Technical Completion Report

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TREATMENT OF RECYCLE STREAMS FROM THERMAL SLUDGE CONDITIONING

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ABSTRACT

The thermal conditioning and dewatering of activated sludges in wastewater treatment plants results in decant and filtrate streams that are high in organic matter. Reported COD and BOD_5 values range as high as 30,000 mg/L and 15,000 mg/L, respectively. Although the volume of the recycle flow is small, the high strength may add as much as 20 % or more to the total organic load on the plant.

The purpose of this research was to answer two questions:

1. What is the impact of the recycle of the high-strength waste streams in terms of increased oxygen consumption and sludge production? and,

2. How effective is the anaerobic filter in treating the recycle flow from thermal sludge conditioning and what loading criteria are indicated for such applications?

The anaerobic filter arose from research conducted at Stanford University by Young and McCarty (1,2,3) in the mid 1960s. Since then the process has been applied to a wide variety of wastes, especially those that are high in soluble organic matter. Young applied the anaerobic filter to the treatment of a complex protein-carbohydrate waste and a simple volatile acids waste in upflow beds containing stone with a nominal diameter of 1 to 1-1/2 inches. The filters were six inches in diameter and six feet deep. Young achieved COD removals of 80% at loadings in excess of 100 lb COD/1000 cu ft of filter volume at 25^{o}C (3).

This research was conducted in three inter-related phases as follows:

Phase I: The aerobic biological treatment of the thermal conditioning wastes to determine endogenous decay and sludge yield coefficients for use in Phase III of the research,

Phase II: The anaerobic filter treatment of thermal conditioning wastes from Dubuque and Cedar Rapids, Iowa, in laboratory scale, upflow reactors to determine performance characteristics at various loadings, and

Phase III: The development of a model of the Dubuque treatment system for use in predicting the impact of the recycle stream on the treatment system and in assessing the effectiveness of various degrees of treatment.

Phase I results indicate that the Dubuque, Iowa, thermal conditioning wastes had an average 5-day BOD of 9,600 mg/L and a BOD exertion rate of 0.2063 per day (base 10). This indicates an ultimate to 5-day BOD ratio of 1.1. The studies with aerobic biological reactors indicated that treatment of the thermal conditioning wastes in the activated sludge process would yield sludge in the amount of 0.51 lb VSS per lb of BOD_5 removed and 0.37 lb VSS per lb of COD removed. The endogenous decay coefficient was found to be 0.104 per day.

Phase II results on the application of the anaerobic filter to the Dubuque thermal conditioning wastes indicated that a 20-day BOD removal of 84% could be achieved with a filter eight feet in depth and loaded at a nominal 200 lb of BOD_{20}/1000 cu ft of filter volume. When applied to the thermal conditioning wastes from Cedar Rapids, the 8-ft deep anaerobic filter achieved an 80% BOD_{20} removal when loaded at 244 lb BOD_{20}/1000 cu ft of filter volume. Thus efficiencies of BOD removal were quite comparable for the Dubuque and Cedar Rapids thermal conditioning wastes.

Phase III results indicate that the recycle of thermal conditioning wastes at Dubuque increases the BOD_5 load on the plant by 20.0% of the total plant influent BOD_5 . Treatment of the thermal conditioning liquor with an anaerobic filter to an 85% BOD_{20} removal level would reduce this increase to only three percent. Such anaerobic filter treatment of the recycle wastes would also reduce the increase in sludge production from 25.0% to 14.0%, at

at a constant sludge age of four days. Likewise, oxygen consumption is reduced from an increase of 40.0% without recycle treatment to 14.0% with anaerobic treatment of the recycle stream.

It is concluded that the anaerobic filter is an effective way of treating the high-strength waste from thermal conditioning processes, resulting in significant reductions in oxygen consumption and excess sludge production in activated sludge wastewater treatment plants.

KEY WORDS: Biological Wastewater Treatment; Biological Filter, Anaerobic Bacteria

TREATMENT OF RECYCLE STREAMS
FROM THERMAL SLUDGE CONDITIONING

By Richard R. Dague

INTRODUCTION

It is common practice to thermally condition waste activated sludges in wastewater treatment plants employing incineration. Thermal conditioning (heat treatment) improves the dewaterability of activated sludges, enabling a more favorable heat balance upon incineration and reducing the need for supplementary fuels.

The thermal conditioning and dewatering of waste activated sludges results in decant and filtrate streams that are high in organic matter. Reported chemical oxygen demand (COD) and 5-day biochemical oxygen demand (BOD_5) strengths range from 10,000 mg/L to 30,000 mg/L and 5,000 mg/L to 15,000 mg/L, respectively. These potent liquid streams are commonly recycled to the main liquid stream in the wastewater treatment plant. The volume of the recycle flow is quite small in relation to total plant flow, but the high strength may add 20 percent or more to the total organic load on the plant. This results in increases in energy requirements for aeration and in net sludge production due to the re-synthesis of biomass from the recycled BOD.

It is clear that recycle flows from thermal conditioning operations are quite substantial in their effects on liquid stream treatment processes. What is not so clear is the extent of the impact in terms of increased sludge production and oxygen consumption in activated sludge processes. It is not sufficient to say that the BOD_5 load on a plant is increased by a given percentage as a result of the recycle wastes. One must account for the fact that a portion of the recycled BOD has made several passes through the aeration tank. Also, as a result of differences in BOD exertion rates, a unit of recycled BOD_5 may not be equivalent to a unit of raw plant BOD_5.

The impacts of the recycle of wastes from thermal conditioning are substantial. The question is, "What can be done about it?" Should the recycle wastes be treated in a separate system? Or should the main treatment system be increased in size to account for the extra load? In addition, how significant are recycle flows from thermal conditioning in terms of increased oxygen demand and sludge production in a typical wastewater treatment plant?

The purpose of this research was to answer two questions as follows:

1. What is the true impact of the return of high strength recycle streams from thermal conditioning and dewatering in terms of increased sludge production and oxygen consumption in the activated sludge process?

2. How effective is the anaerobic filter treatment of the recycle flow from thermal sludge conditioning and dewatering operations in the removal of organics and what loading criteria are indicated in the sizing of such a system?

BACKGROUND REPORTS

Historical

The concept of the anaerobic filter arose from research conducted at Stanford University about 18 years ago. A 1966 report by McCarty (1) and a 1967 paper by Young and McCarty (2) presented the new treatment process and the results of research performed by Young for his Ph.D. disseration (3).

In their 1967 paper (2), Young and McCarty coined the term "anaerobic filter" which they described as a rock-filled bed, similar to an aerobic trickling filter, but with the flow being upward through the bed of stones so that the filter is completely submerged.

The pioneering research of Young (3) dealt with the application of the anaerobic filter to the treatment of a complex protein-carbohydrate waste and a simple volatile acids waste in upflow beds containing quartzite stone with a nominal diameter in the 1 to 1½ inch range. The filters were six inches in diameter and six feet deep. Young achieved COD removals of 80% at loadings in excess of 100 lb COD/1000 cu ft of filter volume at 25°C. Loadings as high as 212 lb COD/day/1000 cu ft resulted in a liquid retention time (LRT) as low as 4.5 hours and a COD removal of 60 % (2).

Anaerobic Filter Applications

The anaerobic filter has actually seen only a modest number of applications over the past 15 years. This is somewhat surprising, given its advantages when compared with aerobic processes, especially for the treatment of strong industrial wastes. This lack of applications may be due to deficiencies in understanding of the process among designers and potential users. Also, low energy prices throughout much of the past has provided little impetus to move away from the well-known aerobic processes and toward the relatively unknown anaerobic filter process.

An early application of the anaerobic filter process was that of Plummer, et al., reported in 1968 (4). A low solids carbohydrate waste was treated in submerged anaerobic filters containing a media consisting of a mixture of Raschig rings and berl saddles. The filter media provided an approximate bed porosity of 65 to 70%. The filters were loaded at 101, 237, 438, and 638 lb COD/day/1000 cu.ft. of filter volume providing hydraulic detention times of 83, 60, 21, and 13 hours, respectively. The COD and BOD_5 of the raw waste feed was 8,475 mg/L and 5,200 mg/L, respectively. The COD of the effluents from Units 1, 2, 3, and 4, with increasing COD and BOD_5 loads as indicated above, was 546, 2,405, 4,850, and 5,000 mg/L, respectively, reflecting COD removals of 93.5%, 71.6%, 42.8%, and 41.0%, respectively. Based on BOD_5, the removals for the four units were 81.2%, 70.2%, 28.7%, and 25.2%, respectively, for the low to high load units. Plummer, et al. noted that the rapid evolution of gas in the units could result in short circuiting of raw wastes through the unit. A suggested solution to the problem was the recycle of effluent or the staging of the filter units (4).

Another early application of the anaerobic filter was reported by Richter and Mackie in 1971 (5). A high-strength wheat starch waste was treated with an anaerobic filter with resulting COD removals of 75 to 80% at a low cost of 1.3 cents per pound of BOD applied.

Successful treatment of a brewery press liquor with anaerobic filters was reported by Lovan, et al. in 1971 (6). The wastes were treated in two laboratory-scale filters six inches in diameter and six feet in depth and containing a total volume of 1.18 cu ft. The columns were filled with a crushed limestone (1-1.5 in diameter), resulting in a void volume of 15.2 liters (45% of total bed volume). The anaerobic filters were operated at 35° C. The feed waste was quite strong with COD values ranging from 6,000 to 24,000 mg/L. Another important characteristic of the waste was its low pH, typically in the 3.4 to 4.0 range. At a COD loading of 100 lb/day/1000 cu.ft. removals in excess of 90% were achieved. It was noted that most of the COD removal actually took place in the bottom one foot of the columns, indicating that good removals could have been achieved at a much higher COD loading.

Pharmaceutical wastes were treated with anaerobic filters by Jennett and Dennis (7). The waste was diluted, nutrients were added, and the pH was adjusted prior to feeding to the filter over a load range of 14 to 220 lb COD/day/1000 cu.ft. Removals of COD at 35° C ranged from 94 to 98%.

Shock increases in loading did not cause failure. The filters were operated for six months without need for solids wasting.

The anaerobic filter was applied to the treatment of a vegetable tanning effluent by Arora, et al. and reported on in 1974 (8). At 35° C and a three-day detention time, COD removal was 90%.

Chian and DeWalle applied an anaerobic filter to the treatment of a high-strength, acidic leachate from a landfill (9). The laboratory-scale anaerobic filter used in the studies is illustrated in Figure 1. The filter was made of Plexiglas and had an overall height of 246 cm and an outside diameter of 20.2 cm providing a total volume of 67.8 liters. As illustrated in Figure 1, the filter contains a 1.4 liter headspace above the media, a 2.8 liter inlet section, a 3.8 liter solids collection device, and a 5.2 liter recirculation surge vessel. The plastic filter media provided a high specific surface area (206 m^2/m^3 of filter volume) and a high porosity (94%).

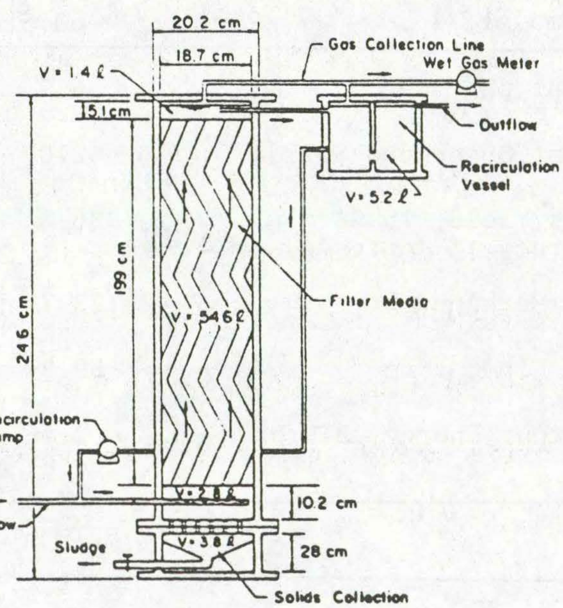

Fig. 1. Anaerobic Filter System Used by Chian and DeWalle(9,10).

The landfill leachate fed to the filters by Chian and DeWalle had a COD of 54,000 mg/L and a pH of 5.4. A high rate of recycle from the column effluent to the influent was employed to neutralize the effects of the low pH feed. It was concluded that a high degree of COD removal could be achieved at a detention time of seven days without the addition of pH buffering. Efficiencies were much lower at detention times less than seven days.

Chian and DeWalle used the same anaerobic filter system to evaluate the effectiveness of the system in the removal of heavy metals from a fatty acid wastewater. The results of this work were presented in a 1977 paper (10). The wastewater fed to the filters was a landfill leachate similar to that used in the previous study (9). The effectiveness of the filter in removing heavy metals is illustrated by the data in Table 1.

Table 1. Concentrations of Heavy Metals in the Influent and Effluent of the Anaerobic Filter (From Chian and DeWalle, Ref. 10).

Element	Influent Concentration Mg/L	Effluent Concentration Total Mg/L	Effluent Concentration Soluble Mg/L	Removals, % Tot	Removals, % Sol
Iron	430	19.4	12.6	95.5	97.1
Zinc	16	1.3	0.95	92.0	94.1
Copper	5.6	1.47	0.67	73.8	88.1
Chromium	1.7	0.24	0.15	85.9	91.2
Nickel	1.2	0.33	0.20	72.5	83.7
Lead	0.38	0.08	0.06	78.9	84.2
Cadmium	0.027	0.019	0.013	29.6	51.9

The data in Table 1 indicate that the completely mixed anaerobic filter used by Chian and DeWalle was very effective in the removal of heavy metals. It was noted that the metals are precipitated as sulfides, carbonates and hydroxodes and were removed from the filter as a slurry that accumulated in the bottom collection device. Analyses for metals at different depths in the filter indicated that most of the metals were removed in the bottom 50 cm of the filter. Chian and DeWalle noted a possible metal toxicity problem only once during the 360 days of operation on the landfill leachate. This problem was corrected by the addition of sulfides to the influent wastes (10).

Jennett and Rand applied laboratory-scale anaerobic filters to treat a synthesized organic pharmaceutical waste having a high COD (70,700 to 87,800 mg/L) and a low pH of 1.5 to 1.6 (11). The anaerobic filters were constructed of clear acrylic tubing and were 48 in high (121.9 cm) and 5.5 in (14 cm) in inside diameter. The filter media was stone having a nominal diameter in the range of 1.0 to 1.5 in. The filters were operated on a methanol feed until steady state was achieved. The filters were then gradually switched to the pharmaceutical waste diluted to a COD of 2,000 mg/L. Under steady-state conditions, with diluted pharmaceutical wastes being fed to provide a filter loading of 34.9 lb COD/day/1000 cu ft of filter volume, COD removals ranged from 70 to 80 % and BOD_5 removals averaged 94 %. The operating temperature was at 35^oC at all times (11).

In 1979, Witt et al. reported on the performance of a full-scale anaerobic filter for the treatment of a high strength guar process waste (12). The wastewater arises from a plant that processes guar beans into guar gum, a polysaccaride, and chemically modified guar gums. This processing generates a wastewater containing soluble gum, impurities, propylene glycol and caustic (12). The anaerobic filter was designed to handle 200 gpm of equalized wastewater at a loading rate of 1.0 lb COD/day/cu ft of filter void volume to obtain a 65% COD removal with a one day hydraulic residence time. As described by Witt et al., the filter tank is 40 ft in diameter and 30 ft tall and is packed with media that provides a void volume of 36,000 cu ft. Wastes are introduced into the bottom of the filter through a distribution manifold. The filter is designed to operate at a temperature of 98^{o} F. Steady-state operating data for the system are presented in Table 2 (12).

Table 2. Steady-State Operating Data (From Ref. 12)

Characteristic	Mean	Range
Feed Rate, gpm	151	55-199
Loading Rate, lb COD/day/ft^3	0.47	0.16-0.69
Feed COD, mg/L	9140	4340-12,130
Effluent COD, mg/L	3590	2170-5200
COD Removal, %	60.3	49.8-67.2
Effluent pH	6.9	6.5-7.3
Effluent Suspended Solids, mg/L	210	48-330
Biomass Yield, lb SS per 1000 lb COD Removed	36.3	11-55.5
Offgas Methane, %	72.7	58.0-80.4
Offgas Flow, scfm	59.8	26.4-81.0
Gas Output Energy, BTU/hr X 10^{-6}	2.46	0.73-3.73

Hudson, et al. reported in 1978 on the application of anaerobic filters to the treatment of a shellfish processing wastewater (13). Two bench-scale units were operated on a single wastewater source. Both filters were fabricated from 15.24 cm I.D. by 152.5 cm plexiglass tubing with a packing media depth of 128.1 cm. One column was packed with 2.5-3.8 cm nominal size granite stone. The other column was packed with whole oyster shells. The stone and oyster shell media provided bed porosities of 53% and 82%, respectively. A significant finding of this study was that the filter containing the oyster shell media achieved significantly better COD removals than did the stone media filter at essentially equal organic and hydraulic loads. Applied COD loadings to the oyster shell column were 0.15, 0.25, and 0.36 $Kg/m^3/day$ with retention times of 3.10, 1.60 and 0.33 days, respectively. By comparison, the stone media filter was loaded at 0.18, 0.24, and 0.34 Kg $COD/m^3/day$ with retention times of 2.51, 1.68 and 0.35 days, respectively. Thus, as noted, differences in loading between the two units were quite small, however differences in performance were quite large. The oyster shell column achieved a COD removal of 81% compared to 33% for the stone media column at their comparable retention times of 3.10 and 2.51 days. At the 1.60 and 1.68 day retention times, the oyster shell column achieved a COD removal of 74% compared with 55% for the stone media column. Hudson, et al. stated that the column packed with oyster shells was able to achieve a COD removal some 20 to 50% greater than that possible with the rock media filter.

Hudson, et al. speculated as to the reasons for the higher performance from the oyster shell media (13). It was speculated that the superior performance of the oyster shell media may be the result of its much greater surface area to volume ratio and bed porosity, as compared with the rock media. It was estimated that the surface area of the oyster shell media was about twice that of the rock media. As noted earlier, the oyster shell media provided a bed porosity of 82% compared with 53% for the rock media. This was one of the first reports to indicate that the characteristics of the packing media may have a significant effect on the performance of an anaerobic filter (13).

Dague, et al. reported on the treatment of a high-strength grain processing waste with an anaerobic filter (14). At a column depth of eight feet and a loading of 150 lb COD/day/1000 cu ft , COD removals of 75 and 90% were achieved at temperatures of 22 and 35^{o} C, respectively. At a temperature of 35^{o} C, COD removals of 75% were achieved at a loading of 350 lb COD/ 1000 cu ft of total filter volume, but the system was vulnerable to failure at this high loading as a result of temperature declines and pH variations.

Dague, et al. also reported in 1980 on the application of anaerobic filters to the treatment of high strength waste liquors from the thermal conditioning and dewatering of activated sludge. The COD and ultimate BOD of the wastes averaged 20,000 mg/L and 9,500 mg/L, respectively. The pH of the waste ranged from 4.6 to 5.1. The wastes were treated in anaerobic columns constructed of 5½ inch I.D. plexiglass with 5/8 inch nominal size, ring-type plastic media to a depth of four feet. The empty volume of each filter was 18.1 liters. With media in place, the columns held 16.3 liters of liquid, indicating a bed porosity of 90.0%. Two columns were operated first in parallel at an ultimate BOD load of 200 lb/day/1000 cu ft on one column and 400 lb/day/1000 cu ft on the other column. After sufficient data were collected, the columns were switched to the series mode (total of 8 ft of column depth) and operated at an ultimate BOD load of 200 lb/day/1000 cu ft.

The columns were maintained at a temperature of 35^{o} C (15).

Dague, <u>et al</u>. reported that the four ft deep columns achieved COD and ultimate BOD removals of 46 and 52, respectively, at an ultimate BOD loading of 400 lb/day/1000 cu ft and 50 and 58%, respectively, at an ultimate BOD loading of 200 lb/day/1000 cu ft. At an eight ft column depth, COD and ultimate BOD removals averaged 63 and 84% at ultimate BOD loadings of 200 lb/day/1000 cu ft (15).

A report by Haug, <u>et al</u>. indicated success in the treatment of thermal conditioning wastes with an anaerobic filter (16). COD and BOD removal efficiencies of 76 and 85%, respectively, were achieved with an anaerobic filter operated at 32^{o} C and at a detention time of two days. Gas production was eight cu ft per pound of COD removed and was 70% methane (16).

<u>Fundamental Concepts</u>

The original anaerobic filters used by Young and McCarty in their laboratory studies were columns six inches in diameter and six feet deep (2,3). The columns were filled with stone of 1.0 to 1.5 inch nominal diameter. Wastes, which consisted of a complex protein-carbohydrate waste and a volatile acids waste, were introduced into the bottom of the rock bed with effluent exiting the top of the filter (2,3).

The anaerobic filters of Young and McCarty were basically "upflow, packed-bed" reactors. Since the early research of Young and McCarty, other workers have studied several design and operational variations of the basic anaerobic filter.

A 1973 report by El-Shafie and Bloodgood presented the concept that the biological activity in the anaerobic filters that they had studied was an exponential function of the number of filters in series (or retention time in the system)(17). It was shown that the effluent COD was linearly related to the influent COD, which indicated that the activity of each filter in series was entirely a function of the concentration of the organic load applied (17). In other words, a constant percentage of the organics were removed in each filter in a series of filters.

The experimental set-up used by El-Shafie and Bloodgood consisted of six anaerobic filters in series (17). Each filter was a Plexiglas cylinder of 5.5 in (14.0 cm) diameter and 18 in (46 cm) height. The media in the filters was a hand-graded gravel of 1.0 to 1.5 in (2.5-3.8 cm) diameter. The depth of the gravel media was 15 in (38 cm). A synthetic waste consisting of Metrecal was fed to the system at a concentration of 10,000 mg/L of COD at a flow rate of one liter per hour. This provided an organic load on the first filter in the series of six amounting to 2,560 lb COD/day/1000 cu ft. The retention time in each filter was 3 hr, or 18 hr in the entire system (17).

In discussing their experimental findings, El-Shafie and Bloodgood state that there is a gradual decrease in the intensity of the biological activity from filter to filter as the feed material passes through the system (17). This is supported by the facts that the first filter always showed the lowest pH values, the lowest concentrations of total alkalinity, the greatest amount of total volatile acids concentrations, the greatest quantity of gas produced, and the highest values of organic removal. Thus, as noted above, there was the gradual decrease in biological activity from filter to filter in an exponential manner. Although not stated by El-Shafie and Bloodgood (17), this observation would indicate a first-order reaction in the removal of organics in their experimental work. It is also significant to note that the experimental set-up of El-Shafie and Bloodgood resulted in a "forced" plug-flow of wastes through the system. If the entire filter volume were placed in one reactor, rather than six in series, the system would tend to approach a completely mixed regime. This mixing arises as a result of gas bubble movement through the anaerobic filter, which becomes very intense as filter loadings increase.

A 1975 report by Mueller and Mancini presents the results of laboratory-scale anaerobic filter studies aimed at evaluating a kinetic model for the process (18). Two types of reaction kinetics were analyzed with the model, Michaelis kinetics, based on the individual biological solids fractions, and first-order kinetics, based on total volatile solids (18). The experimental set-up consisted of two 6½ ft deep cast acrylic columns, 5 inches in diameter. The columns were filled to the four foot level with 5/8 in polypropylene pall rings. The resulting void volume of each filter was 13.1 liters, resulting in a bed porosity of 85%. Both columns were maintained at a temperature of 35^{o} C. A synthetic protein-carbohydrate waste was fed to the filters (18).

Significant observations presented by Mueller and Mancini were that the use of a high porosity, lightweight plastic media has an advantage over rock media, since it allows a greater quantity of biological growth per unit total volume due to the greater void space. For their media and waste, it was concluded that the maximum possible load on the filters would be about 1,100 lb COD/day/1000 cu ft of filter volume. At higher loadings the filter voids would become completely plugged with biological growth, according to estimates made by measuring the volume of liquid that would drain by gravity from the filters after equilibrium periods of application of various organic loads (18).

Mueller and Mancini also concluded that a simple model employing first-order kinetics with measured volatile solids concentrations adequately approximates filter performance and should be more easily usable for system design and analysis than would be the case for Michaelis kinetics (18).

The report of Haug, et al. on the treatment of liquors from heat treatment (16) of sludges at the Hyperion treatment plant of the City of Los Angeles is significant with respect to observations relating to the effect of depth on filter efficiency. The laboratory-scale filter used in the studies was 5.5 inches in diameter and 6.5 ft in depth. The column was packed with smooth quartzite stone with nominal diameter of 1.0 to 1.5 inches. The porosity of the bed was determined to be 43%. The COD and BOD_5 of the feed heat treatment liquor averaged 9,500 and 3,000 mg/L, respectively. Wastes were fed to the filter at a constant rate that provided a detention time, based on filter void volume, of two days. The temperature of the filters was maintained at 90^{o} F (32.2^{o} C). Overall removals of COD and BOD_5 averaged 76 and 85%, respectively. It is significant to note, however, that most of the removal took place in the bottom two or three feet of the filter (16), as illustrated in Figure 2. It was stated by Haug, et al. that the loading on the filter could have been much higher than the 296 lb COD/day/1000 cu ft (93.5 lb BOD_5/ day/1000 cu ft) that was employed in the laboratory study (16).

Van Den Berg and Lentz conducted fundamental studies aimed at evaluating the differences in performance and characteristics between the upflow and downflow modes of operation of anaerobic filters (19). The experimental reactors consisted of glass tubes of equal height (110 cm) but of different diameters. A total of eight glass columns were operated, four in the upflow mode and four in the downflow mode. Column diameters were 1.0, 1.6, 3.8, and 7.5 cm. The reactors were maintained at a temperature of 35^{o} C. The

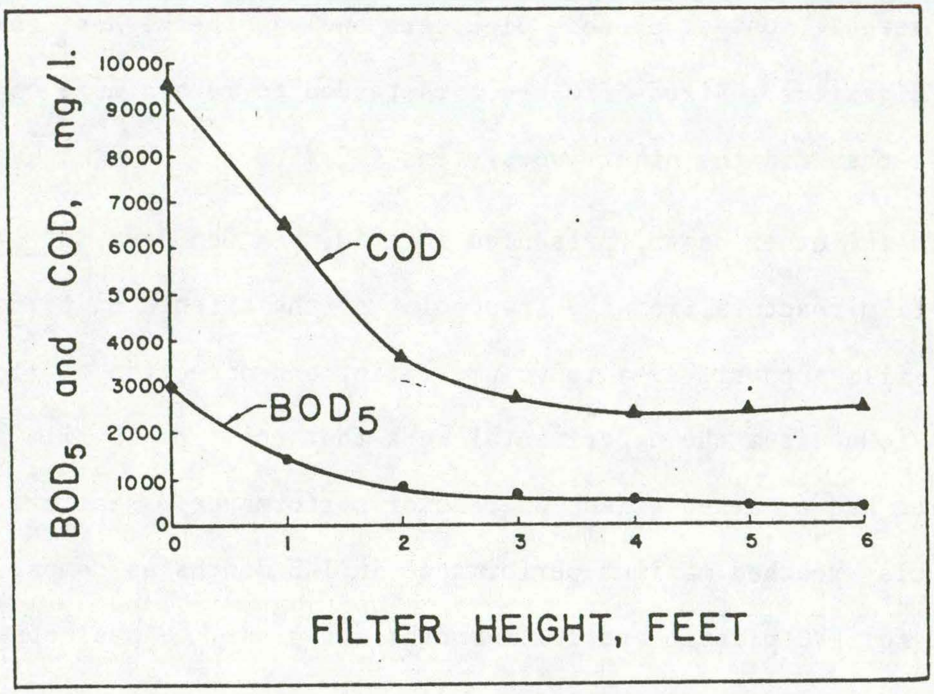

Fig. 2. Profiles of COD and BOD_5 Removal in the Anaerobic Filter (From Haug, et al., Ref. 16).

feed consisted of a bean waste which was fed at a very low rate to provide a 25-day hydraulic retention time in the columns. A significant observation of Van Den Berg and Lentz was that the downflow reactors functioned almost exclusively as fixed film (attached growth) reactors with any activity in the liquid originating from bacteria leaving the film. In contrast, the upflow reactors functioned, at least in part, as fluidized or expanded bed reactors, with a significant part of the activity occurring in the liquid phase, especially in the lower half of the columns (19).

Van Den Berg, et al. have presented two other papers of significance with regard to anaerobic filters (20,21). In one paper (20) comparisons are made between the efficiency of fixed-film reactors, contact digesters, and completely mixed digesters. From this work it was concluded that the minimum hydraulic retention time was shorter for fixed film reactors than for anaerobic contact process digesters and was the highest for completely mixed digesters. Fixed-film reactors tended to retain more of the active biomass than did the other two systems (20).

In the other paper, presented in 1980, Van Den Berg, et al. discussed fixed-film reactors from the standpoint of the effects on performance of depth, film support, area to volume ratio, and direction of flow (21). It was found from the experimental work that the type of film support material had a marked effect on reactor performance. Reactors made of baked clay reached maximum performance in 1-3 months as compared to 7 months for PVC plastic and 10-14 months for glass. Visual observations indicated a more uniform film formed on clay than on glass and that the biofilm did not slough off the clay as easily as it did the glass media (21). It was speculated that the improved performance of clay media over glass and plastic may be related to surface roughness, porosity, and physical-chemical characteristics (21).

Tests with three different reactor heights (0.55, 1.1, and 2.2 m) indicated that film area loadings were little affected by height (21). However, it was noted that the shorter heights tended to be slightly more effective than the deeper columns. It was noted that the deeper reactors may have a greater tendency to foam than the shallower reactors because of the greater gas production per unit of cross sectional area in the deeper reactors (21). Van Den Berg, et al. also reported, as in a previous paper (19), that the upflow reactors differed markedly from the downflow units in that a substantial part of the bio activity resides in the liquid phase in the upflow reactors (21).

Switzenbaum and Jewell reported in 1980 on studies on the application of expanded-bed anaerobic reactors to the treatment of low strength wastes (22). The experiments were designed to evaluate the effects of temperature, influent substrate concentration, organic loading rate, and hydraulic load on the efficiency of the process. Hydraulic retention times of 6 to 0.33 hr were studied with feed COD concentrations ranging from 50 to 600 mg/L. Temperatures were varied from 10^{o} to 30^{o} C. A synthetic substrate was used.

The experimental reactors consisted of clear acrylic columns having a volume of one liter. Approximately 160 g of support material were added to each column and occupied a total volume of 400 ml in an unexpanded mode. The support media was an aluminum oxide, a porous, water-insoluble material manufactured by Corning Glass Company (22). The particles had a diameter of approximately 0.5 mm.

The study of Switzenbaum and Jewell looked at three temperatures of operation, 10^{o}, 20^{o}, and 30^{o} C. For each temperature, six different hydraulic retention times, ranging from 6 hr to 20 min, were evaluated. At each HRT, three different influent substrate COD concentrations (200, 400, and 600 mg/L) were used (22).

The experimental results indicate that the effectiveness of the expanded-bed anaerobic reactors in the treatment of dilute wastes at low temperatures is quite good. A minimum of 80% COD removal was achieved at low HRTs and high organic loading rates, regardless of influent substrate concentration or temperature. Extremely high biomass concentrations, up to 30,000 mg/L, were measured in the reactors. The success of the process was attributed primarily to this large biomass concentration in the reactors and the resulting high solids retention time (22).

RESEARCH PROCEDURE

Phases of Research

This research was conducted in three inter-related phases as follows:

Phase I:

The aerobic biological treatment of the high-strength thermal conditioning wastes in four, laboratory-scale, continuously fed reactors operated at various sludge ages for the purpose of evaluating the sludge yield and endogenous decay coefficients for the wastes with emphasis on the evaluation of Chemical Oxygen Demand, Biochemical Oxygen Demand, solids, and BOD exertion rate constants.

Phase II:

The anaerobic treatment of the thermal conditioning wastes in laboratory-scale, upflow, attached-growth reactors to evaluate the efficiency of removal of organics from the waste and the resulting gas production and operational characteristics at various organic loadings and column depths. Wastes from Dubuque and Cedar Rapids (both in Iowa) were treated in the laboratory scale anaerobic filters.

Phase III:

The development of a mathematical model of a typical treatment system (Dubuque, Iowa) for use in predicting the impact of the recycle stream on the liquid and sludge treatment operations and processes. Of special interest is the prediction of the amount of reduction in sludge production and oxygen utilization that can be achieved through anaerobic treatment of the recycle flow.

Phase I Procedure

The Phase I studies involved two elements, both of importance to the mathematical simulation of Phase III. One element was the characterization of the BOD of the thermal conditioning wastes. A total of 19 separate samples of wastes from the Dubuque, Iowa wastewater treatment plant were analyzed for carbonaceous BOD and its exertion rate. Nitrification was inhibited in all BOD tests. Otherwise, the BOD tests were conducted in accordance with Standard Methods (23).

The other element of Phase I was a determination of sludge yields and endogenous decay coefficients for the activated sludge treatment of the thermal conditioning wastes. A total of four, three-liter, aeration reactors were operated at sludge ages of 2, 3, 4, and 5 days to enable evaluation of sludge yields and endogenous decay coefficients for the wastes (24).

Mixed liquor in different amounts was wasted once daily from each of the four reactors to maintain the selected sludge ages. Each reactor was fed the same daily amount of thermal conditioning wastes on a continuous basis. Differences in reactor liquid volume resulting from the variable amounts of MLSS wasting were made up by adding tap water on a daily basis (24).

Phase II Procedure

Phase II of this research involved the treatment of the wastes from the thermal conditioning and dewatering processes at Dubuque and Cedar Rapids, Iowa (25, 26). The wastes were treated in two anaerobic filters having media depths of four feet and inside diameters of 5½ inches, as illustrated in Figure 3. Each column was packed with 5/8 inch, ring-type, plastic media obtained from Kock Engineering Company, Wichita, Kansas. The empty volume of each column was 18.1 liters. With the media in place, the columns held 16.3 liters of liquid, indicating an empty bed porosity of 90.0 %.

Wastes were pumped to the bottom of the columns with variable-speed, Masterflex, positive displacement pumps. The daily feed volume was controlled by a time clock set to operate the pumps on a periodic basis, the exact length of periods depending on the particular organic load being evaluated. The actual daily feed volume was checked periodically by measuring a 24-hour accumulation in a calibrated vessel.

Column temperatures were maintained at 35°C by circulating water from a water bath through an eight inch water jacket on each column (Figure 3).

The columns were seeded at start-up with supernatant from the Iowa City, Iowa anaerobic digesters. Feeding of dilute concentrations of decant liquor from the Dubuque, Iowa thermal conditioning process began immediately. Thereafter, the load on the filters was increased gradually to allow the anaerobic organisms to acclimate to the waste and to grow in number. During start-up, pH, alkalinity, and gas production were monitored to chart the progress of the reactors. Specific loadings at which the filters were operated will be presented in the Results Section of this report.

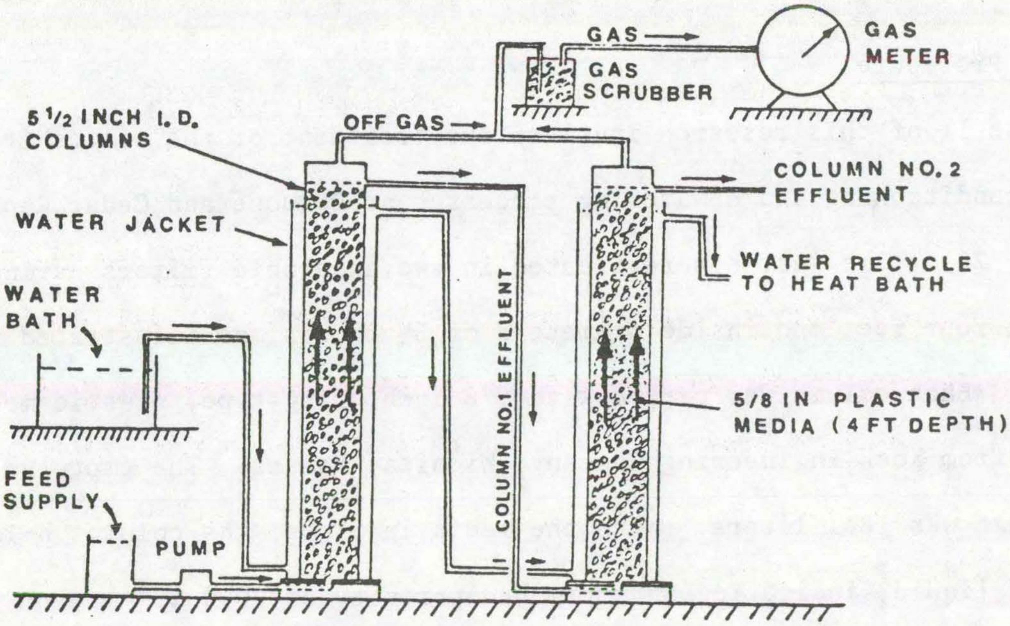

Fig. 3. Laboratory Scale Anaerobic Filters

Phase III Procedure

Phase III involved the development and application of a computer program to simulate the operation of the Duquque, Iowa wastewater treatment plant under various plant loading and waste recycle conditions. The flow diagram for the Dubuque plant is shown in Figure 4.

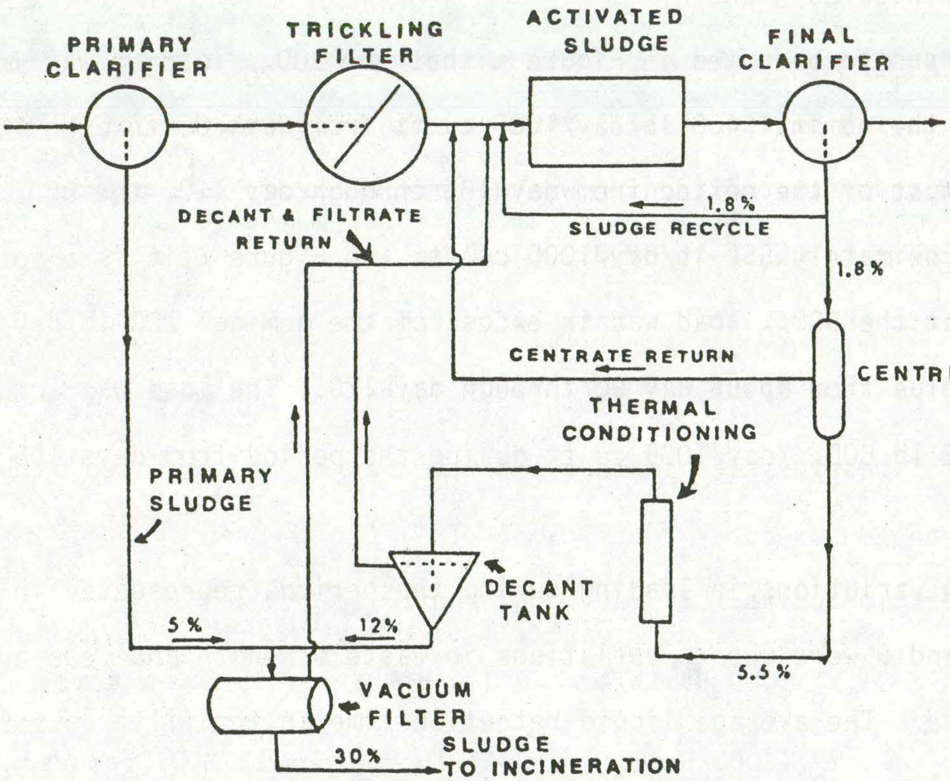

Fig. 4. Wastewater Treatment System at Dubuque, Iowa.

The major components of the treatment system at Dubuque include primary sedimentation, high-rate trickling filters (without clarifiers), oxygen activated sludge, final sedimentation, centrifuges for sludge thickening, thermal conditioning, vacuum filtration, and incineration.

Basic data on sludge yields and endogenous decay coefficients (for calibration of the model) were obtained from Phase I of this research and from actual plant operational data collected by Dubuque operating personnel.

The computer runs were conducted for plant raw influent BOD_5 loadings varying from 20,000 to 40,000 lb BOD_5/day. At the time the computer runs were being conducted (1980) the Dubuque plant was receiving a BOD_5 load of 26,000 lb/day. Average influent wastewater flow to the plant was 10 mgd.

RESULTS

Phase I Results

The results of the Phase I studies, based on analyses of 19 separate samples of thermal conditioning wastes from Dubuque, indicate an average BOD exertion rate constant of 0.2063 (base 10). This is a rather high BOD exertion rate and reflects a ratio of ultimate to 5-day BOD of 1.1. The BOD_5 of these 19 samples averaged 9,600 mg/L.

Phase I results also include a determination of suspended solids yields (Y_o) and endogenous decay coefficients (k_d) for the continuously fed laboratory aeration units. It was found that:

Y_o (COD Basis) = 0.37 lb VSS per lb COD removed

Y_o (BOD_5 Basis) = 0.51 lb VSS per lb BOD_5 removed

k_d (Based on VSS) = 0.104 per day

These data were used in the prediction of the impact of the anaerobic treatment of the strong side stream in terms of reduced net sludge production and oxygen consumption in the activated sludge system (Phase III).

Phase II Results (Dubuque Wastes)

The Phase II anaerobic filter studies on the Dubuque thermal conditioning wastes extended over a period of eight months. Thermal conditioning wastes were transported from Dubuque to the Philip F. Morgan Environmental Engineering Research Laboratory at the University of Iowa in 13 gallon carboys, usually six at a time. The wastes were pumped directly from the carboys into the anaerobic filters in the lab. Samples for influent waste analyses were collected directly from the carboys. The characteristics of the thermal conditioning wastes from Dubuque are presented in Table 3.

Table 3. Characteristics of Thermal Conditioning Wastes From the Dubuque, Iowa Wastewater Treatment Plant.

Characteristic	Value
Temperature, ^{o}C (at Dubuque sampling tap)	49
Chemical Oxygen Demand, gm/l	
Maximum	28.7
Minimum	13.6
Average	20.0
20-Day Biochemical Oxygen Demand, gm/l	
Maximum	15.3
Minimum	6.0
Average	9.5
pH	
Maximum	5.1
Minimum	4.6
Solids, gm/l	
Total	17.80
Total Volatile	10.10
Total Fixed	7.70
Suspended	0.50
Dissolved	17.30

After a start-up period of 80 days, the two, four-feet deep columns were brought to equilibrium at nominal 20-day BOD* loads of 200 and 400 lb/day/1000 cu ft of filter volume. Data were then collected for 40 days on input and output COD and BOD_{20} and gas production. The tempera-

* The 20-day BOD values are essentially equal to the ultimate carbonaceous BOD.

ture of both columns during this period averaged 38^{o}C. The results are shown in Figures 5 and 6.

It should be noted in Figure 5 that the BOD_{20} loading was in excess of the nominal 400 lb/day/1000 cu ft from days 85 through 120. During most of the period from day 105 through day 120, the BOD_{20} load was approximately 550 lb/day/1000 cu ft. In Figure 6 it is also evident that the BOD_{20} load was in excess of the nominal 200 lb/day/1000 cu ft value from about day 90 through day 120. The load was actually near 275 lb BOD_{20}/day/1000 cu ft during the period from days 105 through 120.

The variations in loading during the periods represented in Figures 5 and 6 were due to variations in waste strength and feed pump flow rate. The average liquid retention time in the filters, based on gross column volume, was 1.25 days and varied between 1.14 and 1.34 days.

The pH, alkalinity, and volatile acids in both columns during the period shown in Figures 5 and 6 were within satisfactory ranges. The pH tended to be high in both columns (7.7 to 7.9). Alkalinity was also quite high, generally in the range of 5,000 to 7,500 mg/l, as $CaCO_3$. Volatile acids, as acetic, were commonly around 3,000 mg/l in the column loaded at 400 lb BOD_{20}/day/1000 cu ft and 2,000 mg/l in the column loaded at 200 lb BOD_{20}/day/1000 cu ft.

After completion of data collection in the parallel mode, the two columns were switched to the series mode, providing a total column depth of eight feet. The nominal load was established at 200 lb BOD_{20}/ day/1000 cu ft. This was accomplished by placing the column that had

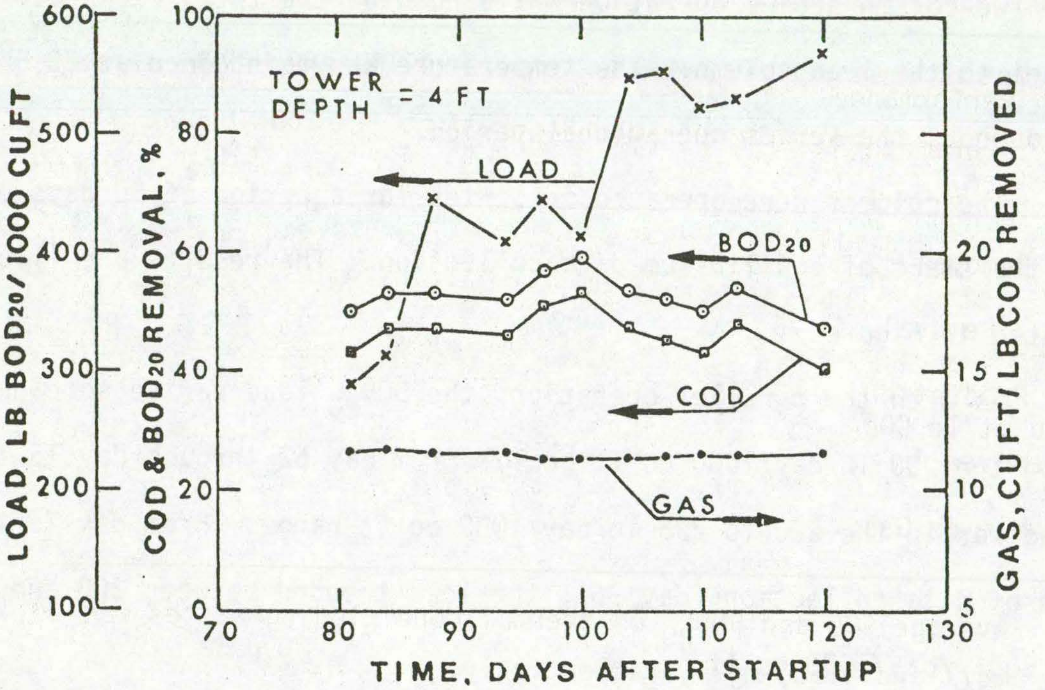

Figure 5. Anaerobic Filter Response at 400 lb BOD_{20} Load and Four Foot Depth.

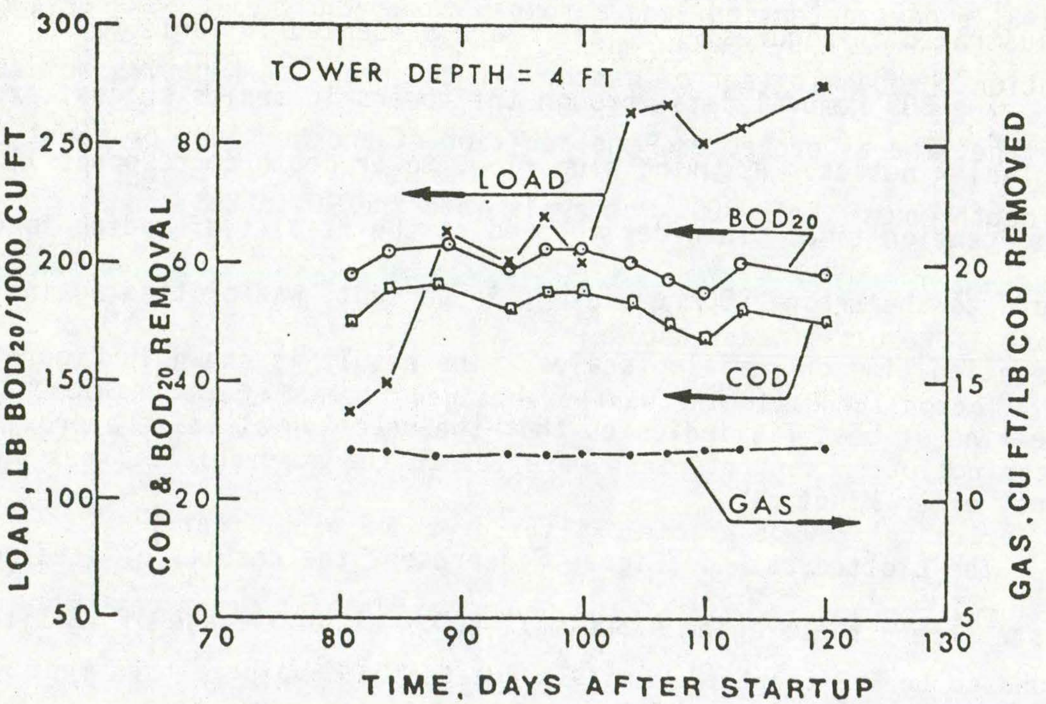

Figure 6. Anaerobic Filter Response at 200 lb BOD_{20} Load and Four Foot Depth.

been at the 400 lb BOD_{20}/day/1000 cu ft load into the lead position in the two-column series operation while holding the total feed rate constant to the lead column. The temperature was maintained at 35.5°C throughout the series operational period.

The columns were operated in series for a period of 80 days prior to the start of equilibrium data collection. The results are illustrated in Figure 7.

As with the parallel operation, the BOD_{20} load varied somewhat from the 200 lb/day/1000 cu ft goal. From day 62 through day 75 the load was in the 200 to 225 lb/day/1000 cu ft range. From day 75 to the end of data collection (day 96), the load trended between 200 and 175 lb BOD_{20}/day/1000 cu ft.

During the series operational period, the head column consistently had a lower pH (7.2 vs. 7.7) and alkalinity (5,000 vs. 6,500 mg/l) and a higher volatile acids (2,500 vs. 1,200 mg/l) than did the tail column.

The average performance of the anaerobic filters during the periods illustrated in Figures 5, 6, and 7 are presented in Table 4.

The BOD removal data through the towers in series suggest exponential kinetics. Assuming plug flow, tower depth corresponds linearly to detention time. In order to predict the results of adding tower depth to the train, BOD remaining, in percent, was plotted against detention time on semi-log scales. The result is shown in Figure 8 The line of best fit indicates that the reaction at least approximates first order kinetics.

The plotted data in Figure 8 represent the results of feeding a waste strength averaging 9,500 mg/l BOD_{20} at an average of 13 liters

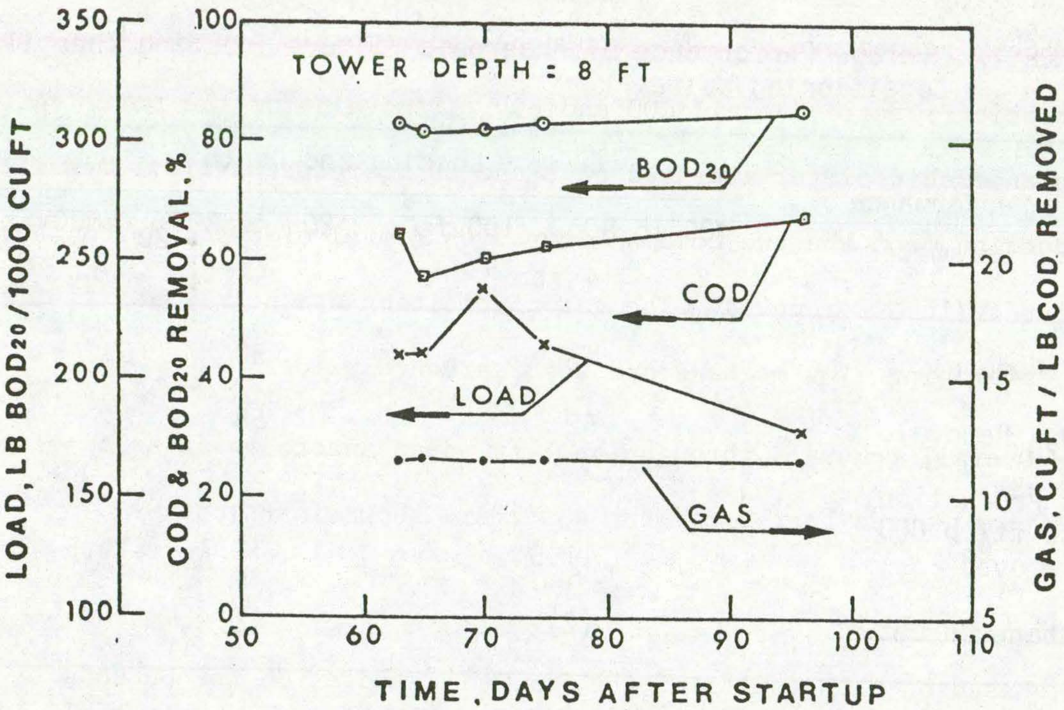

Figure 7. Anaerobic Filter Response at 200 lb BOD_{20} Load and Eight Foot Depth.

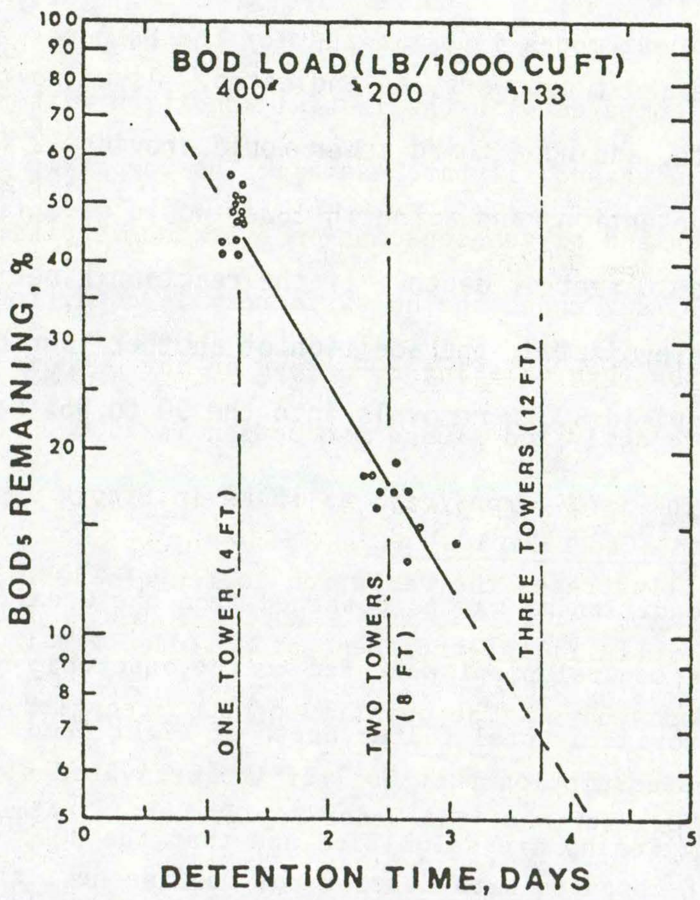

Figure 8. Projected BOD_{20} Removal by Anaerobic Filter at Depth of 12 Feet.

Table 4. Average Performance of Anaerobic Filters Treating Thermal Conditioning Wastes.

Performance Parameter	Loading and Depth		
	400 lb BOD_{20}/100 ft^3	200 lb BOD_{20}/1000 ft^3	
	4 ft	4 ft	8 ft
COD Removal, %(1)	46	50	63
BOD_{20} Removal, %(1)	52	58	84
Gas Production, cu ft/lb COD Removed	11.5	12.7	11.5
Methane in Gas, %	(2)	(2)	56

(1) Average COD and BOD_{20} of thermal conditioning wastes was 20,100 mg/l and 9,500 mg/l, respectively.

(2) Not determined due to failure of gas partitioner.

per day, to one and two towers, as indicated. Assuming the same volumetric feed rate, adding a third tower would provide 12 feet of depth and 3.75 days detention, and a fourth tower would give five days detention through 16 feet of depth. If the reaction kinetics hold true for the line as projected, the addition of another four or eight feet of depth would yield BOD_{20} removals into the 90 to 95% range.

Phase II Results (Cedar Rapids)

Thermal conditioning wastes obtained from the Cedar Rapids, Iowa water pollution control plant were fed to the anaerobic filters operated in series to provide a total filter depth of eight feet.

The COD:BOD_{20} ratio of the Cedar Rapids heat treatment waste was found to be 1.8 compared with 2.1 for the Dubuque heat treatment waste used in the Phase II studies described previously. This indicates that the Cedar Rapids thermal conditioning waste is somewhat more biodegradable than the Dubuque waste.

The average BOD_{20} loading on the anaerobic filters throughout the Cedar Rapids portion of the Phase II studies was 244 lb per 1,000 cu ft of filter volume or a COD loading of 432 lb per 1,000 cu ft.

Based on 23 separate samples of the Cedar Rapids heat treatment waste, the average characteristics of the recycle flows are as shown in Table 5.

Table 5. Average Characteristics of Heat Treatment Wastes from Cedar Rapids, Iowa (total of 23 samples).

Chemical Oxygen Demand, mg/L	21,115
Biochemical Oxygen Demand (20 day), mg/L	11,890
$COD:BOD_{20}$ Ratio	1.77
Alkalinity, as $CaCO_3$, mg/L	1,073
Volatile Acids, mg/L as Acetic, mg/L	3,318
pH	5.4
Total Solids, mg/L	18,017
Total Volatile Solids, mg/L	13,672

Although the primary purpose of the Phase II study of Cedar Rapids heat treatment waste was to study the anaerobic filter treatment at a total column depth of eight feet, samples were also collected from the effluent from Tower No. 1 (four foot depth) in order to evaluate performance at both the four and eight foot column depths.

The COD and BOD_{20} removals through the first column averaged 50 %

and 55 %, respectively. This would be the removals for the 4-ft. deep anaerobic filter. Overall COD and BOD_{20} removals for the total 8-ft. deep anaerobic filter averaged 68 % and 80 %, respectively. Overall gas production from the two columns in series (total of 8-ft. depth) averaged 7.3 cu ft/lb COD removed. The gas composition was nearly constant throughout, averaging 77 % methane and 23 % carbon dioxide.

Overall removals through the 8-ft. deep anaerobic filters treating the Cedar Rapids heat treatment waste are shown in Figure 9.

Phase III Results

Based on the results of the Phase II studies on the Dubuque heat treatment waste, it was assumed in the Phase III computer simulations that the anaerobic filter would achieve an 85 % removal of BOD_5.

All operational modes investigated for the Dubuque wastewater treatment plant were compared with the initial condition with no recycle of thermal conditioning and filtrate wastes. The variation in waste activated sludge production and oxygen consumption over the loading range of 20,000 to 40,000 lb BOD_5/day under the no-waste recycle condition are shown in Figure 10. At the then existing BOD_5 load on the Dubuque plant of 26,000 lb/day, the waste activated sludge production is 22,000 lb/day and the oxygen consumption is 9.3 tons/day, as shown in Figure 10.

Figure 11 illustrates the variation in recycle BOD_5 loading both with and without anaerobic filter treatment at a sludge age in the activated sludge reactor of 4 days. The quantity of BOD_5 recycled was calculated on the basis of the assumption that 30 % of the activated sludge solids treated in thermal conditioning are solublized and that the BOD_5 produced per pound of solids solublized is 0.58. These assumptions check well with actual recycle BOD_5 quantities experienced at Dubuque.

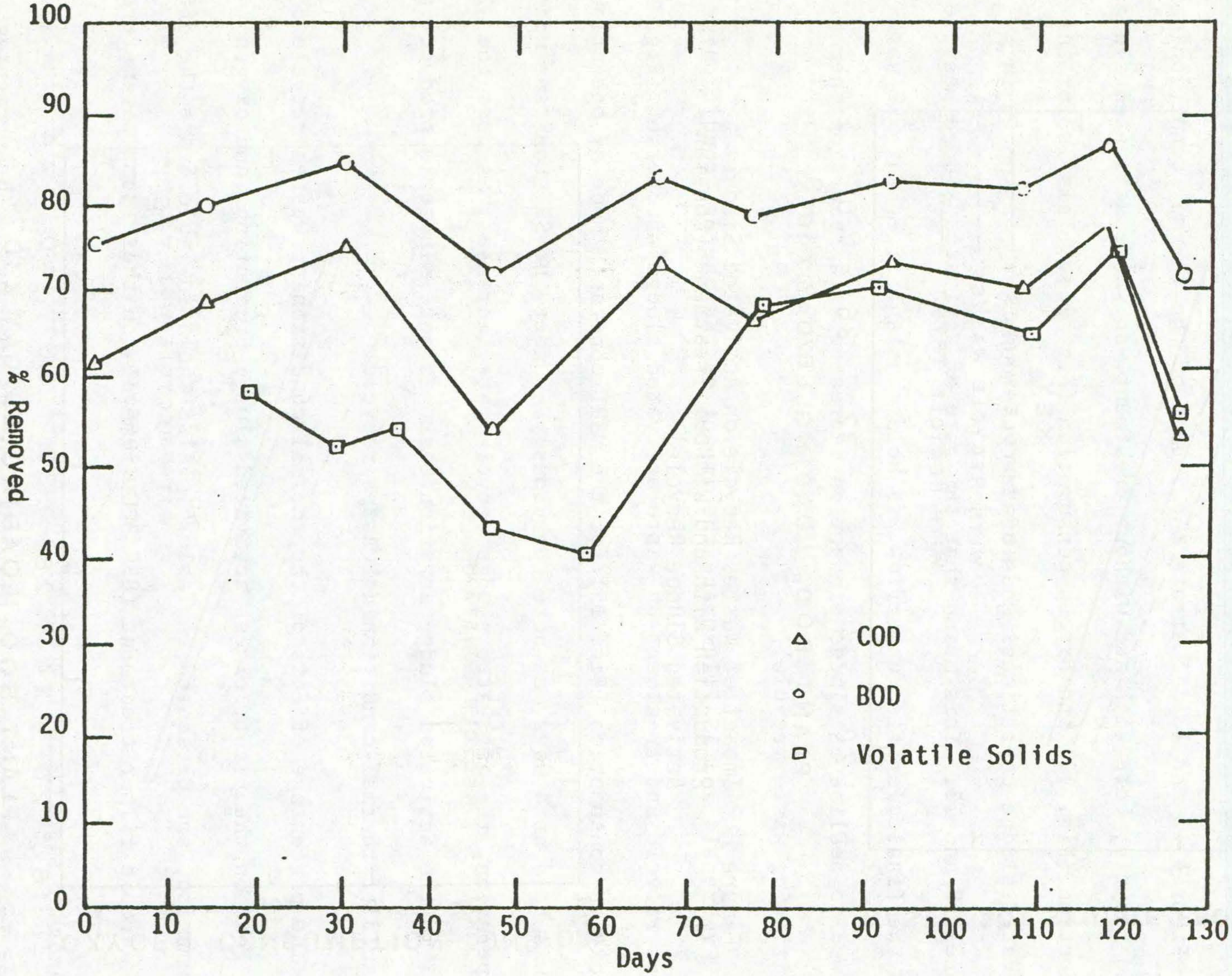

Figure 9. Overall Removals Through 8-Ft. Anaerobic Filter Treating Heat Treatment Wastes from Cedar Rapids, Iowa.

The quantity of BOD_5 added from thermal conditioning recycle amounts to an average of 20.0 % of plant primary influent BOD_5 across the entire range of plant loadings.

Figures 12 and 13 illustrate the impact of the thermal conditioning waste recycle, both with and without treatment, on waste activated sludge production (Fig. 12) and oxygen consumption (Fig. 13). This is for the activated sludge operational mode of "recycle constant", as noted in Figures 12 and 13. This means that the rate of activated sludge recycle from the final clarifier underflow was held constant (i.e. the SRT was allowed to decline as sludge production increased as a result of thermal conditioning waste recycle).

Figures 14 and 15 illustrate the impact of the thermal conditioning wastes recycle and treatment on waste activated sludge production (Fig. 14) and oxygen consumption (Fig. 15) for the "SRT constant" mode of operation. SRT was held at 4 days, as noted previously. Under the SRT constant mode of operation, the activated sludge recycle rate increases, as does the MLSS level in the activated sludge aeration tank, as more sludge is produced as a result of thermal conditioning wastes recycle.

The percentage effects of the thermal conditioning wastes recycle on BOD_5 load on the plant, excess activated sludge production, and oxygen consumption, are presented in Table 6. Also shown in Table 6 are the effects of anaerobic filter treatment (85% BOD_5 removal) on these same parameters.

Another significant impact of the recycle of thermal conditioning wastes is the effect on final clarifier solids loadings. The percentage increase in suspended solids mass surface loading, both with and without recycle treatment, is illustrated in Figure 16. At an average plant loading of 26,000 lb BOD_5/day, the thermal conditioning waste recycle adds

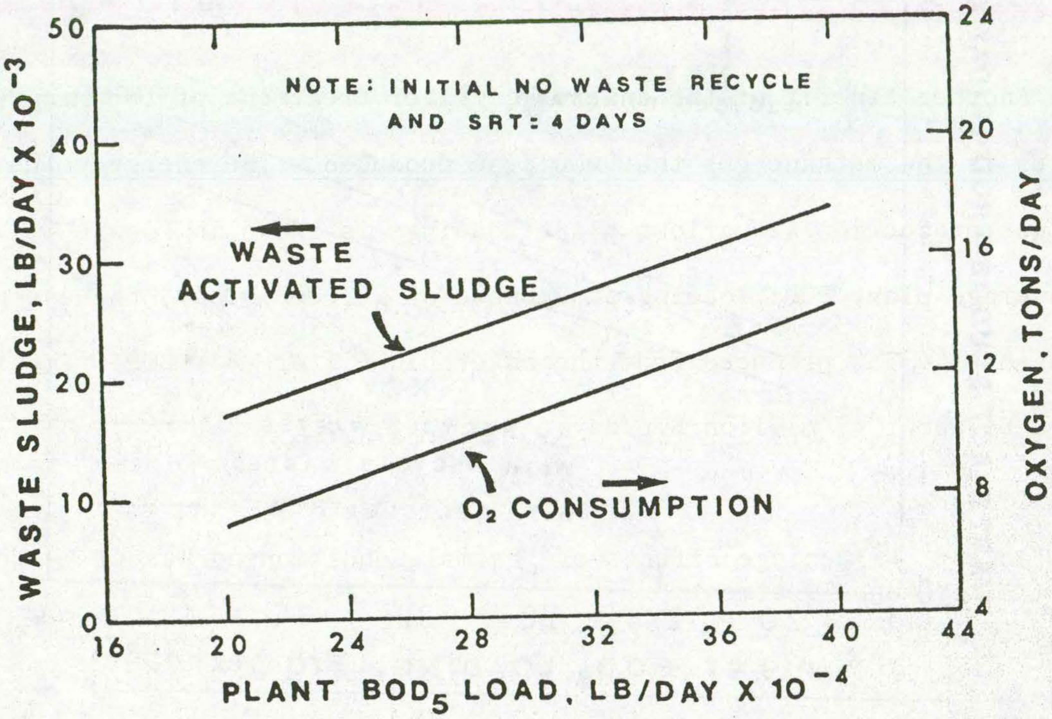

Figure 10. Waste Activated Sludge Production and Oxygen Consumption With No Thermal Conditioning Wastes Recycle.

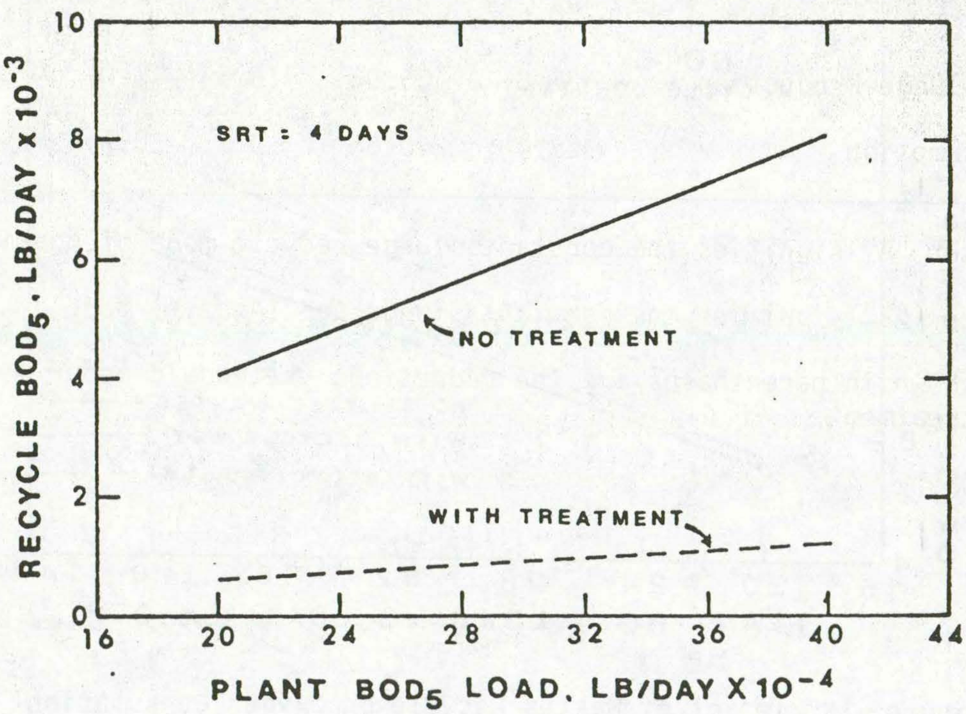

Figure 11. Variation in Recycle BOD_5 Loading With and Without Anaerobic Filter Treatment.

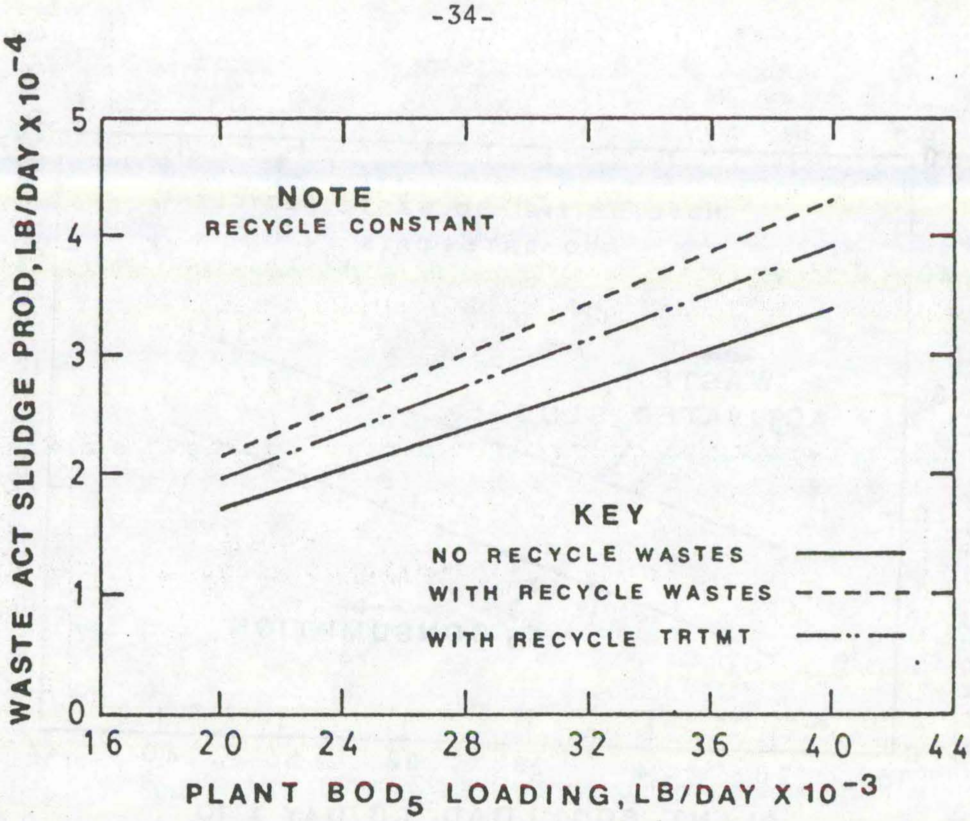

Figure 12. Impact of Wastes Recycle on Activated Sludge Production With and Without Treatment (Constant Activated Sludge Recycle).

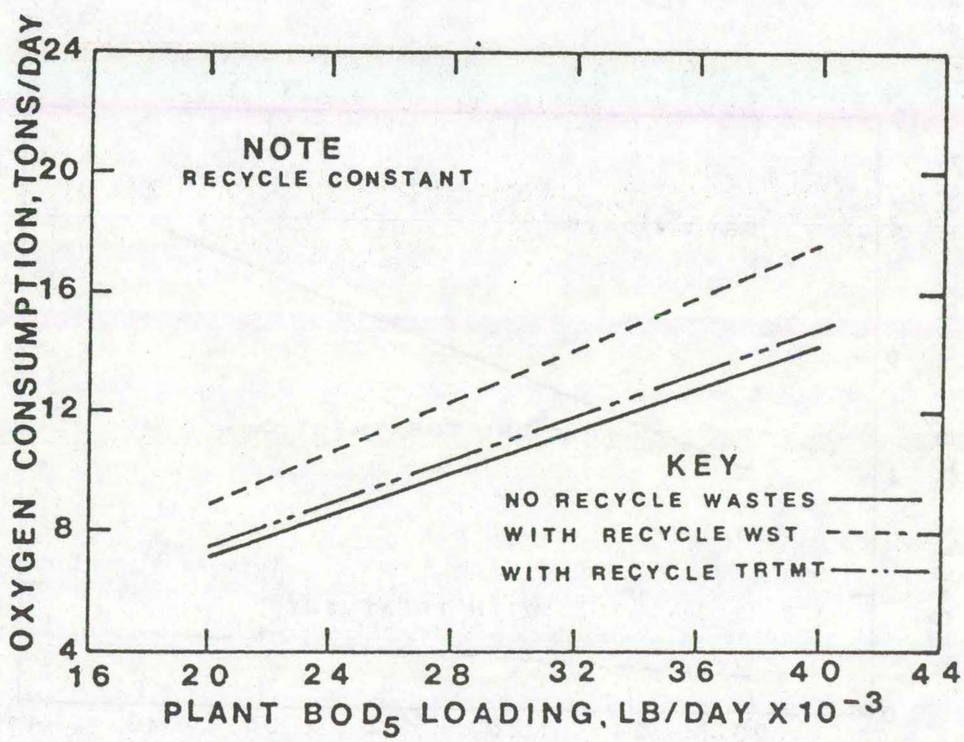

Figure 13. Impact of Wastes Recycle on Oxygen Consumption With and Without Treatment (Constant Activated Sludge Recycle).

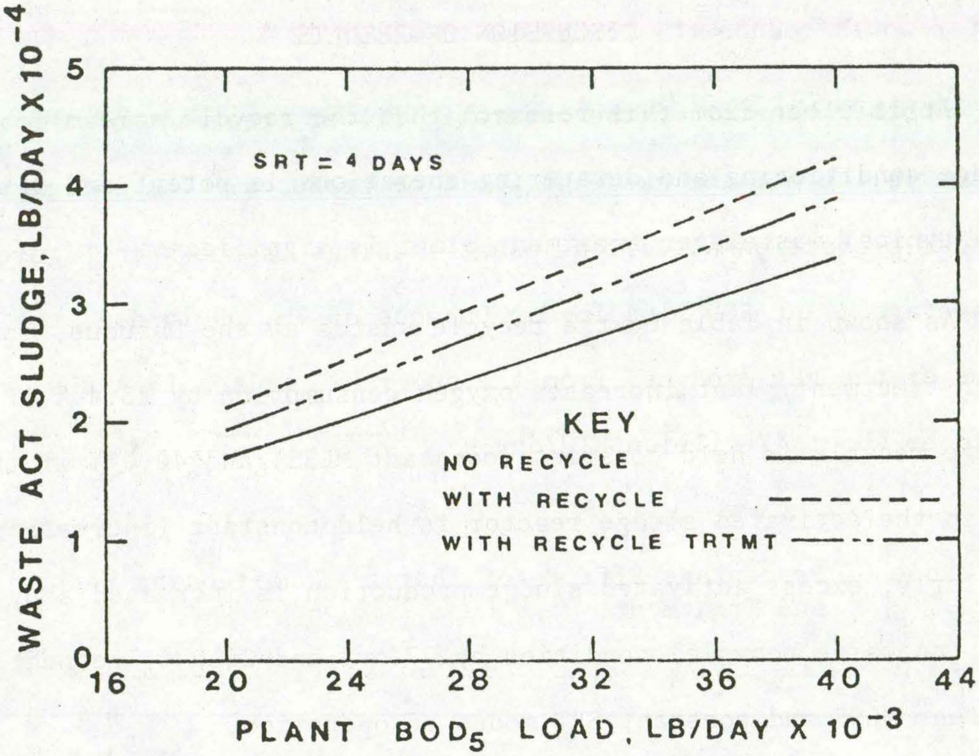

Figure 14. Impact of Wastes Recycle on Activated Sludge Production With and Without Treatment (SRT of Four Days).

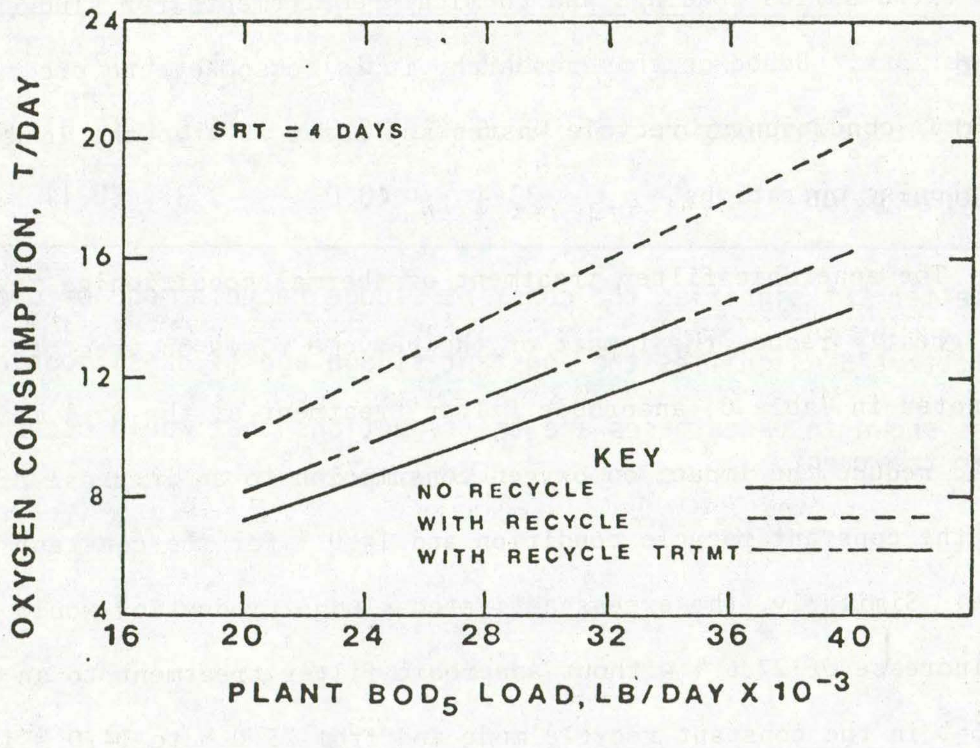

Figure 15. Impact of Wastes Recycle on Oxygen Consumption With and Without Treatment (SRT of Four Days).

about 40 % to the clarifier solids loading. Treatment with the anaerobic filter would reduce this increase to about 22 %.

Another benefit of the anaerobic filter treatment of the recycle wastes is the methane gas that would be produced. The energy value of the gas production at various plant loadings is shown in Figure 17. At an average plant BOD_5 loading at Dubuque of 26,000 lb/day, the energy value of the gas produced from the anaerobic filter (85% BOD_5 removal) would be about 47 million BTU/day.

Table 6. Percentage Effects of Thermal Conditioning Wastes Recycle and Treatment.

Parameter	Increases, %			
	With Recycle		With Treatment	
	A[1]	B[2]	A	B
BOD_5 Load	20.6	20.0	3.1 (-17.5)[3]	3.0 (-17.0)
Activated Sludge Production	27.6	25.0	15.6 (-12.0)	14.0 (-11.0)
Oxygen Consumption	23.4	40.0	3.3 (-20.1)	14.0 (-26.0)

1 The letter "A" signifies the constant sludge recycle mode of operation.

2 The letter "B" signifies the constant sludge age (4 days) mode of operation.

3 Values shown in parenthases are the reductions that would occur with anaerobic filter treatment.

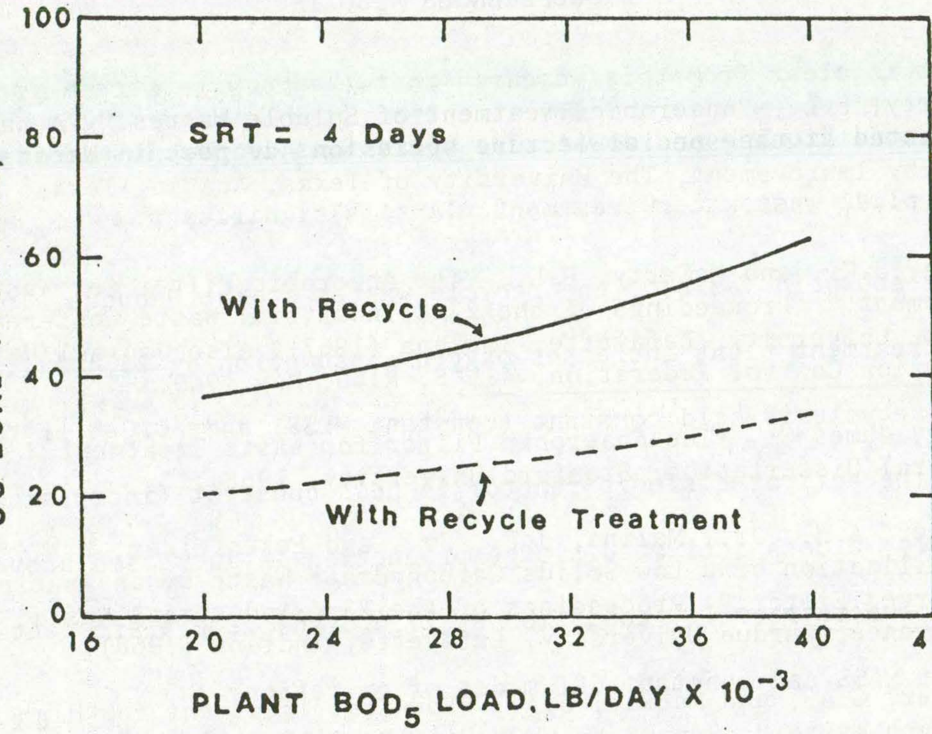

Figure 16. Percentage Increase in Suspended Solids Loading on Final Clarifier With and Without Recycle Treatment.

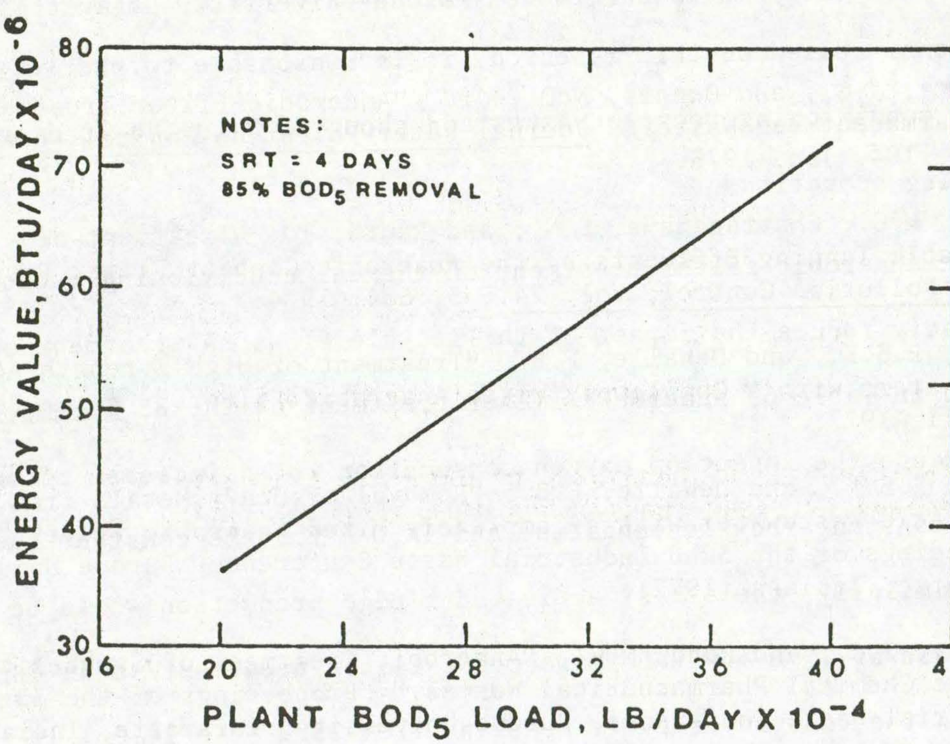

Figure 17. Energy Value of Gas Production as a Result of Anaerobic Filter Treatment of Recycle.

DISCUSSION OF RESULTS

It is clear from this research that the recycle stream from thermal sludge conditioning and dewatering operations is potent and its impact in a typical wastewater treatment plant is significant.

As shown in Table 6, the recycle wastes at the Dubuque, Iowa wastewater treatment plant increases oxygen consumption by 23.4 % if activated sludge recycle is held constant (constant MLSS) and 40.0 % if the sludge age in the activated sludge reactor is held constant (increasing MLSS). Similarly, excess activated sludge production is increased above the base (no waste recycle) condition by 27.6 % and 25.0 %, respectively, for constant MLSS and constant SRT modes of operation.

These are major impacts that must be accounted for in treatment plant design and operation. Other impacts are also significant. These include the extra solids loadings and chemical requirements for sludge thickening operations. Based on this research, it is reasonable to predict that thermal conditioning recycle wastes add about 25 % to the load on sludge thickening operations.

The anaerobic filter treatment of thermal conditioning recycle wastes can greatly reduce the impact of the recycle flows on treatment operations. As noted in Table 6, anaerobic filter treatment at the 85 % removal level would reduce the impact on oxygen consumption to an increase of only 3.3 % for the constant recycle condition and 14.0 % for the constant sludge age mode. Similarly, the excess activated sludge production would be cut from an increase of 27.6 % without anaerobic filter treatment to an increase of 15.6 % in the constant recycle mode and from 25.0 % to 14.0 % in the constant sludge age mode.

CONCLUSIONS

Based on this research, the following conclusions appear warranted:

1. Thermal conditioning wastes have a high BOD exertion rate (0.2063, base 10, in this research) indicating an ultimate to five-day BOD ratio of 1.1 and, in the laboratory aeration studies of this research yielded a sludge production of 0.51 lb volatile suspended solids per pound of BOD_5 removed and an endogenous decay coefficient of 0.104 per day.

2. The recycle wastes from thermal sludge conditioning have a significant impact on treatment systems, increasing the plant influent BOD_5 load by some 20 % and increasing oxygen consumption by some 23 to 40 % and excess sludge production by some 25 to 28 %, depending on the mode of operation of the activated sludge aeration system (constant or decreasing sludge age).

3. The anaerobic filter is an effective method of treatment of thermal conditioning recycle wastes. BOD_{20} removals through an 8-ft. deep column loaded at 200 lb BOD_{20} per 1,000 cu ft averaged 84 % when treating wastes from Dubuque, Iowa. Removals of BOD_{20} averaged 80 % when treating wastes from Cedar Rapids, Iowa at a filter loading of 244 lb BOD_{20} per 1,000 cu ft/day at an 8-ft. column depth.

4. Treatment of the recycle wastes to an 85 % removal level will result in a significant reduction in oxygen consumption and excess sludge production and will reduce the load on sludge thickening operations.

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26. Grinaker, David F., "Anaerobic Filter Treatment of Thermal Conditioning Wastes: Phase II." M.S. Thesis, Library, The University of Iowa, Iowa City, Iowa (May 1982).

The following students worked on this project. The titles and dates of their M.S. theses resulting from the research are as follows:

1. Brindley, Daniel R., M.S., May 1980, "Performance of Anaerobic Filters Applied to Thermal Conditioning Wastes."

2. Liang, Philip S., M.S., Dec. 1980, "Impacts of Recycle Liquor from Thermal Sludge Conditioning on Wastewater Treatment Plant."

3. Grinaker, David F., M.S., May 1982, "Anaerobic Filter Treatment of Thermal Conditioning Wastes: Phase II."

4. Chiang, Chow Feng, M.S., July 1983, "Development of a Design Model for the Submerged Media Anaerobic Reactor."

The following publications were generated as a result of the work:

1. Dague, R.R., Brindley, D.R., and Liang, P.S., "Anerobic Filter Treatment of Recycle from Thermal Sludge Conditioning and Dewatering." Presented at the 53rd Annual Conference of the Water Pollution Control Federation, Las Vegas, Nevada, Sept. 28-Oct. 3, 1980.

2. Dague, R.R., "Anerobic Filter Treatment of Thermal Conditioning Wastes to Save Energy." Proceedings of the Symposium on Energy Conservation in Wastewater Treatment by Retrofit, U.S. Department of Energy, Agronne National Laboratories, Argonne, IL., June 1981.

3. Dague, R.R., "Principles of Anaerobic Filter Design." Proceedings of the 26th Annual Great Plains Wastewater Design Conference, Omaha, NE, March 23, 1982.