent withdrawn daily was saved and allowed to settle. New feed for each day was prepared using the effluent as the liquid to suspend the cellulose.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Operational details of the first 200 d of run 3 have been described in detail in an earlier report;[3] therefore, they are simply summarized here. Normal operation with simulated cellulose feed was carried out for the first 215 d. Operation with effluent supernatant recycle began on day 216 and ended on day 341. Solka-Floc was used as the feed cellulose starting on day 238 and continued through day 359. During the final phase of operation, a starvation test (day 385 through day 401) and a large batch-fed test (day 414 through day 423) were completed. An extensive compilation of the operating data from these tests is given in the Appendix.

A summary of the overall results of run 3 is shown in Table 1. Average values for the parameters listed were calculated by dividing the total for each by the total number of samples for each. The hydraulic retention time (HRT) was calculated for each day based on the amount of sample withdrawn and fed. Average values were calculated from the daily values; the maximum and minimum values for the parameters were obtained from data after the start-up phase of operation had been completed.

Table 1. Digester performance over 423-d batch-fed run

Parameter	Average	Maximum	Minimum
TSS, g/L	9.40	37.36	1.66
VSS, g/L	8.23	34.54	1.44
COD, g/L	10.38	33.34	1.50
TVA, g/L	0.41	2.56	0.001
Alkalinity, g/L	2.74	5.10	1.13
TVA/alkalinity	0.16	1.26	0.0004
HRT, d	52.90	120.70	5.60
Digester volume, L	61.80	74.20	47.50
pH	6.79	7.55	5.80
VSS rate, g/L•d	1.83	6.63	0.01
Gas rate, L/L•d	1.18	5.83	0.01

Table 2 describes the carbon balance on the digester for the duration of run 3. The total amount of carbon fed was calculated based on the known amount of synthetic feed and its carbon content. The gas produced is the amount of gas measured by the wet-test meter, corrected to standard conditions and no water vapor, and divided by 22.4 to obtain the mol of carbon. The mol of solid carbon removed were calculated based on the volume of the sample removed and the experimental VSS determination for that day. The soluble carbon removed was calculated based on the volume removed and the soluble COD that was experimentally measured. The carbon balance was then found by dividing the total carbon out by the total carbon in. For run 3, 93% of the carbon fed was accounted for by the carbon out as gas, solids, and soluble carbon. The remaining 7% can be allocated in part to loss of material during several equipment failures (described later).

Table 2. Carbon balance for 423-d run

	Carbon (mol)	
Source	In	Out
Feed	1602	
Off-gas		1144
Solids[a]		173
Soluble[a]		173
Total	1602	1490

[a]Includes periodic effluent and contents of digester at termination of run.

The third batch experiment was started using concentrations of 0.1% cellulose and 300 mg/L methanol, along with ORWESTP anaerobic digester sludge at 3% v/v concentration. The concentration of cellulose was gradually increased, and the TVA concentration was closely monitored to prevent the rapid buildup that had inhibited earlier batches.[3] The gas production averaged 0.02 to 0.05 L/L•d as the solids concentration was increased to 3000 mg/L (0.3%). After 70 d, stability was attained at a solids concentration of 0.65%, a gas production rate of 1.2 L/L•d, and a solids degradation rate of 1.45 g/L•d. These rates exceeded the design rates of 0.6 g cellulose/L•d and 0.5 L gas/L•d at an HRT of 35 d.

During the next 30 d, the feeding interval was decreased and the amount of cellulose in the feed was increased. As a result, the solids concentration in the digester increased to more than 1.5%. During one 5-d period, the digester was fed daily at an HRT of 16 d. The gas production was greater than 0.5 L/L•d during this time, but the propionic and butyric acid components of the TVA began to slowly increase, causing an increase in the ratio of TVA to alkalinity, as shown in Figs. 4 and 5 near day 100. Impending problems in the digester are indicated when the ratio of TVA to alkalinity is >0.5. A healthy digester has a ratio <0.3.

Several methods were employed to lower the TVA concentration and the ratio of TVA to alkalinity. These included (1) reducing the feed rate, (2) increasing the HRT to 50 d, and (3) decreasing the HRT at a low feed concentration to dilute the TVA by washing it out. The best results were obtained with the third method; after 14 d, the TVA was reduced by 60%, while the feed concentration and the HRT had increased sufficiently to give a digester solids concentration of >1% and an HRT

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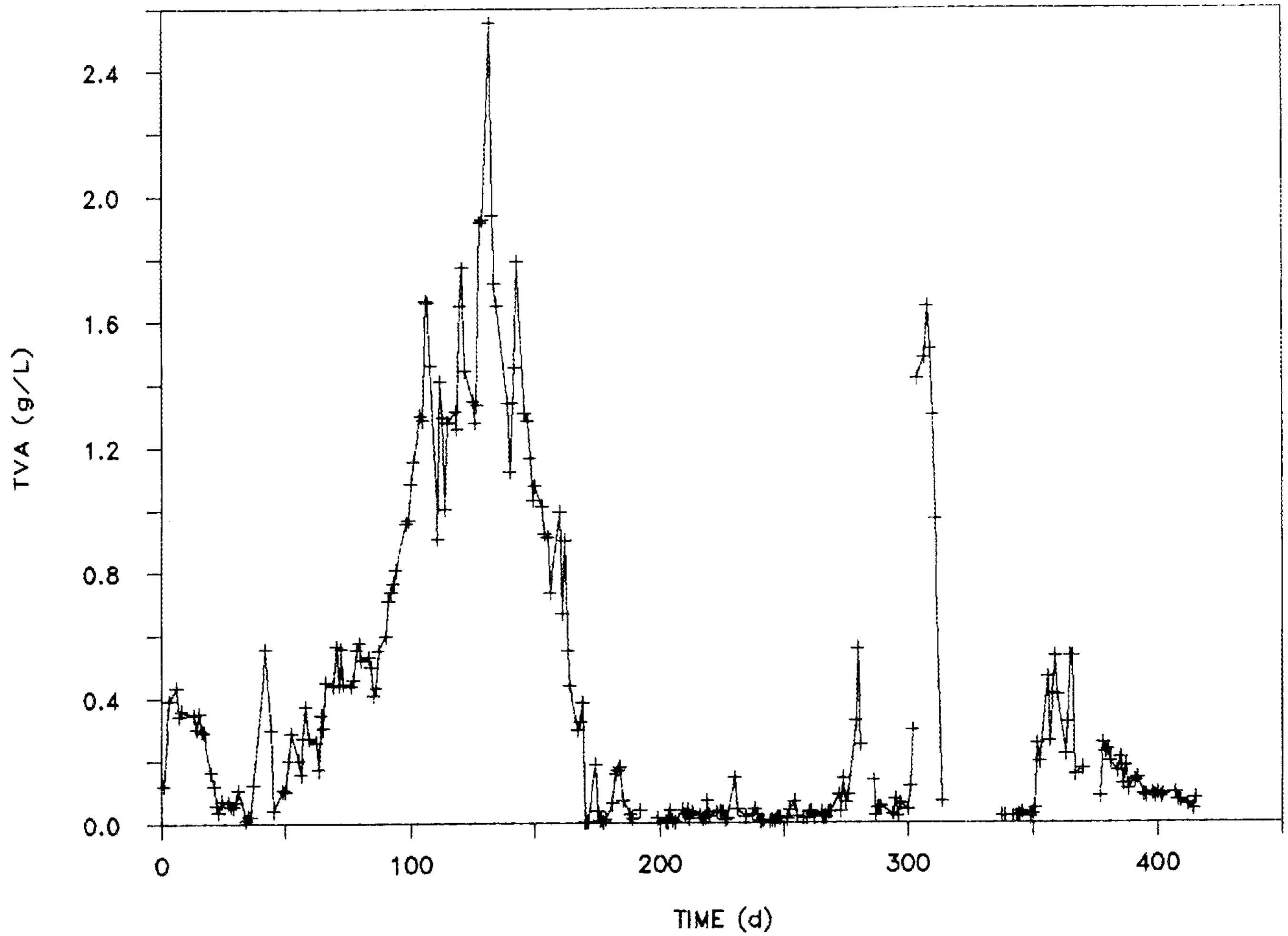

Fig. 4. Total volatile acids (TVA) in the digester for Run 3.

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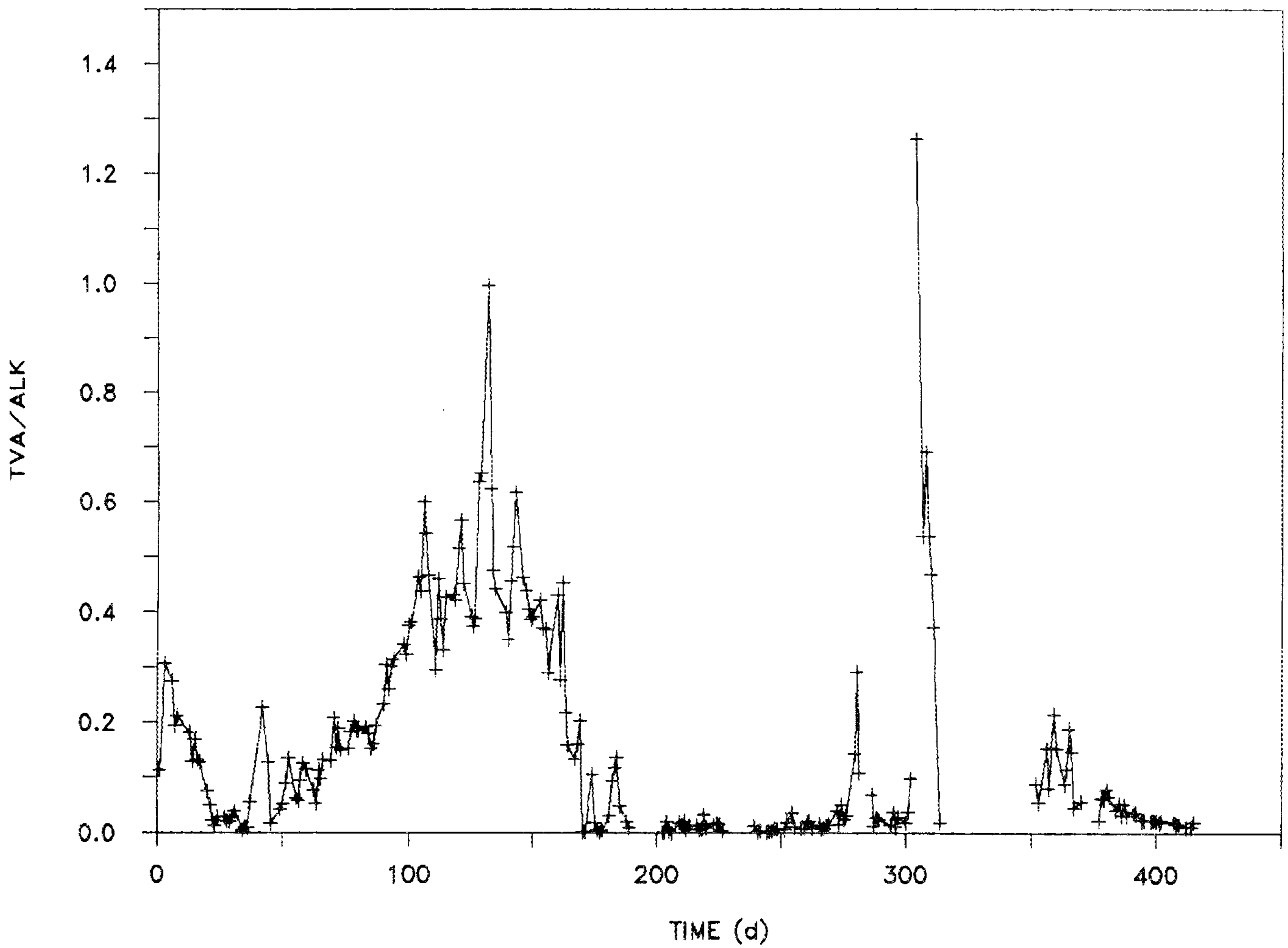

Fig. 5. Ratio of TVA to alkalinity for Run 3.

of 25 d. At this point, the digester developed the ability to degrade propionic and butyric acids, resulting in TVA/alkalinity (ALK) ratios of <0.1.

Figures 4–12 give an overall picture of the results of the 423-d experimental run. Figure 4, as previously discussed, is a plot of the TVA and shows peaks at days 50 to 150, again near day 300, and also at day 360. The latter two peaks occurred during changes in the feeding rates and coincide with peaks on the TVA/ALK graph in Fig. 5. When the peaks occurred in the TVA/ALK ratio, the pH was raised to increase the alkalinity. The large peaks were usually caused by a loss of dissolved CO_2 due to plugging of the wet-test meter with foam, pressurization of the digester, rupture of the digester rupture disk, and subsequent loss of pressure (and dissolved CO_2). Figure 6 is a plot of the digester pH; the deep dips around 300 d correspond to the high TVA/ALK discussed above. Very little pH control was required over the course of the run, and the pH was fairly stable between 6.5 and 6.9, depending on the time since feeding.

The liquid volume in the digester during the course of the run (see Fig. 7) was held at 65 L during the first 100 d and then varied from 61 to 69 L up to day 200. At that point, the volume was reduced to ~58 to 60 L, where it was maintained until the upsets near day 300. These upsets, shown by a sudden decrease and slow increase in volume, occurred when the digester foamed and plugged the wet-test meter, causing the digester rupture disk to rupture and several liters of digester contents to be lost. The volume was gradually restored to its original level by withdrawing only enough material from the digester for sample analysis and feeding the usual amount.

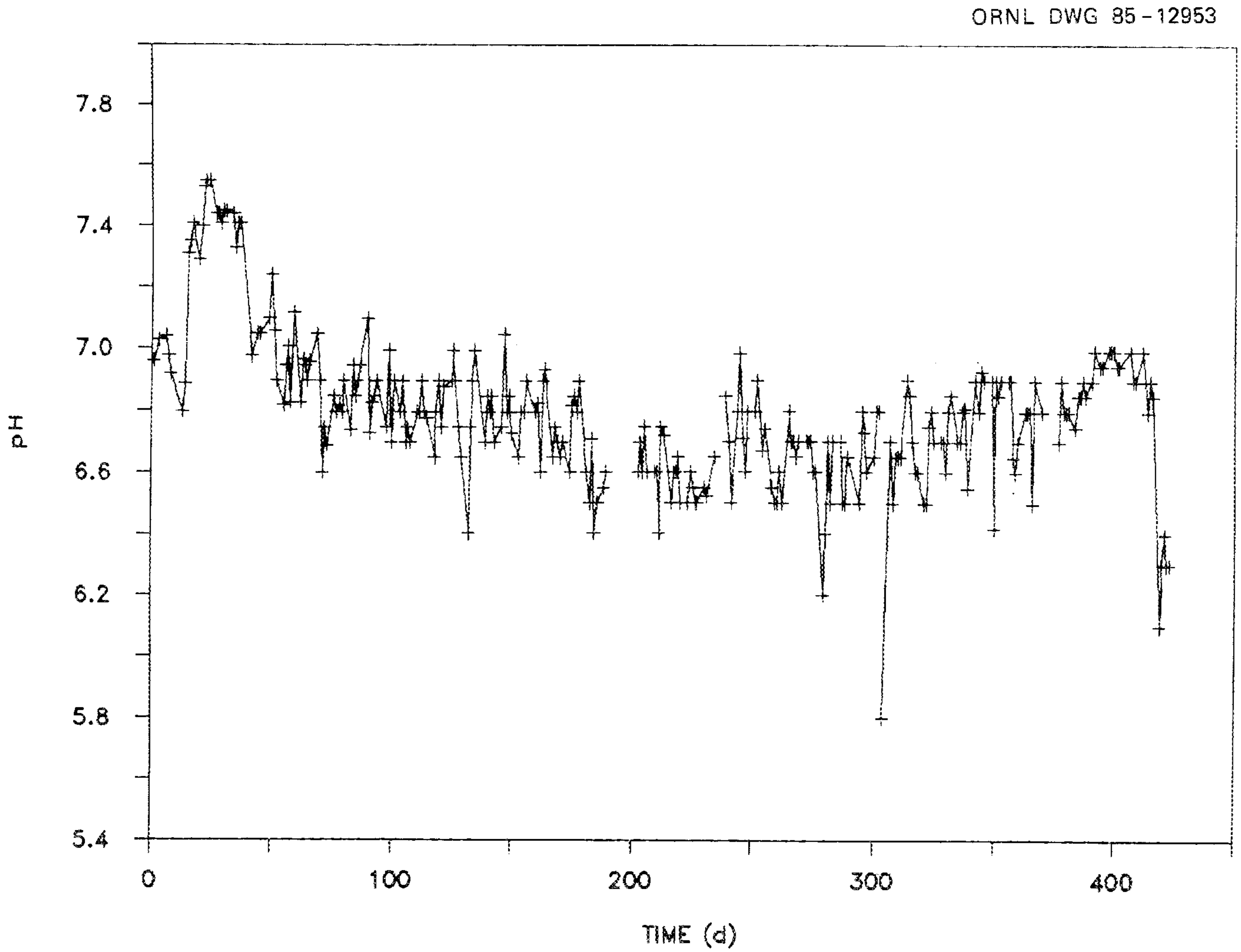

Fig. 6. Digester pH for Run 3.

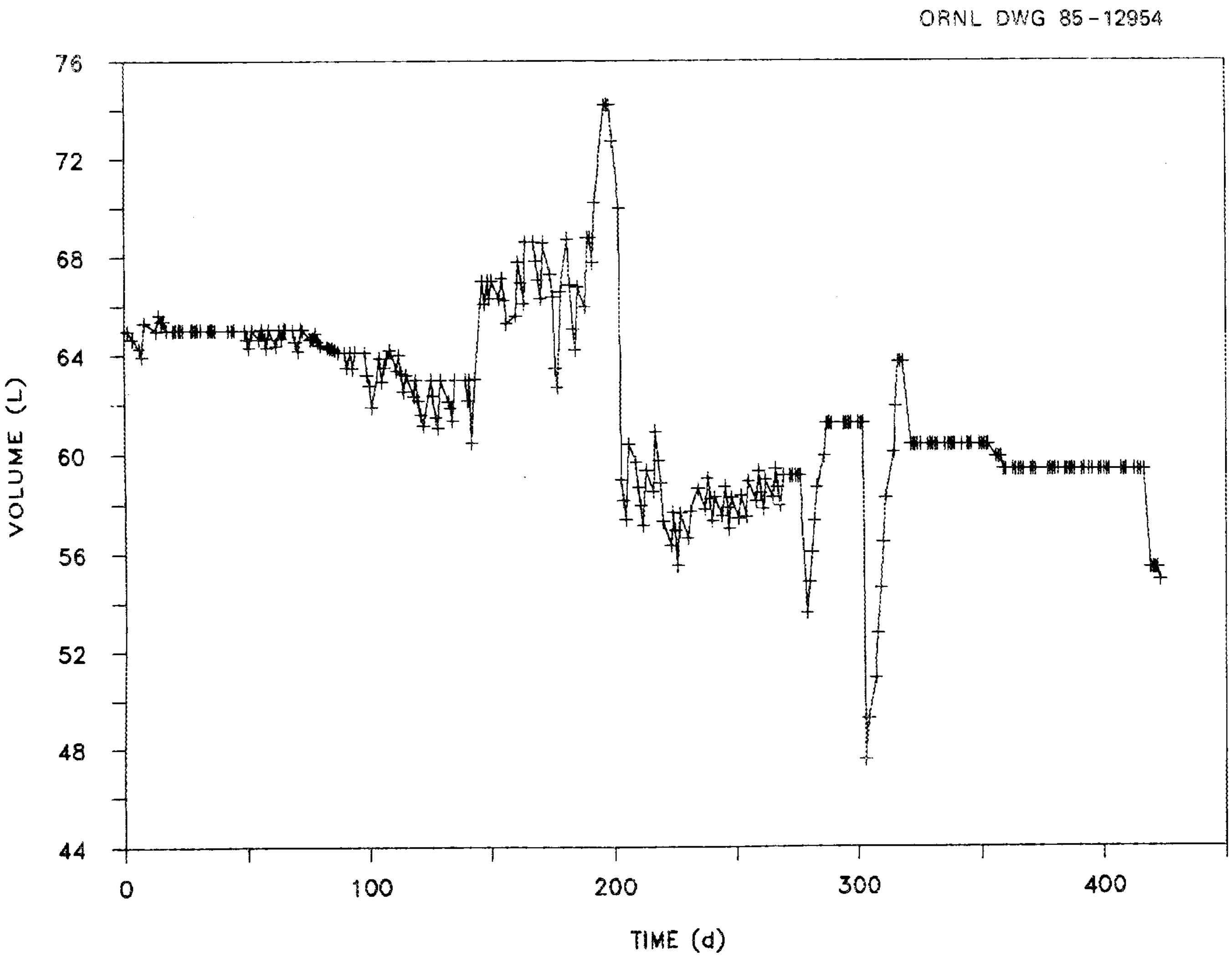

Fig. 7. Digester volume for Run 3.

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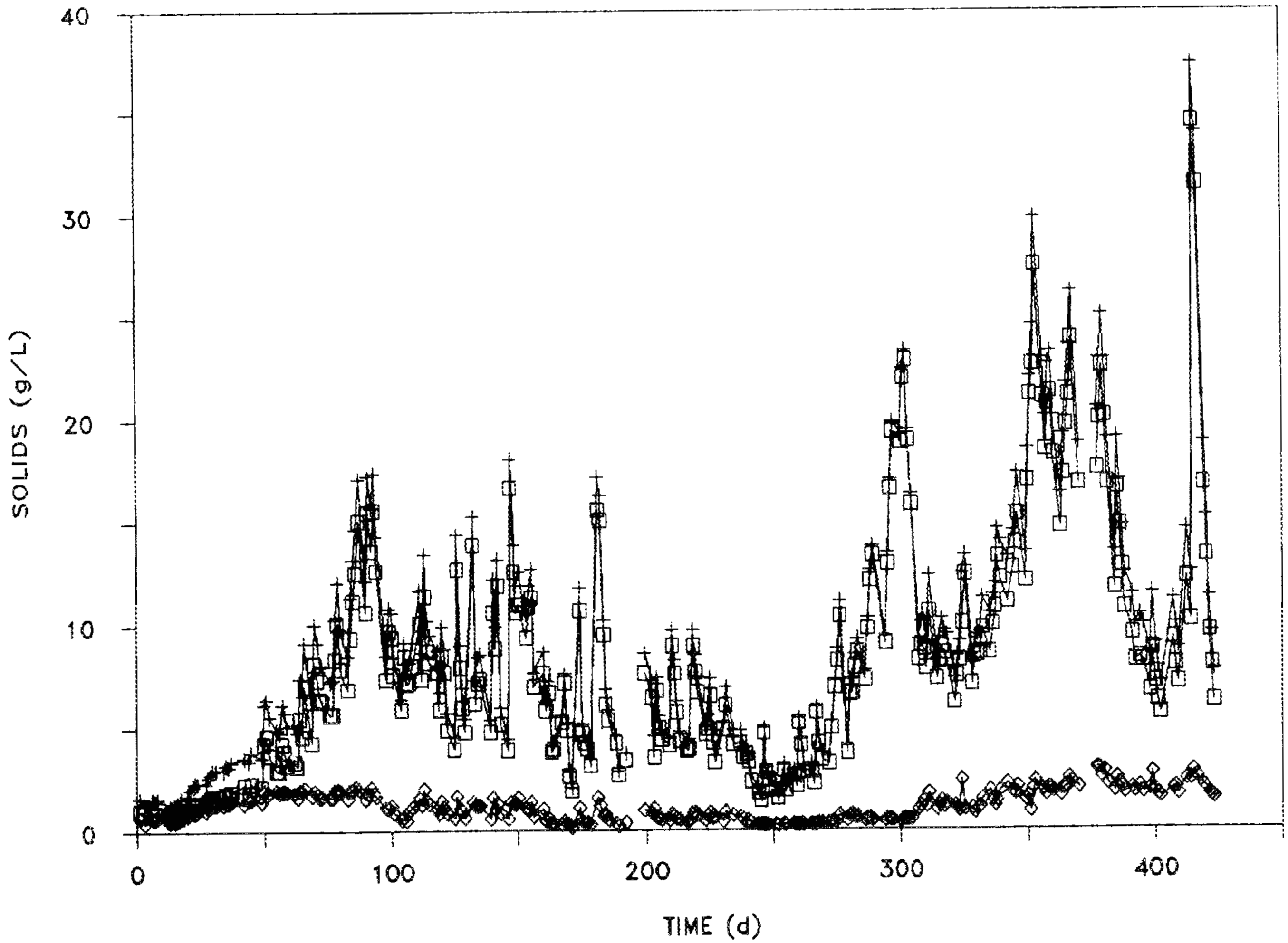

Fig. 8. Digester solids concentration for Run 3. Legend:
+ = total suspended solids (TSS); □ = volatile suspended solids (VSS); ◇ = inert suspended solids (ISS).

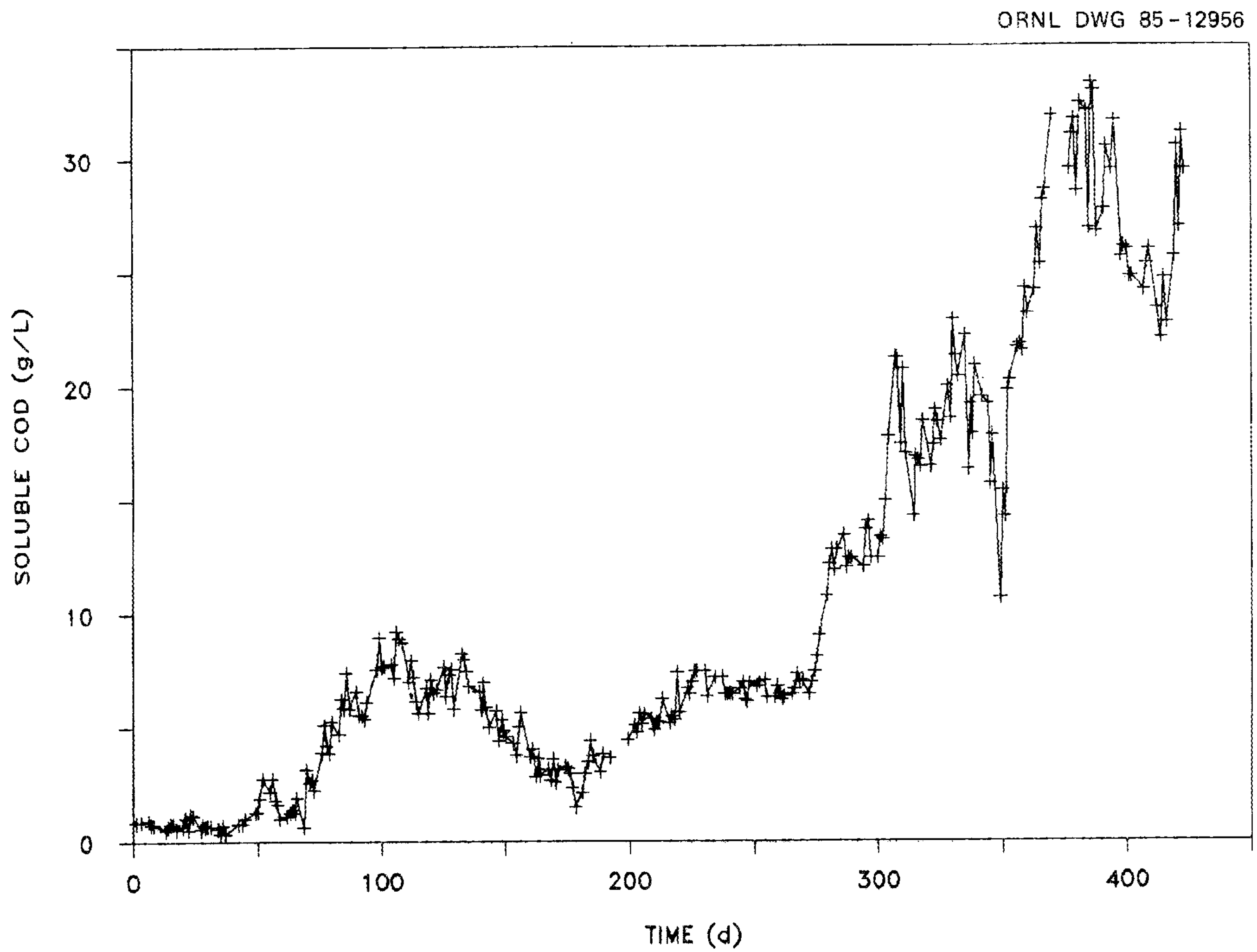

Fig. 9. Soluble chemical oxygen demand (COD) in the digester for Run 3.

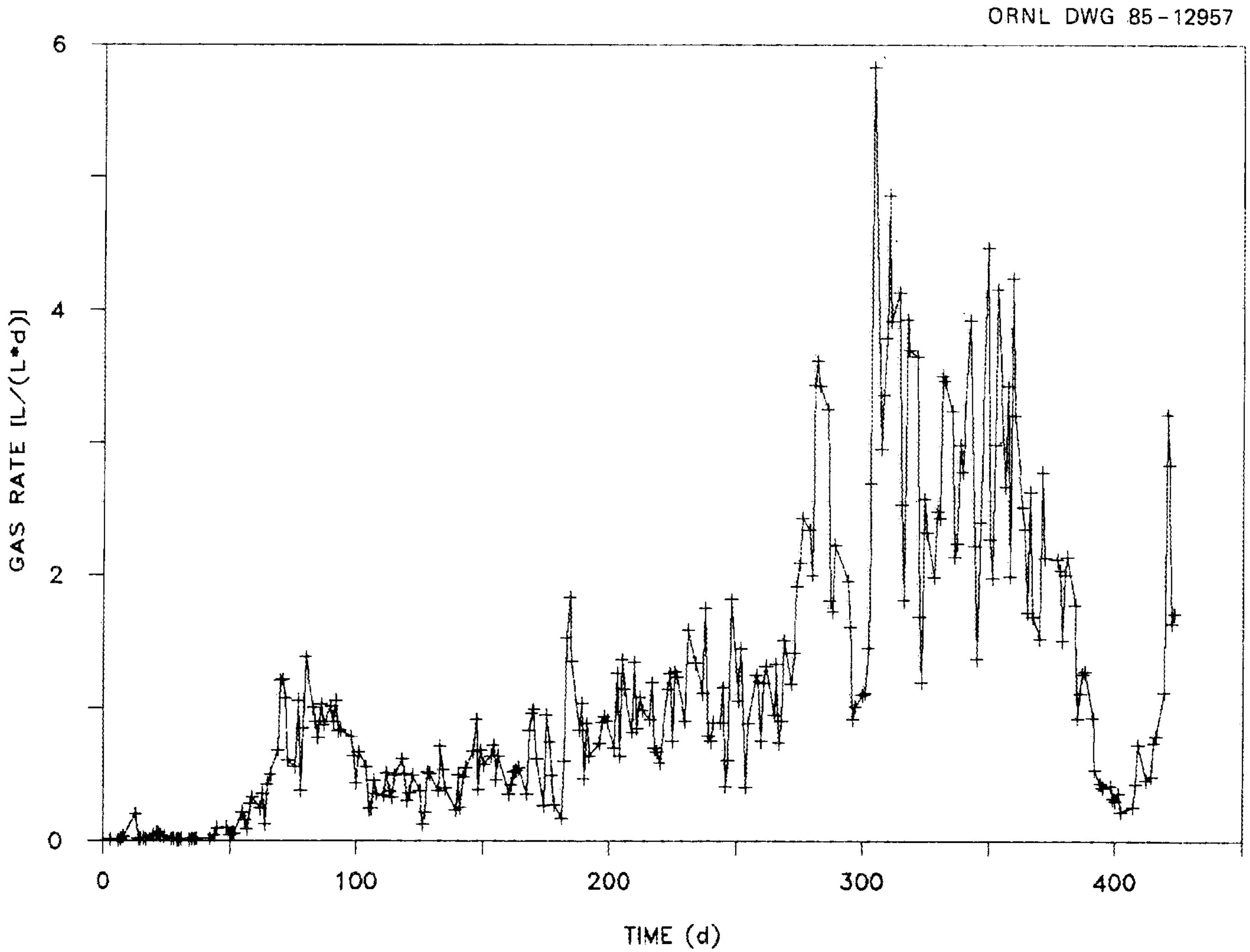

Fig. 10. Off-gas production rate for the digester for Run 3.

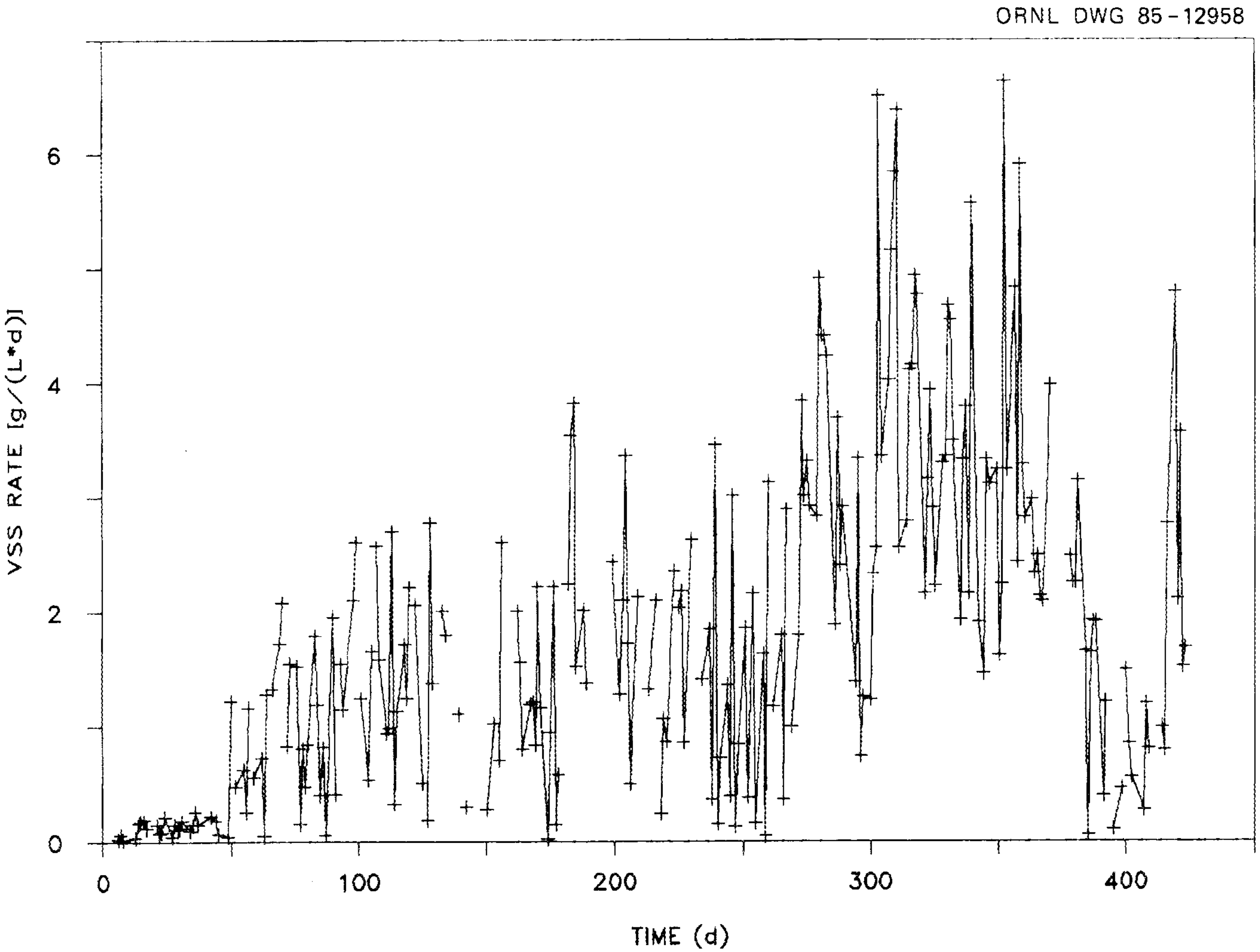

Fig. 11. Volatile solids degradation rate for the digester for Run 3.

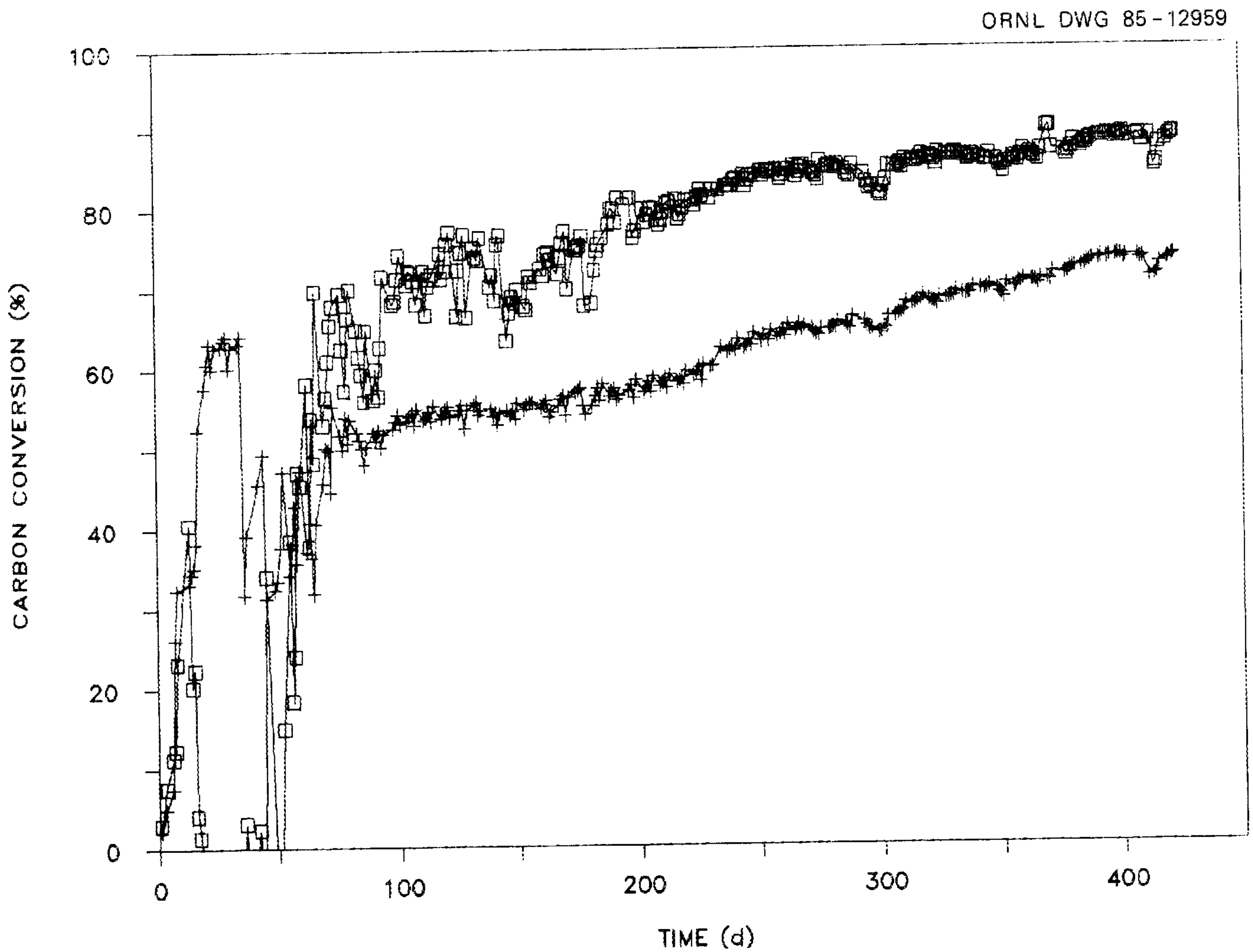

Fig. 12. Conversion of solids to gas and total conversion of solids to gas and soluble carbon. Legend: + = conversion to gas; □ = total conversion.

Figure 8 shows the experimental results for the digester solids determinations for VSS, TSS, and inert suspended solids (ISS). The ISS value is the difference between the TSS and VSS values. The data show considerable scatter, primarily because of the difficulty in obtaining a representative sample of the contents after the digester had been fed. This problem is caused by large clumps of solids. The large peaks that occur gradually result from increased feed rate or feed concentration and are the expected behavior. The digester becomes acclimated to the higher feed rates, and then the VSS and TSS values decrease and tend to stabilize. The ISS values increased during feeding of the simulated waste but decreased when Solka-Floc was fed instead. The ISS values were also used to determine whether representative samples had been obtained because the ISS should be relatively constant from day to day.

The soluble COD (see Fig. 9) measured on centrifuged, filtered samples, was a measure of the amount of cellulose that was solublized but not yet converted to CH_4 or CO_2. The TVA, although a part of the COD, was not a large fraction after the first 200 d. After recycle operation commenced, the COD increased but was not associated with a concurrent rise in the amount of measured TVA present.

Figure 10 is a graph of the gas production rate. A peak of almost 6 L/L•d was reached, but typically the rates varied from 0.5 to ~4.0 L/L•d. The high values amounted to >250 L of gas from the digester in a day. The associated solids degradation rates, shown in Fig. 11, are more erratic than the gas rates because they are calculated from the experimentally measured values of VSS. The rates varied from ~0.8 to 2.0 g/L•d during the first 300 d of the run, and from 2.0 to 6.5 g/L•d from

~300 to 400 d. Figures 8, 10, and 11 show the cyclical nature of the batch-fed operation as the fine structure on the plots. The gas and solids rates and the VSS concentration initially increase after feeding and then gradually decrease until the next feeding.

Figure 12 shows the conversion of the solids to gas and the total conversion of solids to gas and soluble carbon during the progress of the run. The first 100 d are the start-up period, after which the digester conversion steadily increases up to the end of the run. The conversion to gas reaches almost 80%, while the total solids destruction ends at a point where almost 90% of the total cellulose has been converted to a soluble carbon or gaseous product.

Several short- and long-term experiments were conducted during the extended run. Among these was an experiment designed to simulate the operation of the digester with recycle of the supernatant from an effluent settling step to provide the liquid to slurry the entering feed. The experiment was performed by saving all of the extra effluent from the digester in a cold room at 4°C in a 50-L barrel, where it was allowed to settle. The scum was skimmed off the top with a 4-mesh screen, and the supernatant was used to suspend Solka-Floc for feeding the digester. The scum (undigested cloth fragments, string, etc.) and the solids from the bottom of the barrel were reserved for grout formulation studies. The recycle experiment was run during days 216 through 341 (125 d). During this time, a total of 23.8 kg of cellulose solids was fed, including 1.7 kg of prepared simulated feed and 22.1 kg of Solka-Floc after the supply of simulated waste was exhausted. An interesting representation of total liquid recycle operation can be obtained via comparison with a batch reactor which is fed an equivalent amount of cellulose. In this case, the batch digester would initially require 23.8 kg of feed in 58.7 L (a solids concentration of 40.58% w/v). The batch-fed, liquid-recycle digester required 125 d to process this much feed.

During the recycle operation, the soluble organic fraction (soluble COD) of the digester contents increased after daily feedings were begun at day 269; however, the increase was apparently not caused by an increase in the volatile acids that were measured (see Fig. 13). The peaks in the TVA graph coincide with the beginning of daily feeding (day 269) and the aftermath of the incident described earlier in which a rupture disk was blown. Some oxygen contamination of the digester then occurred, and a general upset followed. A period of several days was required to recover the rates and concentrations that were present before the incident.

Another test involved the deliberate starvation of the digester for a period of 17 d near the end of the 423-d run. When samples were withdrawn, an equal volume of water was added; on two days, a mineral-nutrient solution was added. The digester was fed twice during the 2 weeks that followed; then it was fed 1500 g of Solka-Floc at one time. The gas and solids degradation rates were monitored over the next several days until the digester was shut down. The results, shown in Figs. 14–17, show that the digester was responsive to the feedings and produced high gas rates after the 1500-g feeding. The solid line in Fig. 17 is the model simulation (described later).

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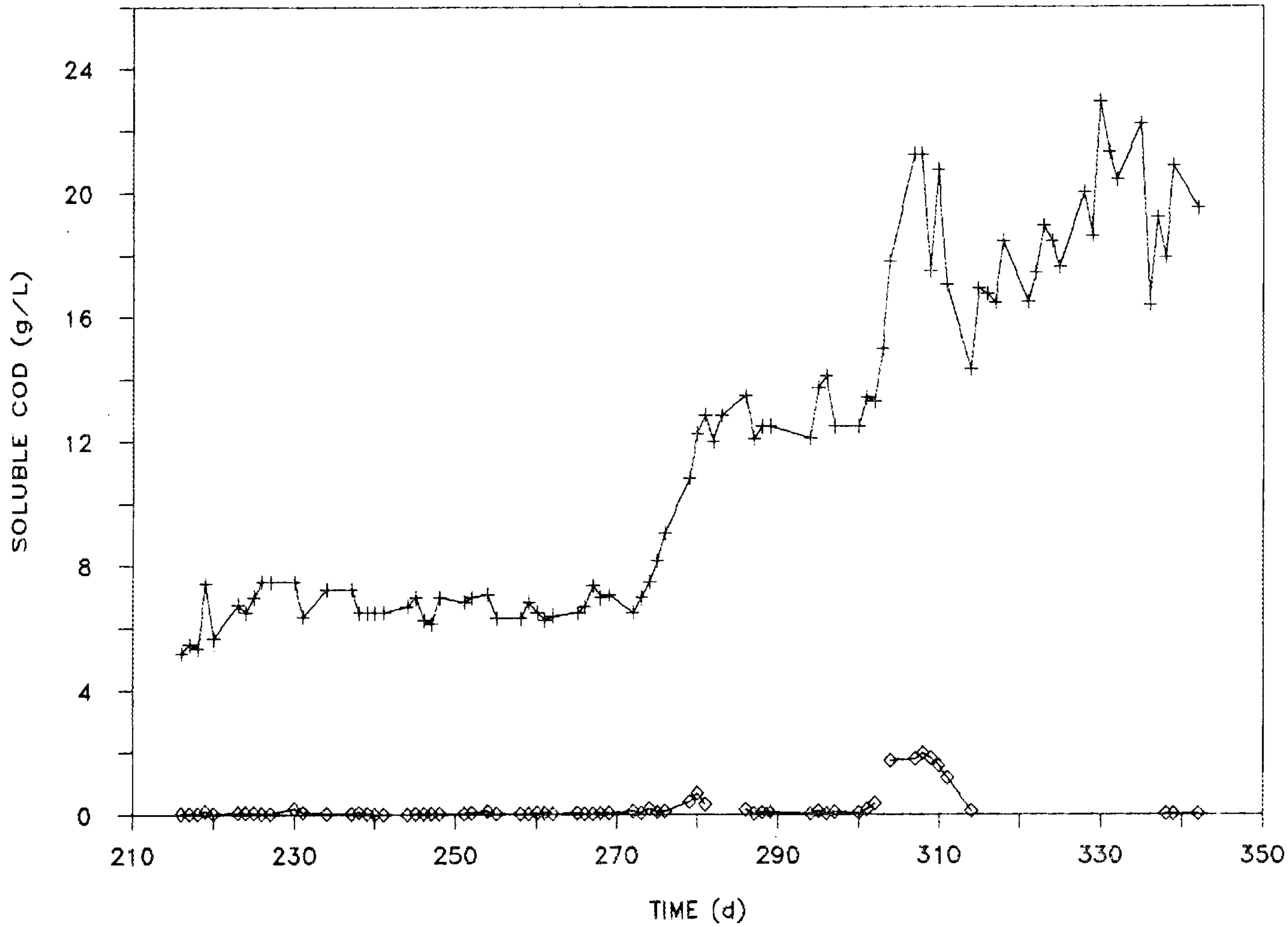

Fig. 13. Soluble COD and TVA response to digester operation on effluent recycle. Legend: + = COD; ◇ = TVA.

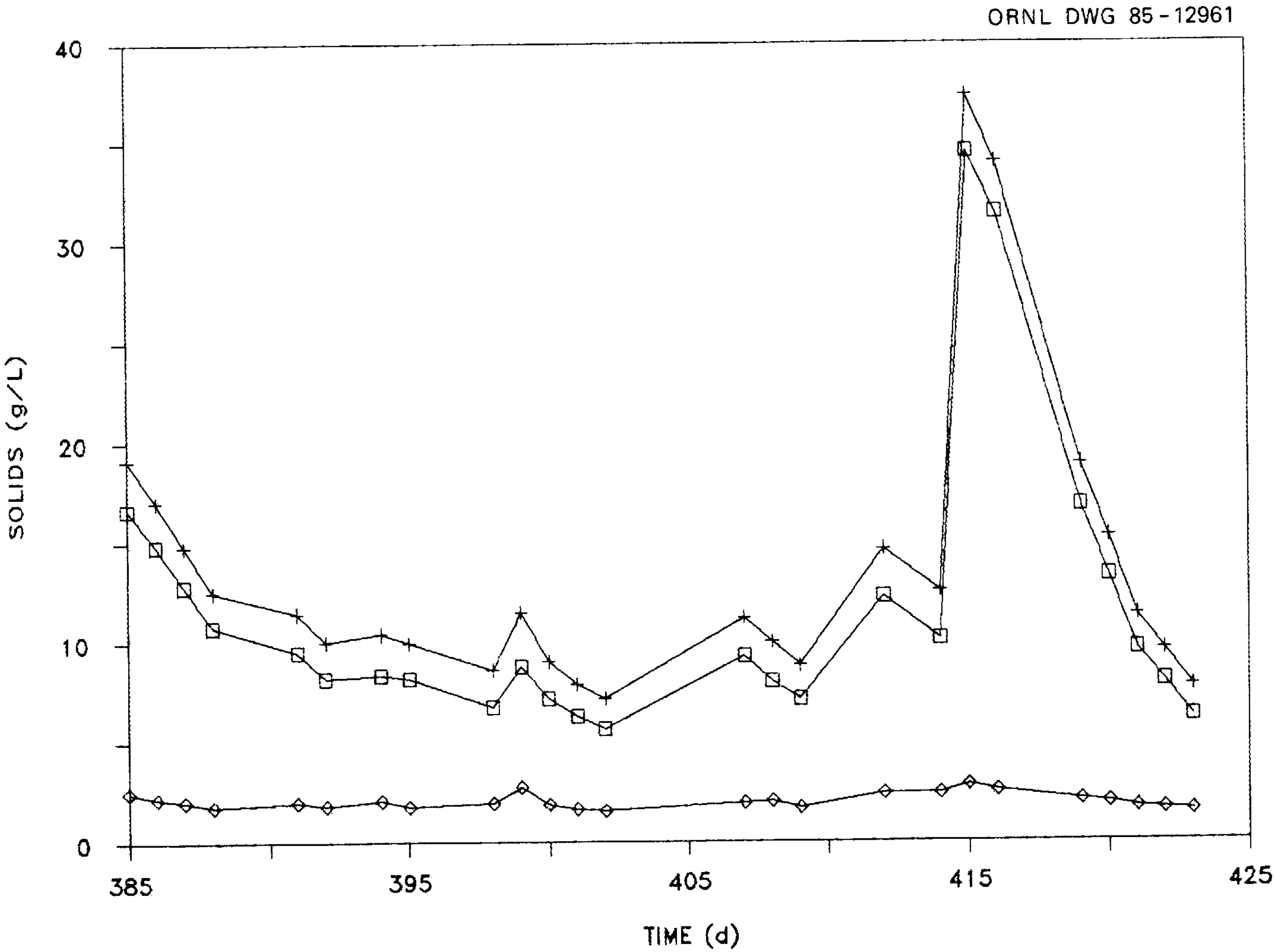

Fig. 14. Digester solids during starvation and pulse feed test.
Legend: + = TSS; □ = VSS; ◇ = ISS.

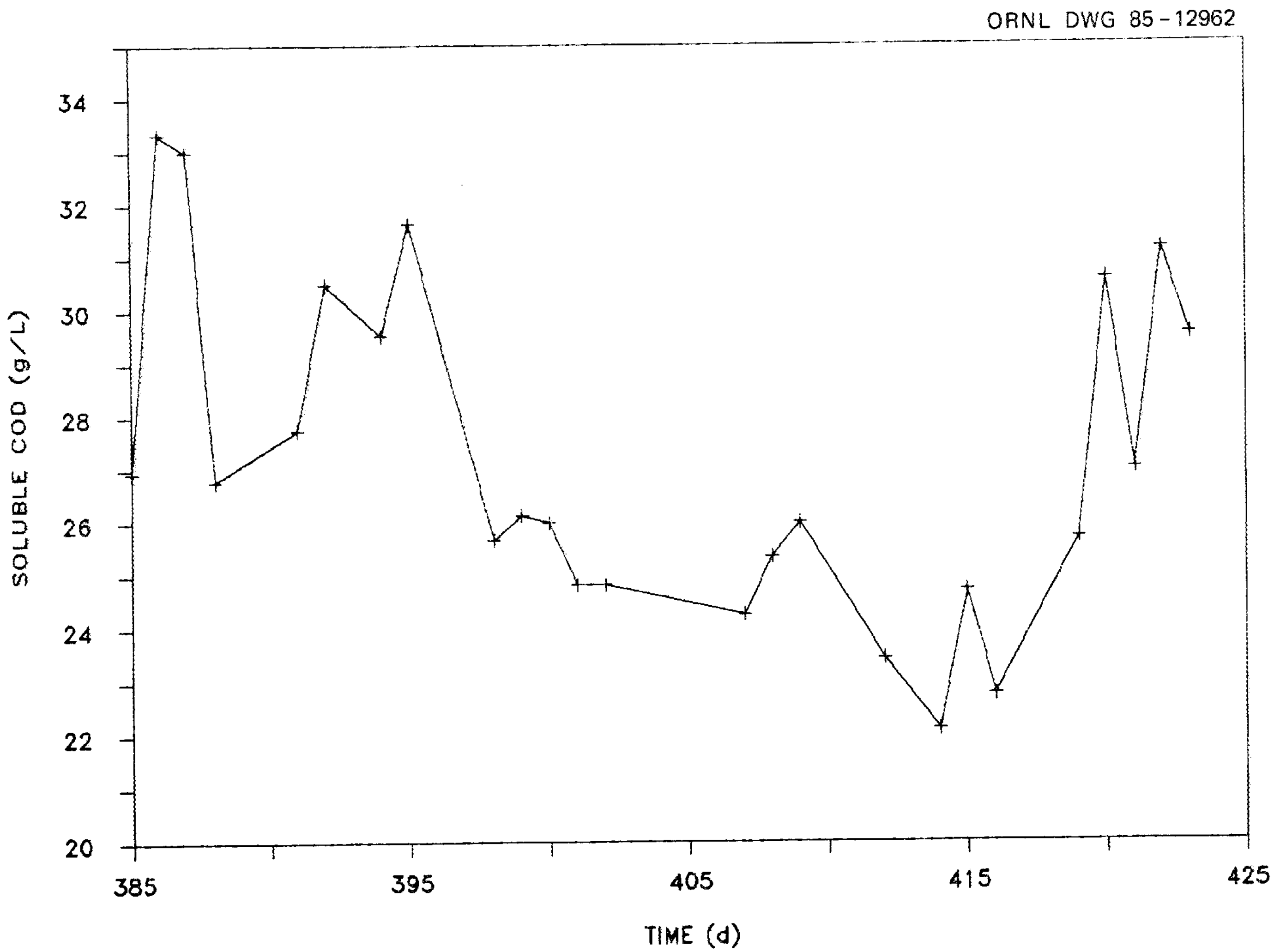

Fig. 15. Digester soluble COD during starvation and pulse feed test.

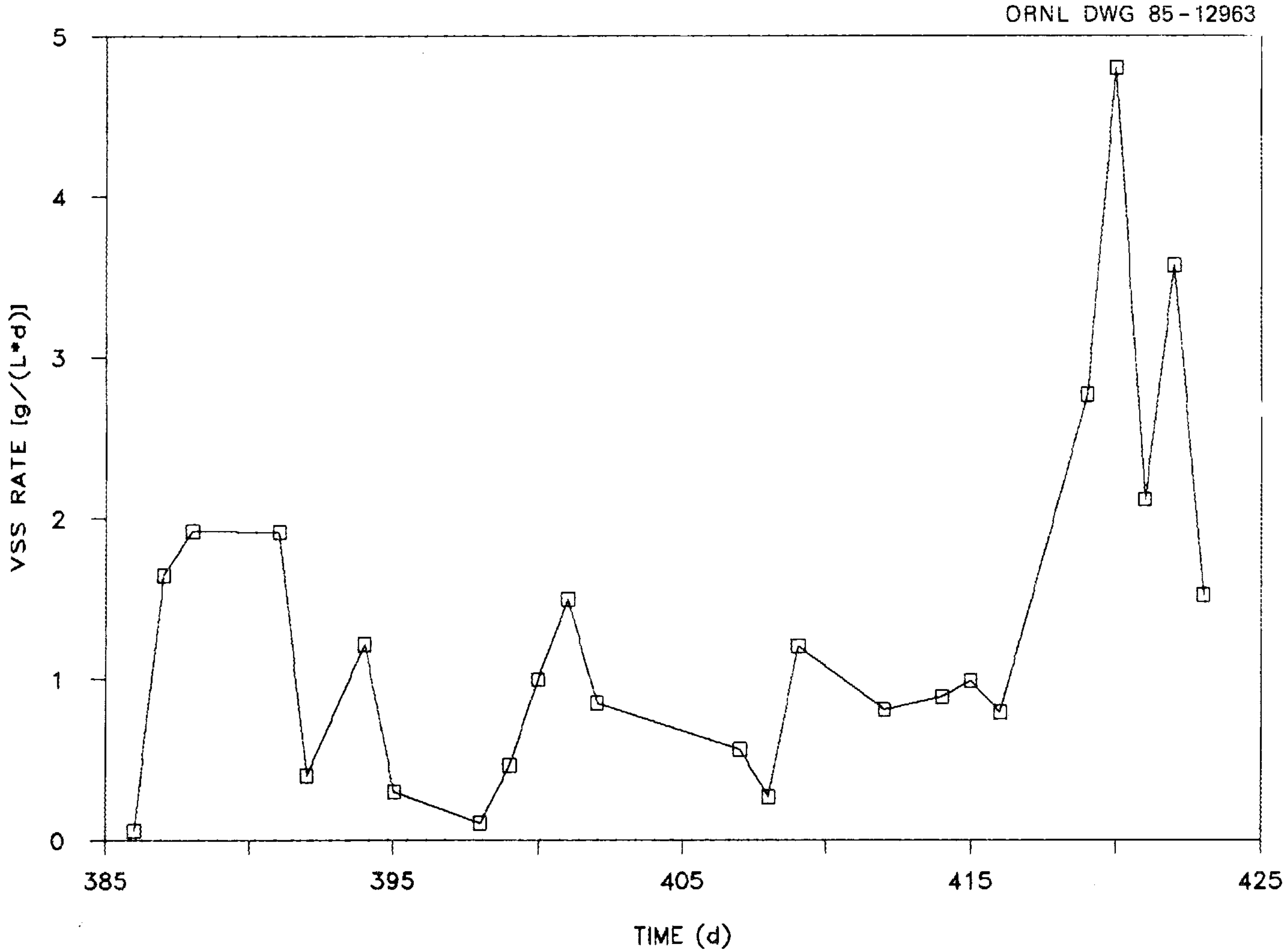

Fig. 16. Digester VSS destruction rate during starvation and pulse feed test.

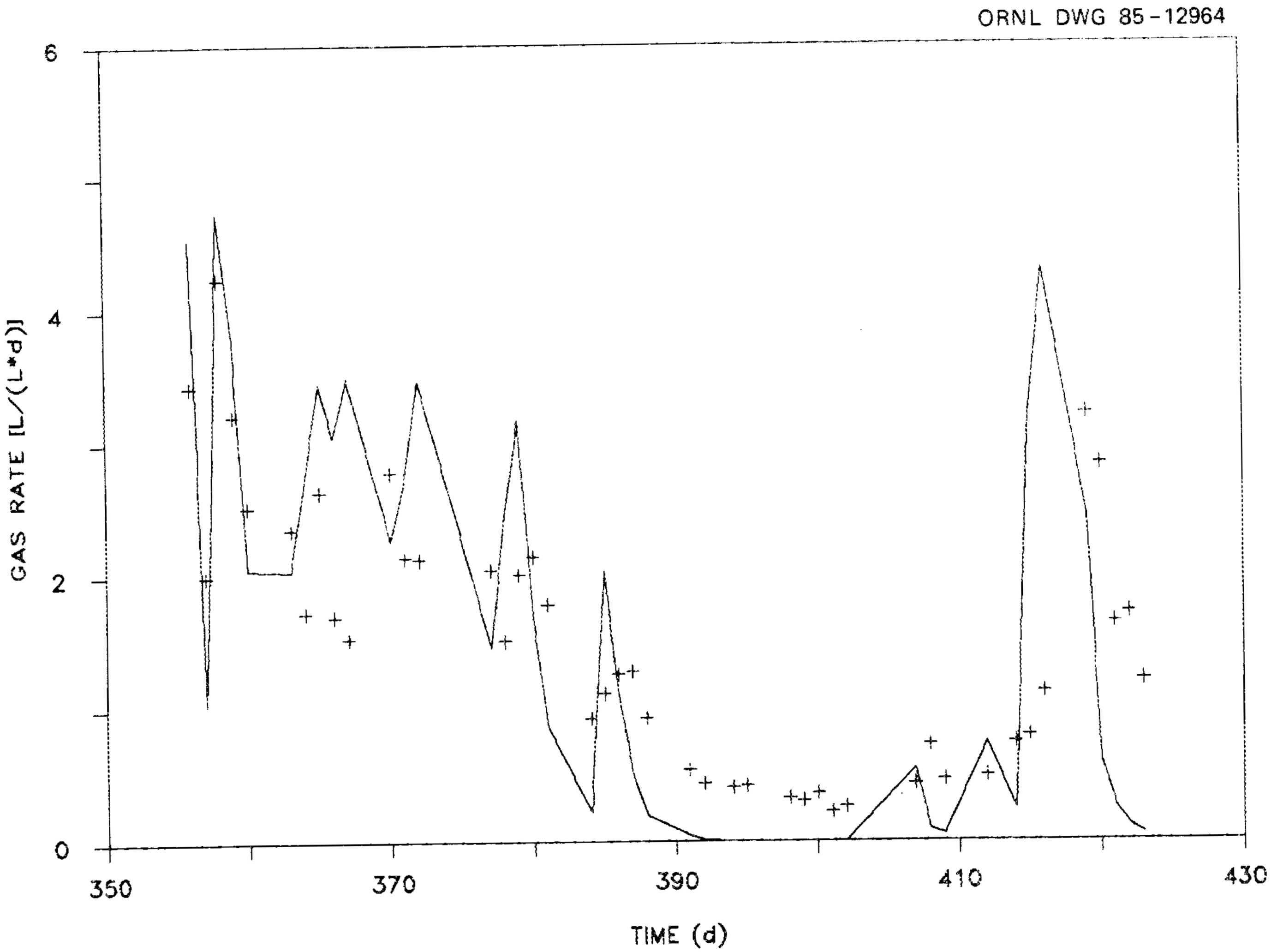

Fig. 17. Digester gas production rate during starvation and pulse feed test. Legend: + = gas rate data points; ——— = simulation of the digester operation.

4. EFFLUENT DISPOSAL STUDIES

Two options for disposing of the liquid and sludge effluents have been proposed for the ORNL facility (Fig. 2). The first is hydrofracture, using the existing facility at ORNL. This option is believed to be technically feasible, although there are questions concerning pumpability and potential plugging of the injection slot by the undigested solids. A suitable grout recipe could probably be developed. Such questions would need to be resolved through further experimental studies. However, hydrofracture is not being actively considered at this time because of the uncertainty concerning continued operation of the hydrofracture facility.

The second option for effluent disposal is fixation of the sludge in concrete for burial and treatment of the liquid effluent in the low-level waste evaporator system. A solids-liquid separation would be carried out to give a sludge with satisfactory water content for cement formation and a liquid with satisfactory properties for the evaporator system. Initial studies to characterize the liquid fraction were made.

Issues to be addressed for treatment of the liquid by evaporation include the physical behavior during evaporation (e.g., foaming), carry-over of organics to the condensate, and the nature of the residual concentrate. Studies have shown that the pH of the digester effluent is ~7 and that the concentration of weak organic acids ranges up to 0.15 N. The acid concentration can be reduced through improved operation of the digester. After neutralization to pH 10, the liquid foams excessively at the boiling point, but the foaming can be controlled with antifoam. In the waste evaporator system, the digester effluent would be diluted with other wastes, which should minimize foaming.

Measurements of pH, COD, total and inorganic carbon, and TVA in the digester effluent, the concentrate, and several condensate fractions are shown in Table 3 for two separate liquid samples. The first sample was taken before the digester began to actively convert the higher acids to CH_4 and CO_2; the second was taken some time after the conversion began. It can be seen that most of the COD and acids remain in the concentrate residue, although some lighter acids may be carried into the condensate. Based on these studies, it has been predicted that the addition of digester effluent to the evaporator system will have no adverse effects on the water quality of White Oak Creek.[5]

Studies on fixation of the solids in concrete have not been completed, but personnel experienced in that area have indicated that no unusual problems are to be expected.

5. PROCESS SIMULATION

5.1 DESCRIPTION OF MODEL

A dynamic three-culture simulation model, corresponding to the three major bioconversion steps shown in Fig. 1, has been developed to aid in process development work. In the model, the cellulose hydrolyzers convert cellulose to sugars, the acetogens convert sugars to acetic acid and a small amount of other products, and the methanogens convert acetic acid to CH_4 and CO_2. In addition, each culture generates cell mass from its own substrate and produces CO_2 as a metabolic by-product. Note that the H_2 + CO_2 route to methane is not included. We have found it unnecessary to include the latter process in order to simulate our data in a satisfactory manner. An extended discussion of the model structure and parameters can be found in ref. 3.

Table 3. Characterization of effluent fractions following evaporation and concentration

Sample	pH	Chemical oxygen demand (mg/L)	Total carbon (mg/L)	Inorganic carbon (mg/L)	Volatile acids as acetic acid[a] (mg/L)
Sample 1, September 1983					
Original effluent	6.43	13,200[b]	9,470		1,060
Concentrate	10.21	16,500	4,735		
First condensate fraction (20 mL)	9.95	460	4,090	4,000	24
Second condensate fraction (250 mL)	9.05	140	420	400	18
Third condensate fraction (250 mL)	8.10	90	120	100	14
Sample 2, September 1984					
Original effluent	6.70	5,400			550
Concentrate		73,200			175
First condensate		175	205	100	30
Second condensate		163	110	50	26
Third condensate		78	35	10	16
Fourth condensate		75	32	0	38
Fifth condensate[c]		750	340	70	50
Composite (1–4)		120	170	120	27

[a]The first and second condensate samples in Sample 1 contained some lower-boiling organics, such as formic acid, that were not resolved.

[b]This sample contained solids that were included in the chemical oxygen demand. The others were clear liquids. Similar samples with no solids contained 7000 to 8000 mg/L of COD.

[c]This sample contained some of the bottoms that "burped over" during evaporation.

5.2 SIMULATION RESULTS

Experimental data and simulation results are compared in Figs. 17–20. Figure 17 shows the gas production rate data for the experiment and simulation for a 70-d period during which the digester was starved and then fed a single large concentration of cellulose. The simulation follows the experimental data semiquantitativily, although the peaks and valleys are more exaggerated. The gas rate in the simulation falls to zero about a week after the starvation period begins, while the experimental rate never does fall all the way to zero. The simulation also predicts a higher peak for the gas rate after feeding the large concentration of cellulose. In general, the simulation predicts a faster response to perturbations than is produced in the digester.

Figure 18 shows the long-term behavior of volatile solids in the digester for the duration of the 423-d run. In the simulation, the actual feed input to the experimental digester was used as the simulation batch feed and the corresponding effluent was calculated from simulated conditions in the digester just prior to feeding. Thus, variations in the experimental and simulated feed curves are due to differences in the effluent concentrations observed experimentally and calculated in the simulation.

The volatile solids parameter shown in Fig. 18 is a combination of microorganisms, undigestibles, and cellulose. This parameter is difficult to measure accurately in the digester because of the difficulty in obtaining a representative sample of the larger suspended particulate solids, as discussed earlier. For this reason, more variation is present in the experimental data than is seen in the simulation.

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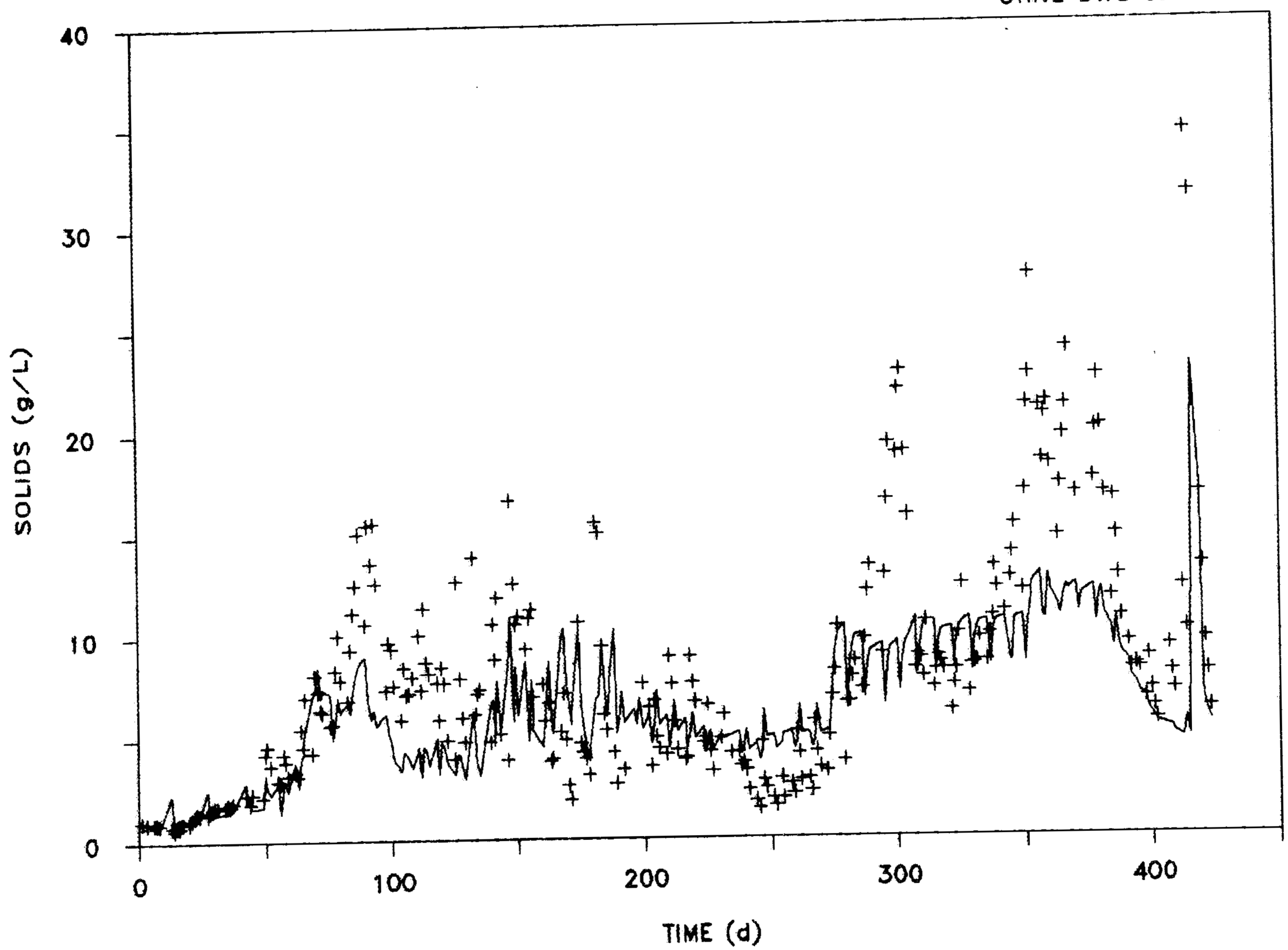

Fig. 18. Comparison of experimental and simulated VSS. Legend: + = experimental data; ——— = simulation.

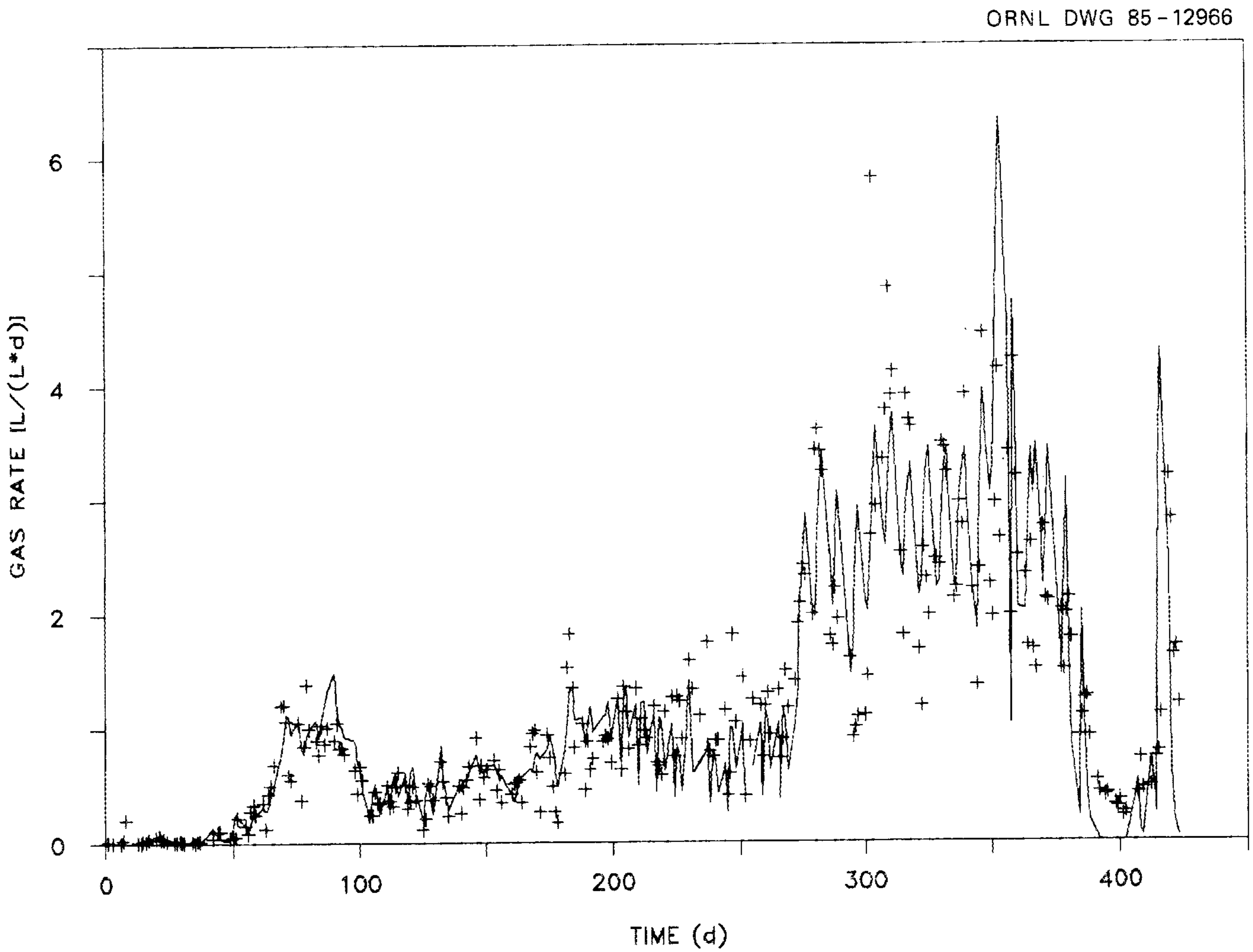

Fig. 19. Comparison of the experimental and simulated gas production rates. Legend: + = data; ——— = simulation.

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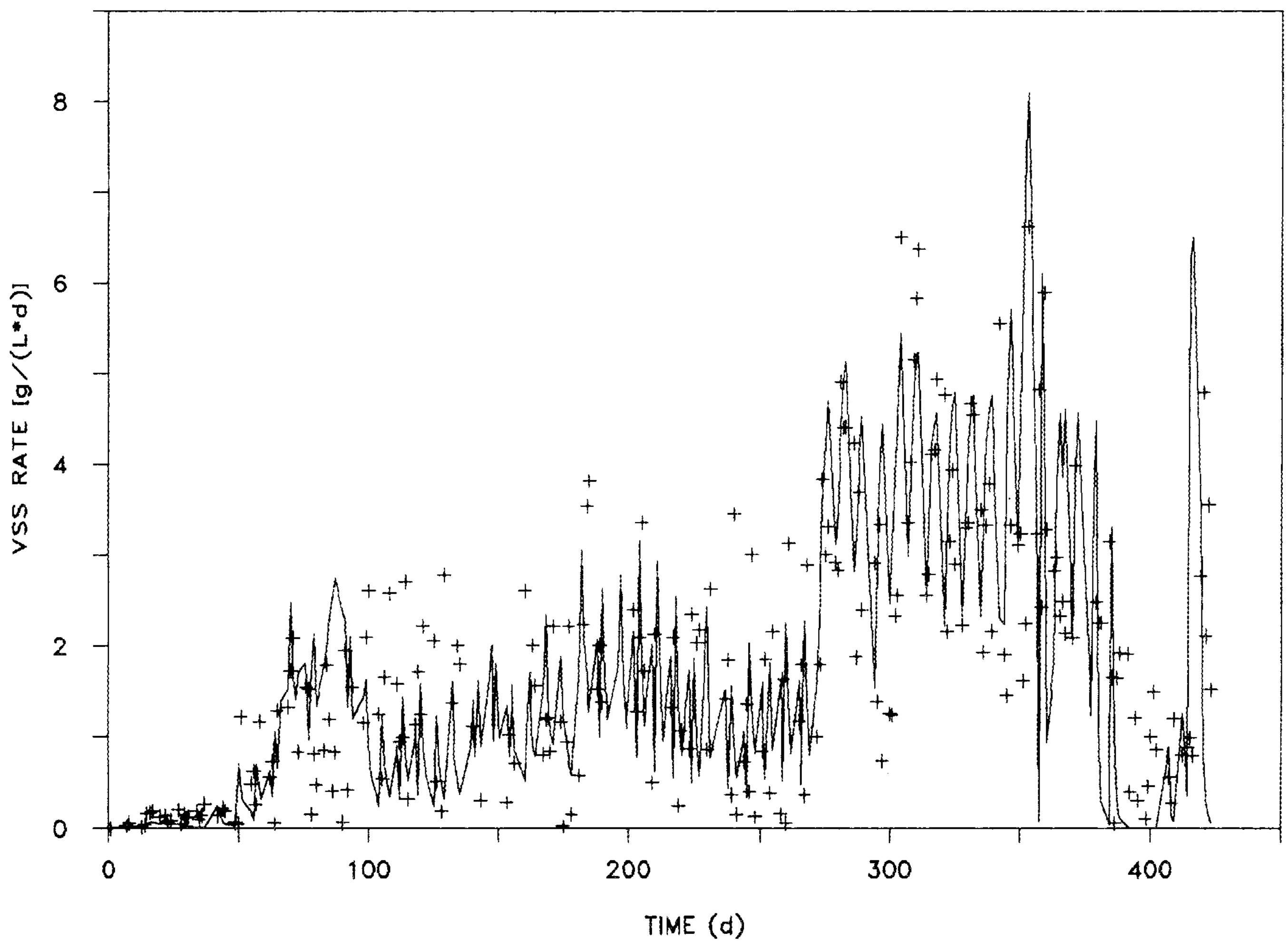

Fig. 20. Comparison of the experimental and simulated solids degradation rates. Legend: + = data; ——— = simulation.

The simulation data were printed out using the same basis as that used for the experimental data. For example, the gas production was totaled for a period and then divided by the length of the period to give an average rate for the interval, analogous to the experimental data. The rates are therefore integrated averages and not instantaneous values for a given time. This method causes considerable smoothing of the simulation data.

No particular effort was made to adjust parameters in the model to fit the experimental data, with the exception of the fractions of sugar converted to acetic acid and "other" soluble carbon. The parameters[3] used in the simulation were obtained primarily from published reports. They were held constant throughout the 423-d period of the simulation.

Figure 19 shows the long-term behavior of the gas production rate for the duration of the run. The first 40 d constituted a start-up period with negligible gas production. The gas production rate was calculated by dividing the total gas produced for a period by the length of the period and then dividing by the current digester volume. The simulation gas rate was calculated by adding the CH_4 and CO_2 produced for a given period and dividing by the length of that period and the volume of the digester. The agreement between the experimental data and the simulation is semiquantitative in both frequency and amplitude.

Figure 20 shows a comparison of the experimental and simulated solids degradation rates. The rates were computed for the experimental data by subtracting the VSS value for the current day from the VSS of the previous day (after adding the feed and subtracting the sample from the previous day) and then dividing by the elapsed time. This method resulted in some scatter because of the problems mentioned previously in obtaining a representative sample of the VSS each day. The VSS for the simulation was calculated by adding the biomass for the cellulose, inerts, and organisms provided by the simulation for each day and then proceeding as for the experimental data at the same time intervals, with the same volumes of feed and effluent and the same feed cellulose content.

6. SUMMARY

The process development work on this project has led to the following accomplishments, observations, and conclusions:

1. Rates and yields obtained in earlier scouting studies have been verified at a nominal 75-L scale. The solids degradation rate, the gas production rate, and the extent of solids degradation have substantially exceeded the original design values used in the preliminary design of the ORNL facility.[2] A reduction in equipment size or an increase in throughput capacity by a factor of ~2 is indicated.
2. Start-up procedures have been developed and tested for the case of sewage sludge inocula. A relatively low concentration of cellulosics (~0.1%) and supplementation with methanol are desirable to avoid inhibition by reaction intermediates and to promote establishment of the proper organisms. The time required for start-up, 1 to 2 months, appears to be satisfactory from a practical standpoint.

3. The digester was operated for an extended period of time with varied feed composition and feed rate under conditions of almost total recycle of the digester effluent supernatant. The digester was able to tolerate and recover from process upsets with little loss of efficiency under all tested conditions.
4. A simple dynamic process model has been developed that satisfactorily simulates the experimental dynamic behavior under stable operating conditions, as well as some process upset conditions. The value of this model lies in its utility for process control and operational guidance for a full-scale digester.
5. The digester was operated for more than 4 months using a recycle condition in which the liquid fraction of the effluent was recycled to slurry the feed, thereby reducing the quantity of liquid effluent for disposal. That procedure resulted in somewhat higher concentrations of the soluble carbon species, but the solids digestion rates were not noticeably inhibited by their presence.
6. The digester was stressed by starvation (no cellulose feed for up to 2 weeks) and feeding a high cellulose concentration (five times the normal daily feed amount) with no apparent ill effects. Another stress involved the lack of micronutrients (usually supplied once or twice each week with a feeding), and that procedure resulted in a slowing of the rates of gas production and VSS degradation. The digester recovered rapidly when the nutrients were reintroduced.
7. The digester was operated periodically at 1.5 to 2.5% volatile solids with no apparent problems except for a foaming problem that occurred at the high gas rates and occasionally carried foam and

solids into the off-gas system and plugged the wet-test meter. The foaming could be controlled by the addition of a suitable antifoam agent.

7. ACKNOWLEDGMENTS

S. N. Lewis performed many of the analyses on the digester contents and assisted in the operation of the digester. G. W. Strandberg frequently provided valuable technical advice. The effluent characterization studies were performed by J. M. Chilton and coordinated by B. D. Patton. The cellulosic feedstock was wet-shredded free of charge by American Delphi, Inc., Westminster, California.

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APPENDIX: EXPERIMENTAL DATA

Day	Feed In, g	Sludge In, mol C	Digest Vol. L	Eff. Out, L	Vol. Fed, L	C fed mol	TSS mg/L	VSS mg/L	Gas L	Alk mg/L	TVA mg/L	VA/ALK	pH	Sol COD mg/L	HRT d
1	70	0.00	65.00	0.35	0.00	2.60	1625	979	0.63	1065	120	0.113	6.96	850	
3	0	0.00	64.65	0.35	0.00	2.60	1353	942	0.77	1270	391	0.308	7.03	875	
6	0	0.00	64.30	0.35	0.00	2.60	1576	896	1.85	1578	433	0.274	7.04	925	
7	0	0.00	63.94	0.36	0.00	2.60	1486	860	1.65	1765	342	0.194	6.98	725	
8	3	0.11	65.34	2.35	3.75	2.76	1564	851	13.32	1695	358	0.211	6.92	725	17.42
13	0	0.00	64.99	0.35	0.00	2.76	1243	739	4.28	1908	345	0.181	6.80	488	
14	0	0.32	65.64	0.35	1.00	2.77	1171	554	0.61	2320	301	0.130	6.89	625	65.64
15	0	0.32	65.39	1.25	1.00	2.78	1234	756	1.02	2093	352	0.168	7.31	762	65.39
16	0	0.32	65.39	1.00	1.00	2.80	1417	727	0.70	2233	297	0.133	7.35	762	65.39
17	0	0.00	65.04	0.35	0.00	2.80	1603	918	2.14	2270	289	0.127	7.41	538	
20	0	0.32	65.04	1.00	1.00	2.81	1719	938	10.15	2193	164	0.075	7.29	656	65.04
21	0	0.32	65.04	1.00	1.00	2.83	2032	1069	3.97	2410	120	0.050	7.40	1031	65.04
22	0	0.32	65.04	1.00	1.00	2.84	2200	1244	2.40	2565	56	0.022	7.53	500	65.04
23	0	0.32	65.04	1.00	1.00	2.85	2312	1385	2.05	2783	35	0.013	7.55	1188	65.04
24	6	0.11	65.04	4.00	4.00	3.07	2353	1347	1.06	2560	72	0.028	7.55	1125	16.26
27	0	0.32	65.04	1.00	1.00	3.09	2323	1322	2.28	2453	68	0.028	7.44	531	65.04
28	0	0.32	65.04	1.00	1.00	3.10	2603	1461	0.41	2568	52	0.020	7.44	719	65.04
29	0	0.32	65.04	1.00	1.00	3.12	2763	1568	0.73	2623	53	0.020	7.41	656	65.04
30	0	0.32	65.04	1.00	1.00	3.13	2949	1678	0.67	2423	67	0.028	7.45	656	65.04
31	6	0.43	65.04	5.00	5.00	3.37	2960	1689	0.36	2697	107	0.040	7.45	656	13.01
34	0	0.32	65.04	1.00	1.00	3.38	2986	1710	2.52	2535	10	0.004	7.44	594	65.04
35	0	0.32	65.04	1.00	1.00	3.39	3201	1821	0.58	2405	22	0.009	7.33	313	65.04
36	0	0.32	65.04	1.00	1.00	3.41	3098	1709	0.97	2223	20	0.009	7.41	688	65.04
37	97	0.00	65.04	4.00	4.00	7.01	3353	1884	0.87	2193	122	0.056	7.41	313	16.26
42	0	0.32	65.04	1.00	1.00	7.02	3596	2242	13.32	2443	557	0.228	6.98	750	65.04
44	0	0.32	65.04	1.00	1.00	7.04	3392	1853	11.66	2348	300	0.128	7.05	750	65.04
45	0	0.32	65.04	1.00	1.00	7.05	3836	2281	6.64	2385	41	0.017	7.05	1000	65.04
49	146	0.73	65.04	5.00	5.00	12.48	3580	2159	11.13	2462	106	0.043	7.10	1300	13.01
50	0	0.00	64.67	0.37	0.00	12.48	6182	4269	3.12	1942	100	0.051	7.24	1300	
51	0	0.00	64.32	0.35	0.00	12.48	6410	4637	3.43	2222	200	0.090	7.06	1875	
52	0	1.46	65.04	1.28	2.00	12.55	5575	3700	14.12	2118	288	0.136	6.90	2750	32.52
55	0	0.00	64.67	0.37	0.00	12.55	4925	2951	30.00	3178	200	0.063	6.82	2188	
56	146	0.00	65.07	3.61	4.00	17.95	4800	2910	5.44	2675	156	0.058	6.95	2750	16.27
57	0	0.00	64.71	0.36	0.00	17.95	6160	4260	17.93	2845	270	0.095	7.01	1795	
58	0	0.00	64.34	0.37	0.00	17.95	5800	3880	21.24	2955	374	0.127	6.83	1627	
59	146	0.00	65.07	3.28	4.00	23.35	5100	3200	16.04	2362	271	0.115	7.12	1011	16.27
62	0	0.00	64.41	0.66	0.00	23.35	5200	3345	68.20	3345	258	0.077	6.83	1077	
63	194	0.00	65.07	3.34	4.00	30.55	4790	3150	8.10	3235	171	0.053	6.97	1250	16.27
64	0	0.00	64.71	0.36	0.00	30.55	7440	5490	27.36	3065	346	0.113	6.95	1380	
65	194	0.00	65.07	3.64	4.00	37.75	6560	4610	32.56	3115	304	0.098	6.90	1250	16.27
66	292	0.00	65.07	4.00	4.00	48.55	9170	7060	44.50	3407	450	0.132	6.96	1936	16.27
69	340	0.00	65.07	4.10	4.10	61.15	6000	4300	235.60	3355	438	0.131	7.05	634	15.87
70	0	0.00	64.57	0.50	0.00	61.15	10045	8130	78.29	2712	565	0.208	6.90	3182	
71	0	0.00	64.18	0.39	0.00	61.15	9160	7340	68.97	2850	442	0.155	6.60	2584	
72	97	0.00	65.07	3.12	4.00	64.75	8060	6420	39.37	2937	558	0.190	6.75	2681	16.27
73	292	0.00	65.07	4.00	4.00	75.55	7990	6310	36.00	2950	445	0.151	6.69	2238	16.27
76	0	0.00	64.68	0.39	0.00	75.55	7250	5640	204.61	2862	438	0.153	6.85	3907	
77	194	0.00	64.69	3.99	4.00	82.75	7320	5700	24.50	2512	459	0.183	6.80	5118	16.17
78	194	0.00	64.89	3.80	4.00	89.95	10300	8350	55.05	2725	553	0.203	6.82	4211	16.22

Day	Feed In, g	Sludge In,mol C	Digest Vol. L	Eff. Out, L	Vol. Fed, L	C fed mol	TSS mg/L	VSS mg/L	Gas L	Alk mg/L	TVA mg/L	VA/ALK	pH	Sol COD mg/L	HRT d
79	0	0.00	64.54	0.35	0.00	89.95	12100	10100	89.65	3050	575	0.189	6.80	3869	
80	292	0.00	64.42	4.12	4.00	100.76	9840	7880	64.86	2812	521	0.185	6.90	5283	16.11
83	194	0.00	64.35	4.07	4.00	107.96	8500	6910	173.15	2763	532	0.193	6.74	4714	16.09
84	194	0.00	64.28	4.07	4.00	115.16	11320	9370	49.87	2763	498	0.180	6.95	6267	16.07
85	194	0.00	64.28	4.00	4.00	122.36	13200	11200	66.57	2675	408	0.153	6.85	5857	16.07
86	194	0.00	64.22	4.06	4.00	129.56	14680	12550	56.10	2700	434	0.161	6.90	7427	16.06
87	292	0.00	64.14	4.08	4.00	140.36	17100	15100	65.04	2837	550	0.194	6.95	5825	16.04
90	194	0.00	64.14	4.00	4.00	147.56	12180	10620	172.30	2562	599	0.234	7.10	6612	16.04
91	0	0.00	63.50	0.64	0.00	147.56	17300	15500	67.21	2325	710	0.305	6.73	5590	
92	194	0.00	64.14	3.36	4.00	154.76	15700	13600	53.20	2838	739	0.260	6.83	5535	16.04
93	0	0.00	63.49	0.65	0.00	154.76	17400	15600	52.90	2538	766	0.302	6.85	5393	
94	292	0.00	64.14	3.35	4.00	165.56	14340	12660	50.20	2575	811	0.315	6.90	6126	16.04
98	194	0.00	64.14	4.00	4.00	172.76	8510	7390	164.37	2800	959	0.343	6.75	7564	16.04
99	0	0.00	63.22	0.92	0.00	172.76	10800	9730	27.65	2987	970	0.325	7.00	8979	
100	0	0.00	62.76	0.46	0.00	172.76	10600	9420	42.07	2875	1085	0.377	6.70	7696	
101	0	0.00	61.89	0.87	0.00	172.76	8450	7600	34.37	3012	1155	0.383	6.90	7725	
104	194	0.00	63.89	2.00	4.00	179.96	6430	5920	46.46	2812	1303	0.463	6.80	7778	15.97
105	0	0.00	62.95	0.94	0.00	179.96	9160	8490	15.39	2938	1288	0.438	6.90	7220	
106	0	2.78	63.50	0.45	1.00	180.08	7610	7140	28.58	2775	1667	0.601	6.70	9232	63.50
107	0	2.78	63.90	0.60	1.00	180.21	8170	7210	22.57	3063	1663	0.543	6.75	8936	63.90
108	185	2.78	64.22	4.48	4.80	187.17	9160	8020	21.87	3125	1460	0.467	6.70	8747	13.38
111	0	0.00	63.37	0.85	0.00	187.17	11700	10100	96.46	3075	910	0.296	6.80	7022	
112	185	2.78	64.02	4.15	4.80	194.13	8660	7400	23.74	3063	1411	0.461	6.80	7975	13.34
113	0	0.00	63.27	0.75	0.00	194.13	13425	11400	20.76	3338	1295	0.388	6.90	7233	
114	0	0.00	62.52	0.75	0.00	194.13	10200	8750	31.00	3025	1007	0.333	6.80	6181	
115	185	2.78	63.22	4.10	4.80	201.10	9510	8200	39.19	2995	1281	0.428	6.78	5652	13.17
118	0	0.00	62.32	0.90	0.00	201.10	8760	7700	94.49	3038	1315	0.433	6.65	6772	
119	185	2.78	63.02	4.10	4.80	208.06	6750	5920	18.90	2988	1262	0.422	6.80	5656	13.13
120	0	0.00	62.15	0.87	0.00	208.06	9925	8500	22.19	3200	1651	0.516	6.90	7133	
121	0	0.00	61.58	0.57	0.00	208.06	8850	7710	30.44	3125	1776	0.568	6.75	6556	
122	0	0.00	61.13	0.45	0.00	208.06	5740	4910	22.98	3187	1445	0.453	6.88	6687	
125	175	0.00	63.02	1.71	3.60	214.54	4600	3970	22.63	3425	1348	0.394	6.90	7691	17.51
126	0	0.00	62.38	0.64	0.00	214.54	14400	12725	13.28	3400	1279	0.376	7.00	6361	
127	0	0.00	61.48	0.90	0.00	214.54	9050	7950	31.85	3438	1338	0.389	6.90	7362	
128	0	0.00	61.05	0.43	0.00	214.54	6940	5970	30.65	3012	1918	0.637	6.75	7571	
129	369	0.00	63.01	5.64	7.60	228.22	5440	4820	23.90	2950	1925	0.653	6.65	5834	8.29
132	0	0.00	62.14	0.87	0.00	228.22	15300	13900	133.30	2563	2555	0.997	6.40	8272	
133	0	0.00	61.85	0.59	0.30	228.22	7350	6170	33.24	3113	1941	0.624	6.75	8005	206.17
134	0	0.00	61.33	0.52	0.00	228.22	8420	7200	24.42	3612	1724	0.477	6.90	7484	
135	218	0.00	63.01	6.17	7.85	236.28	8560	7360	14.60	3725	1652	0.443	7.00	6817	8.03
139	175	0.00	63.01	8.00	8.00	242.76	5390	4811	125.40	3350	1344	0.401	6.70	6598	7.88
140	0	0.00	62.16	0.85	0.00	242.76	12200	10600	15.77	3188	1123	0.352	6.85	5799	
141	185	0.00	63.01	7.15	8.00	249.60	9900	8860	30.44	2925	1342	0.459	6.80	7006	7.88
142	0	0.00	60.43	2.58	0.00	249.60	13200	11900	33.29	2800	1457	0.520	6.85	5920	
143	292	0.00	63.03	5.40	8.00	260.40	5990	5190	42.45	2900	1794	0.619	6.70	5036	7.88
146	175	0.00	67.03	8.00	12.00	266.88	4460	3900	184.75	2825	1312	0.464	6.75	5756	5.59
147	0	0.00	66.09	0.94	0.00	266.88	18100	16700	25.57	2925	1286	0.440	7.05	4449	
148	185	0.00	67.03	7.06	8.00	273.72	13900	12600	45.54	2875	1169	0.407	6.80	5344	8.38
149	0	0.00	66.31	0.72	0.00	273.72	11900	10600	37.95	2662	1033	0.388	6.85	4876	

Day	Feed In, g	Sludge In, mol C	Digest Vol. L	Eff. Out, L	Vol. Fed, L	C fed mol	TSS mg/L	VSS mg/L	Gas L	Alk mg/L	TVA mg/L	VA/ALK	pH	Sol COD mg/L	HRT d
150	219	0.00	67.03	7.28	8.00	281.83	12600	11000	42.90	2750	1080	0.393	6.73	4604	8.38
153	0	0.00	66.33	0.70	0.00	281.83	10500	9390	143.85	2400	1013	0.422	6.65	4318	
154	175	0.00	67.13	7.20	8.00	288.31	11900	10900	30.82	2487	924	0.372	6.80	3795	8.39
155	0	0.00	66.26	0.87	0.00	288.31	12700	11300	42.45	2475	916	0.370	6.80	5073	
156	0	0.00	65.31	0.95	0.00	288.31	7660	6990	22.90	2515	734	0.292	6.90	5700	
160	219	0.00	65.63	7.68	8.00	296.41	8700	7650	111.76	2300	994	0.432	6.80	3735	8.20
161	175	0.00	67.82	5.81	8.00	302.89	6280	5820	34.90	2400	669	0.279	6.83	4046	8.48
162	0	0.00	66.98	0.84	0.00	302.89	7250	6720	35.46	1988	904	0.455	6.60	2852	
163	0	0.00	66.11	0.87	0.00	302.89	4140	3820	36.41	2520	550	0.218	6.90	3664	
164	350	0.00	68.61	9.50	12.00	315.85	4290	3970	24.10	2738	439	0.160	6.94	2902	5.72
167	257	0.00	68.61	10.00	10.00	325.35	5520	5250	172.11	2200	297	0.135	6.65	3173	6.86
168	0	0.00	67.83	0.78	0.00	325.35	7640	7200	65.05	2013	324	0.161	6.75	2694	
169	0	0.00	67.06	0.77	0.00	325.35	5200	4870	66.42	1875	383	0.204	6.70	3624	
170	0	0.00	66.32	0.74	0.00	325.35	2850	2620	41.20	1838	1	0.001	6.65	2620	
171	439	0.00	68.58	9.94	12.20	341.63	2060	1940	18.31	1875	1	0.001	6.70	3129	5.62
174	0	0.00	67.30	1.28	0.00	341.63	11800	10700	191.67	1750	185	0.106	6.60	3276	
175	0	0.00	66.39	0.91	0.00	341.63	5160	4730	49.65	2025	38	0.019	6.82	3207	
176	0	0.00	63.49	2.90	0.00	341.63	4560	4240	31.38	2138	7	0.003	6.85	2975	
177	0	0.00	62.72	0.77	0.00	341.63	4340	3970	16.86	2200	2	0.001	6.80	2355	
178	389	0.00	66.58	6.14	10.00	356.03	3450	3160	11.55	2200	9	0.004	6.90	1501	6.66
181	437	0.00	68.72	1.86	4.00	372.23	17200	15600	124.18	2012	62	0.031	6.60	2134	17.18
182	0	0.00	66.87	1.85	0.00	372.23	16300	15100	102.60	1638	155	0.095	6.50	2963	
183	0	0.00	65.07	1.80	0.00	372.23	10200	9480	119.60	1413	168	0.119	6.71	3501	
184	0	0.00	64.22	0.85	0.00	372.23	6870	6130	87.12	1288	177	0.137	6.40	4444	
185	389	0.00	66.80	9.42	12.00	386.63	5840	5370	55.60	1438	70	0.049	6.50	3770	5.57
188	0	0.00	65.98	0.82	0.00	386.63	4620	4280	205.30	1400	27	0.019	6.55	3070	
189	348	0.00	68.79	0.78	3.59	399.54	2880	2670	32.00	1474	12	0.008	6.60	3837	19.19
190	0	0.00	68.79	0.00	0.00	399.54			61.00						
191	0	0.00	67.79	1.00	0.00	399.54			43.50						
192	389	0.00	70.23	1.56	4.00	413.94	3750	3388	51.70		40			3672	17.56
196	389	0.00	74.23	0.00	4.00	428.34			263.75						18.56
197	0	0.00	74.23	0.00	0.00	428.34			69.55						
198	0	0.00	74.23	0.00	0.00	428.34			67.17						
199	437	0.00	72.73	6.00	4.50	444.54	8600	7630	50.98		16			4457	16.16
202	0	0.00	69.97	2.76	0.00	444.54	7280	6470	265.36	2213	4	0.002	6.60	5129	
203	408	0.00	58.93	4.89	4.20	459.66	4580	3544	37.78	2013	1	.000	6.70	4793	14.03
204	0	0.00	58.08	0.85	0.00	459.66	7430	6810	79.58	2038	40	0.020	6.60	5664	
205	0	0.00	57.28	0.80	0.00	459.66	5540	4980	65.65	2488	6	0.002	6.75	5166	
206	374	0.00	60.37	0.76	3.85	473.50	4880	4410	49.39	2500	1	.000	6.60	5602	15.70
209	0	0.00	59.63	0.74	0.00	473.50	4560	4130	241.10	2175	39	0.018	6.60	5408	
210	367	0.00	58.60	4.80	3.78	487.10	9700	8950	49.61	2025	28	0.014	6.60	4916	15.52
211	0	0.00	57.85	0.75	0.00	487.10	8300	7620	62.70	2000	40	0.020	6.40	5260	
212	0	0.00	57.05	0.80	0.00	487.10	6300	5750	56.06	2438	12	0.005	6.75	5223	
213	354	0.00	59.29	1.40	3.64	500.21	4810	4340	54.44	2413	35	0.015	6.72	6268	16.29
216	0	0.00	58.44	0.85	0.00	500.21	4250	3890	209.74	2188	25	0.011	6.50	5182	
217	321	0.00	60.87	0.87	3.30	512.09	4400	3970	42.96	2225	11	0.005	6.60	5479	18.45
218	0	0.00	59.67	1.20	0.00	512.09	9730	8940	39.99	2250	14	0.006	6.60	5360	
219	0	0.00	58.77	0.90	0.00	512.09	8520	7690	34.50	2188	72	0.033	6.65	7445	
220	321	0.00	57.22	4.85	3.30	523.97	7450	6700	65.54	2125	20	0.009	6.50	5675	17.34

Day	Feed In, g	Sludge In, mol C	Digest Vol. L	Eff. Out, L	Vol. Fed, L	C fed mol	TSS mg/L	VSS mg/L	Gas L	Alk mg/L	TVA mg/L	VA/ALK	pH	Sol COD mg/L	HRT d
223	0	0.00	56.23	0.99	0.00	523.97	5090	4670	214.00	2250	35	0.016	6.50	6750	
224	214	0.00	57.59	0.84	2.20	531.89	5620	4930	43.55	2225	38	0.017	6.60	6500	26.18
225	0	0.00	56.85	0.74	0.00	531.89	7370	6530	72.74	2125	32	0.015	6.55	7000	
226	0	0.00	55.43	1.42	0.00	531.89	4830	4260	68.62	2175	9	0.004	6.50	7500	
227	500	0.00	57.55	0.88	3.00	550.41	3920	3290	52.05		13		6.50	7500	19.18
230	0	0.00	56.56	1.00	0.00	550.41	5280	4870	270.10		144		6.55	7500	
231	200	0.00	57.60	0.95	2.00	557.83	6940	6090	77.48		43		6.52	6375	28.80
234	300	0.00	58.58	2.02	3.00	568.94	4890	4180	196.33		18		6.65	7250	19.53
237	(S.F.)*	0.00	57.73	0.85	0.00	568.94	4830	4210	304.40		28			7250	
238	200	0.00	58.99	0.74	2.00	576.36	4030	3560	46.81		44			6500	29.50
239	0	0.00	58.15	0.84	0.00	576.36	4050	3710	43.65	2188	26	0.012	6.85	6500	
240	0	0.00	57.25	0.90	0.00	576.36	3790	3330	51.04	2150	4	0.002	6.70	6500	
241	200	0.00	58.23	1.02	2.00	583.77	2700	2350	51.95	2062	6	0.003	6.50	6500	29.12
244	0	0.00	57.45	0.78	0.00	583.77	2010	1770	200.06	2500	4	0.002	6.80	6700	
245	300	0.00	58.63	0.82	2.00	594.88	1660	1440	23.94	2525	7	0.003	6.99	7000	29.32
246	0	0.00	57.79	0.84	0.00	594.88	4960	4710	35.00	2488	8	0.003	6.71	6250	
247	0	0.00	56.96	0.83	0.00	594.88	3030	2810	103.91	2200	16	0.007	6.60	6150	
248	300	0.00	58.19	0.77	2.00	605.99	2660	2420	61.36	2263	18	0.008	6.80	7000	29.10
251	0	0.00	57.33	0.86	0.00	605.99	2140	1920	249.48	2112	13	0.006	6.80	6833	
252	300	0.00	58.30	1.04	2.00	617.11	1740	1550	23.30	2225	39	0.018	6.90	7000	29.15
254	0	0.00	57.41	0.88	0.00	617.11	3140	2910	101.95	1912	69	0.036	6.67	7077	
255	300	0.00	58.87	0.54	2.00	628.22	2190	1940	73.77	2050	20	0.010	6.74	6345	29.44
258	0	0.00	58.08	0.79	0.00	628.22	2900	2630	209.38	1962	15	0.008	6.55	6345	
259	300	0.00	59.27	0.81	2.00	639.33	2410	2160	44.76	1912	14	0.007	6.50	6833	29.64
260	0	0.00	58.41	0.86	0.00	639.33	5440	5210	69.75	1850	34	0.018	6.50	6500	
261	0	0.00	57.77	0.64	0.00	639.33	4410	4120	75.97	1788	37	0.021	6.60	6250	
262	300	0.00	58.96	0.81	2.00	650.44	3060	2830	55.92	1862	18	0.010	6.50	6400	29.48
265	0	0.00	58.22	0.74	0.00	650.44	3230	2930	233.70	2288	31	0.014	6.80	6500	
266	300	0.00	59.36	0.86	2.00	661.55	2520	2280	43.75	2588	18	0.007	6.70	6700	29.68
267	0	0.00	58.63	0.73	0.00	661.55	6010	5750	53.20	2525	19	0.008	6.70	7375	
268	0	0.00	57.87	0.76	0.00	661.55	4570	4230	87.50	2375	34	0.014	6.65	7000	
269	300	0.00	59.09	0.78	2.00	672.66	3740	3400	69.97	2488	34	0.014	6.70	7075	29.55
272	300	0.00	59.09	2.00	2.00	683.77	3575	3232	251.33	2225	89	0.040	6.70	6500	29.55
273	300	0.00	59.09	2.00	2.00	694.88	5316	4967	113.56	2287	37	0.016	6.70	7000	29.55
274	300	0.00	59.09	2.00	2.00	706.00	7260	6935	123.82	2850	143	0.050	6.70	7500	29.55
275	300	0.00	59.09	2.00	2.00	717.11	8816	8242	143.83	2712	66	0.024	6.60	8175	29.55
276	300	0.00	59.09	2.00	2.00	728.22	11100	10380	138.50	2888	89	0.031	6.60	9075	29.55
279	300	0.00	53.52	7.57	2.00	739.33	4176	3752	321.79	2262	326	0.144	6.20	10825	26.76
280	300	0.00	54.77	0.76	2.00	750.44	7306	6624	188.37	1900	557	0.293	6.40	12250	27.38
281	300	0.00	56.00	0.77	2.00	761.56	7385	6664	202.83	2275	250	0.110	6.70	12875	28.00
282	300	0.00	57.28	0.72	2.00	772.67	8550	7911	196.50	2338			6.50	12000	28.64
283	300	0.00	58.66	0.62	2.00	783.78	9254	8641	190.90	1988			6.70	12875	29.33
286	300	0.00	59.91	0.75	2.00	794.89	7749	7312	325.92	1975	137	0.069	6.70	13500	29.96
287	300	0.00	61.24	0.67	2.00	806.00	10290	9781	105.95	1838	24	0.013	6.50	12094	30.62
288	300	0.00	61.24	2.00	2.00	817.12	12650	12125	136.65	1738	48	0.028	6.50	12500	30.62
289	300	0.00	61.24	2.00	2.00	828.23	13800	13340	119.95	2150	52	0.024	6.65	12500	30.62
294	300	0.00	61.24	2.00	2.00	839.34	9469	9046	495.42	2038	28	0.014	6.50	12125	30.62
295	300	0.00	61.24	2.00	2.00	850.45	13487	12950	56.30	2062	76	0.037	6.80	13750	30.62
296	300	0.00	61.24	2.00	2.00	861.56	17087	16600	62.00	2125	21	0.010	6.73	14125	30.62

Day	Feed In, g	Sludge In,mol C	Digest Vol. L	Eff. Out, L	Vol. Fed, L	C fed mol	TSS mg/L	VSS mg/L	Gas L	Alk mg/L	TVA mg/L	VA/ALK	pH	Sol COD mg/L	HRT d
297	300	0.00	61.24	2.00	2.00	872.68	19875	19425	67.44	2188	62	0.028	6.60	12500	30.62
300	300	0.00	61.24	2.00	2.00	883.79	19250	18887	204.40	2338	42	0.018	6.65	12500	30.62
301	300	0.00	61.24	2.00	2.00	894.90	22487	22012	89.30	3163	117	0.037	6.80	13438	30.62
302	300	0.00	61.24	2.00	2.00	906.01	23400	22912	164.90	3000	297	0.099	6.80	13313	30.62
303	300	0.00	47.54	15.70	2.00	917.12	19500	19000	357.10					15000	23.77
304	300	0.00	49.22	0.32	2.00	928.24	16337	15837	145.30	1125	1421	1.263	5.80	17812	24.61
307	300	0.00	50.90	0.32	2.00	939.35	9226	8285	512.97	2750	1487	0.541	6.70	21250	25.45
308	300	0.00	52.70	0.20	2.00	950.46	10082	8764	199.80	2375	1648	0.694	6.50	21250	26.35
309	300	0.00	54.55	0.15	2.00	961.57	10148	8780	265.40	2800	1515	0.541	6.65	17500	27.28
310	300	0.00	56.40	0.15	2.00	972.68	8998	7868	220.90	2775	1304	0.470	6.65	20740	28.20
311	300	0.00	58.20	0.20	2.00	983.80	12380	10598	240.45	2600	972	0.374	6.65	17080	29.10
314	300	0.00	60.05	0.15	2.00	994.91	8297	7337	457.43	3775	68	0.018	6.90	14335	30.03
315	300	0.00	61.90	0.15	2.00	1006.02	9356	8194	112.72	3712			6.85	16958	30.95
316	300	0.00	63.75	0.15	2.00	1017.13	10252	8854	250.50	3038			6.70	16775	31.88
317	300	0.00	63.75	2.00	2.00	1028.24	9679	8595	236.10	2738			6.60	16470	31.88
318	300	0.00	63.75	2.00	2.00	1039.36	9509	8252	232.67	2412			6.60	18483	31.88
321	300	0.00	60.35	5.40	2.00	1050.47	7367	6212	306.10	2375			6.50	16517	30.18
322	300	0.00	60.35	2.00	2.00	1061.58	8456	7466	72.15	2975			6.50	17435	30.18
323	300	0.00	60.35	2.00	2.00	1072.69	9141	8246	155.75	3500			6.75	18964	30.18
324	300	0.00	60.35	2.00	2.00	1083.80	12440	10031	140.27	3913			6.80	18460	30.18
325	300	0.00	60.35	2.00	2.00	1094.92	13375	12437	120.30	3700			6.70	17646	30.18
328	300	0.00	60.35	2.00	2.00	1106.03	8072	7077	449.81	3063			6.70	20024	30.18
329	300	0.00	60.35	2.00	2.00	1117.14	9229	8451	146.90	3038			6.70	18627	30.18
330	300	0.00	60.35	2.00	2.00	1128.25	9434	8462	211.82	3275			6.60	22953	30.18
331	300	0.00	60.35	2.00	2.00	1139.36	9682	8597	209.10	3662			6.80	21331	30.18
332	300	0.00	60.35	2.00	2.00	1150.48	11250	9781	195.76	3825			6.85	20430	30.18
335	300	0.00	60.35	2.00	2.00	1161.59	10507	8622	387.96	3650			6.70	22232	30.18
336	300	0.00	60.35	2.00	2.00	1172.70	11412	9969	135.30	3675			6.70	16404	30.18
337	300	0.00	60.35	2.00	2.00	1183.81	11950	10816	180.06	3262			6.80	19228	30.18
338	300	0.00	60.35	2.00	2.00	1194.92	14650	13262	168.10	4212	20		6.81	17949	30.18
339	300	0.00	60.35	2.00	2.00	1206.04	14100	12225	236.75	4962	20		6.55	20879	30.18
342	300	0.00	60.35	2.00	2.00	1217.15	13283	11055	402.85	4125	21		6.90	19551	30.18
344	300	0.00	60.35	2.00	2.00	1228.26	14550	12725	165.92	4037	20		6.80	19231	30.18
345	300	0.00	60.35	2.00	2.00	1239.37	15662	13937	145.00	3712	23		6.93	15769	30.18
346	400	0.00	60.35	0.50	0.50	1254.19	17375	15325	269.71	3138	34		6.90	17865	120.71
349	400	0.00	60.35	0.50	0.50	1269.00	13525	12087	411.79	3050	19		6.90	10719	120.71
350	400	0.00	60.35	0.50	0.50	1283.82	18587	16987	119.54	3125	28		6.42	15483	120.71
351	500	0.00	60.35	0.50	0.50	1302.34	22112	21225	180.00	3150	46		6.90	14292	120.71
352	500	0.00	60.35	0.50	0.50	1320.86	24662	22700	251.20	2875	252	0.088	6.85	19830	120.71
353	500	0.00	60.35	0.50	0.50	1339.38	29900	27550	160.94	3475	193	0.056	6.90	20247	120.71
356	0	0.00	59.85	0.50	0.00	1339.38	23000	21100	615.90	3062	468	0.153	6.90	21735	
357	500	0.00	59.85	0.50	0.50	1357.90	20150	18487	119.52	3250	262	0.081	6.90	21864	119.71
358	241	0.00	59.85	0.50	0.50	1366.83	22750	20775	254.00	2662	412	0.155	6.65	21559	119.71
359	(B.P.)#	0.00	59.35	0.50	0.00	1366.83	23325	21337	190.40	2475	532	0.215	6.60	24308	
360	328	0.00	59.35	0.50	0.50	1378.98	20175	18325	149.15	2662	408	0.153	6.70	23208	118.71
363	300	0.00	59.35	0.50	0.50	1390.09	16387	14737	418.05	2500	219	0.088	6.80	24247	118.71
364	300	0.00	59.35	0.50	0.50	1401.20	19275	17325	102.20	2800	322	0.115	6.80	26873	118.71
365	224	0.00	59.35	0.50	0.50	1409.50	21762	19737	155.98	2825	532	0.188	6.80	25379	118.71
366	300	0.00	59.35	0.50	0.50	1420.61	23687	21200	100.43	3612	531	0.147	6.50	28144	118.71

Day	Feed In, g	Sludge In, mol C	Digest Vol. L	Eff. Out, L	Vol. Fed, L	C fed mol	TSS mg/L	VSS mg/L	Gas L	Alk mg/L	TVA mg/L	VA/ALK	pH	Sol COD mg/L	HRT d
367	300	0.00	59.35	0.50	0.50	1431.72	26287	23975	90.43	3438	153	0.045	6.90	28633	118.71
370	300	0.00	59.35	0.50	0.50	1442.83	18862	16862	494.50	3038	171	0.056	6.80	31887	118.71
371	300	0.00	59.35	0.00	0.00	1453.94			126.85						
372	300	0.00	59.35	0.00	0.00	1465.06			125.80						
377	300	0.00	59.35	0.50	0.50	1476.17	20575	17600	605.41	4012	84	0.021	6.70	29580	118.71
378	300	0.00	59.35	0.50	0.50	1487.28	22987	20012	90.05	4050	254	0.063	6.90	31067	118.71
379	0	0.00	59.35	0.50	0.50	1487.28	25175	22637	119.30	3625	223	0.062	6.80	31728	118.71
380	0	0.00	59.35	0.50	0.50	1487.28	23012	20187	127.16	2950	233	0.079	6.60	28567	118.71
381	0	0.00	59.35	0.50	0.50	1487.28	19073	16862	105.89	2927	194	0.066	6.80	32462	118.71
384	300	0.00	59.35	0.50	0.50	1498.39	13575	11725	164.94	3962	164	0.041	6.75	32138	118.71
385	0	0.00	59.35	0.50	0.50	1498.39	19100	16625	66.31	3812	207	0.054	6.85	26940	118.71
386	0	0.00	59.35	0.50	0.50	1498.39	17012	14837	74.63	4037	123	0.030	6.85	33338	118.71
387	0	0.00	59.35	0.50	0.50	1498.39	14800	12787	75.75	3475	181	0.052	6.90	33001	118.71
388	0	0.00	59.35	0.50	0.50	1498.39	12512	10761	55.30	3437	105	0.031	6.85	26772	118.71
391	0	0.00	59.35	0.50	0.50	1498.39	11462	9476	96.05	3500	134	0.038	6.90	27755	118.71
392	0	0.00	59.35	0.50	0.50	1498.39	9991	8176	25.89	4050	143	0.035	7.00	30515	118.71
394	0	0.00	59.35	0.50	0.50	1498.39	10437	8364	48.00	3637	90	0.023	6.95	29541	118.71
395	0	0.00	59.35	0.50	0.50	1498.39	9777	8191	24.88	3725	84	0.023	6.95	31651	118.71
398	0	0.00	59.35	0.50	0.50	1498.39	8635	6735	56.98	3988	93	0.023	7.00	25668	118.71
399	0	0.00	59.35	0.50	0.50	1498.39	11474	8756	18.01	3950	82	0.021	7.00	26132	118.71
400	0	0.00	59.35	0.50	0.50	1498.39	9039	7184	21.18	4275	96	0.022	7.00	26010	118.71
401	0	0.00	59.35	0.50	0.50	1498.39	7880	6266	12.92	4275	80	0.019	6.95	24839	118.71
402	300	0.00	59.35	0.50	0.50	1509.50	7176	5650	15.43	4288	90	0.021	6.95	24839	118.71
407	0	0.00	59.35	0.50	0.50	1509.50	11212	9307	127.50	4737	94	0.020	7.00	24254	118.71
408	0	0.00	59.35	0.50	0.50	1509.50	10030	8020	43.10	4788	72	0.015	6.90	25360	118.71
409	300	0.00	59.35	0.50	0.50	1520.62	8822	7141	27.35	4463	70	0.016	6.90	26010	118.71
412	(S.F.)*	0.00	59.35	0.50	0.50	1520.62	14625	12237	86.91	5100	58	0.011	7.00	23427	118.71
414	1500	0.00	59.35	0.50	0.50	1576.18	12537	10146	87.72	4312	43	0.010	6.80	22125	118.71
415	0	0.00	59.35	0.50	0.50	1576.18	37362	34537	47.02	4250	76	0.018	6.90	24728	118.71
416	0	0.00	59.35	0.50	0.50	1576.18	34012	31475	66.50	3950			6.85	22776	118.71
419	0	0.00	55.35	4.50	0.50	1576.18	18887	16812	533.84	2188			6.10	25705	110.71
420	0	0.00	55.35	0.50	0.50	1576.18	15237	13325	156.90	2200			6.30	30585	110.71
421	0	0.00	55.35	0.50	0.50	1576.18	11300	9634	90.70	2175			6.40	27006	110.71
422	0	0.00	56.35	0.50	0.50	1576.18	9602	8022	94.97	2150			6.30	31164	110.71
423	0	0.00	54.65	0.50	0.00	1576.18	7759	6255	66.35	2037			6.30	29541	

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