COMBINED TREATMENT OF LANDFILL LEACHATE AND DOMESTIC SEWAGE

by

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Department of Civil Engineering

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

October, 1984

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ABSTRACT

Leachate generation from a sanitary landfill site often causes a serious pollution problem. Amongst the various options available to the engineer, collection and subsequent treatment of leachate is gaining wide acceptance.

This study investigated the feasibility of treating leachate in combination with domestic sewage. Conventional activated-sludge units were operated at SRT's of 5, 10 and 20 days. A continuous-flow reactor and two fill-and-draw reactors, each with a reactor volume of 5 L, were operated at different organic loadings and temperatures. One fill-and-draw system was fed once a day, while the other was fed the same amount of food in two feeding operations. The organic loadings applied corresponded to sewage:leachate mixtures of 80:20 and 60:40, by volume. The temperatures studied were 22°C (average room temperature), 10°C, and 6°C. Leachate used in the experiment was collected, in one sampling, from a landfill site, while sewage was collected on a weekly basis from the UBC pilot-plant influent feed tank. The COD of the landfill leachate was 3530 mg/L, whereas the average COD of the domestic sewage was 275 mg/L.

The first set of steady-state runs were conducted with a sewage:leachate ratio of 80:20, corresponding to an average influent feed COD of approximately 800 mg/L. COD removal efficiency ranged from 85.7 percent to 92.8 percent, for all the conditions investigated. Settling properties of the biomass, as reflected by the effluent suspended solids and SVI, improved as the sludge age was increased from 5 days to 20 days. However, due to endogenous respiration, cell lysis occurred in all the systems during the 20-day SRT and this caused the average effluent COD to increase. The continuous-flow system experienced the largest increase in the effluent COD since it was in an endogenous respiration state at all times. At the higher SRT's, the once-a-day system was found to be more efficient in treatment as compared to the twice-a-day system, while at the lower SRT, the reverse was true.
The second set of steady-state runs, with a 60:40 sewage:leachate ratio and an average influent COD of approximately 1200 mg/L, performed better in terms of COD removal efficiency. The continuous-flow reactor performed best at the 20-day SRT with a treatment efficiency of 95.0 percent. At the 5-day SRT, however, the once-a-day system produced the best quality effluent (93.3 percent COD removal). The biomass continued to show good settling properties for all the conditions studied. However, in the fill-and-draw systems, at the 20-day SRT, sludge bulking was observed due to the low F/M ratios. This was reflected by the increased SVI values as well as the effluent suspended solids.

Frequent sludge settling problems were encountered at the lower operating temperatures of 10°C and 6°C. A decrease in the treatment efficiency, with temperature, was clearly indicated for all three systems. At 10°C, the continuous-flow system was least efficient due to a high organic loading (72.7 percent COD removal). However, at 6°C, all three systems performed poorly, indicating system failure at that temperature.

Aerobic treatment of a combined sewage:leachate waste stream was found to be feasible, even at high organic loadings. A detailed study of the settling characteristics indicated that settling is governed by the following parameters: food/microorganism (F/M) ratio, organic loading, mixed-liquor suspended solids (MLSS), and temperature. In this study, most of the steady-state runs indicated a properly settling sludge.
# Table of Contents

ABSTRACT .............................................................................................................. ii

LIST OF TABLES ..................................................................................................... vii

LIST OF FIGURES ................................................................................................... viii

ACKNOWLEDGEMENT .............................................................................................. x

1. INTRODUCTION ................................................................................................... 1

2. LITERATURE REVIEW ........................................................................................ 4

   2.1 Composition of Landfill Leachates and Domestic Wastewaters ..................... 4

   2.2 Aerobic Biostabilization of Leachate ............................................................... 7

      2.2.1 General Process Description .................................................................... 7

      2.2.2 Treatment Studies ..................................................................................... 10

         2.2.2.1 Pure Leachate ................................................................................... 10

         2.2.2.2 Combined Wastewaters .................................................................... 13

   2.3 Kinetic Parameters .......................................................................................... 14

      2.3.1 Leachate .................................................................................................. 14

      2.3.2 Combined Wastewaters .......................................................................... 16

   2.4 Factors affecting Aerobic Stabilization ............................................................ 17

      2.4.1 Trace Metals ........................................................................................... 17

      2.4.2 Nutrient Requirements .......................................................................... 18

      2.4.3 Temperature Effects .............................................................................. 20

   2.5 System Performance ......................................................................................... 21

      2.5.1 Settling Characteristics ......................................................................... 21

      2.5.2 Oxygen Uptake Rates .......................................................................... 29

3. EXPERIMENTAL METHODS AND ANALYSIS ............................................... 32

   3.1 Experimental Set Up ....................................................................................... 32

      3.1.1 Reactor Types ......................................................................................... 32

      3.1.2 Apparatus Used ....................................................................................... 33
3.1.3 Reactor Operation .................................................................................................................. 33
  3.1.3.1 Continuous Flow Reactor ................................................................................................. 33
  3.1.3.2 Fill-and-Draw Reactors .................................................................................................. 36
3.2 Experimental Runs and Start Up Procedures ........................................................................... 37
  3.2.1 Runs Conducted .................................................................................................................... 37
  3.2.2 Start Up and Acclimatization .............................................................................................. 40
3.3 Analytical Procedures .............................................................................................................. 43
  3.3.1 Solids and Chemical Oxygen Demand .............................................................................. 43
  3.3.2 Oxygen Uptake Rate ........................................................................................................... 43
  3.3.3 Dissolved Oxygen and pH .................................................................................................. 44
  3.3.4 Sludge Volume Index and Settling ...................................................................................... 44
  3.3.5 Total Kjeldahl Nitrogen and Total Phosphorus ................................................................. 44
  3.3.6 Trace Metals ....................................................................................................................... 45
4. RESULTS AND DISCUSSION ..................................................................................................... 46
  4.1 Feed Characteristics ................................................................................................................ 46
  4.2 Results from the Preliminary Experiment .............................................................................. 48
  4.3 Results from the 80:20 Experimental Runs .......................................................................... 51
    4.3.1 Mixed-Liquor Characteristics ......................................................................................... 51
    4.3.2 Effluent Characteristics .................................................................................................. 64
    4.3.3 Comparison of Different Reactor Types ........................................................................... 69
  4.4 Results from the 60:40 Experimental Run ............................................................................ 79
    4.4.1 Mixed-Liquor Characteristics ......................................................................................... 79
    4.4.2 Effluent Characteristics .................................................................................................. 88
    4.4.3 Comparison of Different Reactor Types ........................................................................... 93
  4.5 Results from the Cold Temperature Study ............................................................................ 99
    4.5.1 Results from the 10°C Temperature Run .......................................................................... 99
    4.5.2 Results from the 6°C Temperature Run ........................................................................... 108
5. CONCLUSIONS AND RECOMMENDATIONS ........................................................................... 115
  5.1 CONCLUSIONS ........................................................................................................... 115
  5.2 RECOMMENDATIONS ................................................................................................. 119

BIBLIOGRAPHY .................................................................................................................. 121
### LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1.</td>
<td>Composition of Typical Leachates</td>
<td>5</td>
</tr>
<tr>
<td>2-2.</td>
<td>Composition of Typical Domestic Wastewater</td>
<td>8</td>
</tr>
<tr>
<td>2-3.</td>
<td>Kinetic Parameters for Various Leachates</td>
<td>15</td>
</tr>
<tr>
<td>2-4.</td>
<td>Kinetic Parameters for a Particular Leachate and a Combined Wastewater</td>
<td>15</td>
</tr>
<tr>
<td>2-5.</td>
<td>Commonly Occurring Filamentous Organisms</td>
<td>23</td>
</tr>
<tr>
<td>3-1.</td>
<td>Steady-State Experimental Program</td>
<td>42</td>
</tr>
<tr>
<td>4-1.</td>
<td>Leachate Characteristics</td>
<td>47</td>
</tr>
<tr>
<td>4-2.</td>
<td>Domestic Sewage Characteristics</td>
<td>47</td>
</tr>
<tr>
<td>4-3.</td>
<td>Preliminary Experiment Results</td>
<td>49</td>
</tr>
<tr>
<td>4-4.</td>
<td>Operational Characteristics for the 80:20 Experimental Run</td>
<td>54</td>
</tr>
<tr>
<td>4-5.</td>
<td>Effect of SRT on Solids and SPOUR Values for the 80:20 Run</td>
<td>61</td>
</tr>
<tr>
<td>4-6.</td>
<td>Effluent Characteristics for the 80:20 Experimental Run</td>
<td>66</td>
</tr>
<tr>
<td>4-7.</td>
<td>Operational Characteristics for the 60:40 Experimental Run</td>
<td>80</td>
</tr>
<tr>
<td>4-8.</td>
<td>Effect of SRT on Solids and SPOUR Values for the 60:40 Run</td>
<td>87</td>
</tr>
<tr>
<td>4-9.</td>
<td>Effluent Characteristics for the 60:40 Experimental Run</td>
<td>90</td>
</tr>
<tr>
<td>4-10.</td>
<td>Characteristics from the 10°C Temperature Run</td>
<td>102</td>
</tr>
<tr>
<td>4-11.</td>
<td>Characteristics from the 6°C Temperature Run</td>
<td>109</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

2-1. SVI as a Function of Temperature ................................................................. 28
2-2. SVI as a Function of Sludge Age ................................................................. 28
2-3. SVI as a Function of Feed Strength .............................................................. 28
2-4. Oxygen Uptake Rate Versus Sludge Age ....................................................... 30
2-5. Oxygen Uptake Rate as a Function of Time for Semibatch Reactors .......... 30
3-1. Fill-and-Draw System ..................................................................................... 34
3-2. Continuous Flow System ................................................................................ 34
3-3. Schematic Operation of a Fill-and-Draw System ........................................... 38
4-1. SPOUR Vs Time for the Fill-and-Draw Systems - Preliminary Experiment ...... 50
4-2. SPOUR Vs Time for the Continuous-Flow System - Preliminary Experiment ...... 50
4-3. Variation of Influent Feed COD with Time .................................................... 53
4-4. F/M Ratio Vs SRT - 80:20 Experimental Run ............................................... 56
4-5. Mixed-Liquor Solids - 80:20 Experimental Run ........................................... 58
4-6. MLSS Vs Days in Steady State - 80:20 Experimental Run ............................. 59
4-7. SPOUR Vs SRT - 80:20 Experimental Run .................................................... 62
4-8. SPOUR Vs Days in Steady State - 80:20 Experimental Run ........................... 63
4-9. pH Vs Days in Steady State - 80:20 Experimental Run .................................. 65
4-10. Effluent Characteristics Vs SRT - 80:20 Experimental Run .......................... 67
4-11. Percent MLVSS Vs SRT - 80:20 Experimental Run ....................................... 71
4-12. SPOUR Vs Time (5 Days SRT) - 80:20 Experimental Run ........................... 72
4-13. SPOUR Vs Time (20 Days SRT) - 80:20 Experimental Run ......................... 74
4-14. D.O. Vs Time (20 Days SRT) - 80:20 Experimental Run .............................. 77
4-15. F/M Ratio Vs SRT - 60:40 Experimental Run .............................................. 82
4-16. Mixed-Liquor Solids - 60:40 Experimental Run ........................................... 84
4-17. MLSS Vs Days in Steady State - 60:40 Experimental Run ............................ 85
4-18. SPOUR Vs SRT - 60:40 Experimental Run ................................................... 89
4-19. Effluent Characteristics Vs SRT - 60:40 Experimental Run.............................................. 92
4-20. Percent MLVSS Vs SRT - 60:40 Experimental Run.............................................................. 94
4-21. SPOUR Vs Time (5 Days SRT) - 60:40 Experimental Run...................................................... 96
4-22. SPOUR Vs Time (20 Days SRT) - 60:40 Experimental Run................................................... 97
4-23. Liquid Temperature Vs Days in Steady State - 10°C Temperature Run............................... 101
4-24. MLSS Vs Days in Steady State - 10°C Temperature Run.................................................... 103
4-25. SPOUR Vs Time for the Fill-and-Draw Systems - 10°C Temperature Run............................ 106
4-26. MLSS Vs Days in Steady State - 6°C Temperature Run...................................................... 111
4-27. SPOUR Vs Time for the Fill-and-Draw Systems - 6°C Temperature Run............................ 113
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1. INTRODUCTION

Sanitary landfills are still considered by many to be the most popular and economically viable means of solid waste disposal. They are also regarded as one of the safest methods of disposal. Leachate generation, from water seeping through the landfill can, however, often cause a serious pollution problem at the site.

In order to keep the landfill environmentally safe, site selection, proper design and operation must be given special attention. The problem of leachate generation can be handled in different ways depending on the hydrogeological characteristics of the site. In some cases it is possible to minimize leachate production at the site. This would normally require extensive sealing of the site. A clay liner is often best suited for sealing the bottom of a landfill. Use of synthetic liners is also common. A landfill designed to produce minimum leachate would be completely sealed after the filling is completed. Recirculation of the leachate is yet another means of minimizing the total volume produced. Since leachate production is usually minimal in low rainfall areas, such efforts to minimize leachate produced is very common in these particular areas.

Another method of controlling pollution due to leachate is by collecting and treating the leachate produced. It is nearly impossible to completely eliminate leachate production at any site, since a landfill cannot be sealed perfectly from all sides (thereby allowing for some infiltration). Therefore, collection and subsequent treatment of leachate is gaining wide acceptance. Most landfills built today have extensive leachate collection and treatment systems. The types of treatment systems used vary from place to place and are usually site specific. The treatment methodology is also site specific. Aerobic biological treatment of most leachates has emerged as a viable means of treatment (Cook and Foree 1974, Boyle and Ham 1974, Chian and Dewalle 1977, Uloth and Mavinic 1977, Temoin and Mavinic 1978, Zapf-Gilje and Mavinic 1981). In a few cases in Germany, on site leachate treatment using oxidation ditches and aerated lagoons is being practised. Some studies (Boyle and Ham 1974) also
indicate the effective use of anaerobic processes for leachate treatment, especially if the leachate is "young" (i.e. high BOD$_5$/COD ratio and high organic content). The use of physical-chemical methods has been found to be restricted and expensive (Chian and Dewalle 1977). Physical-chemical treatment processes are most effective in treating leachates from stabilized landfills (i.e. old leachate) or in further removing organic matter in the effluent of biological units treating leachate (Chian and Dewalle 1977, Cook and Foree 1974, Wong and Mavinic 1982).

Most laboratory leachate treatment studies have been conducted by diluting the leachate with distilled water or by using raw leachate as the influent feed. However, leachate treatment with different ratios of domestic wastewater has received very little attention. Leachate characteristics have been known to vary a great deal and quite often a leachate is found to be nutrient deficient in terms of either nitrogen and/or phosphorus. Domestic wastewater is significantly richer in nutrients and its combination with leachate could result in a more desireable nutrient composition in the combined waste. Also, domestic wastewater has often considerably lower COD and BOD$_5$ values compared to most leachates and mixing of the two waste streams would result in an effective dilution of the leachate and subsequently "easier" treatment.

Different types of bio-reactors operating under identical conditions could result, however, in varying performance efficiencies. For example, fill-and-draw reactors have been known to cause problems due to the shock loadings on the system (Zapf-Gilje and Mavinic 1982). Therefore, operation of fill-and-draw reactors, under different organic loadings could result in a difference in performance efficiencies. This difference could be seen in terms of the effluent characteristics of the system. For a fill-and-draw reactor, increased organic loadings have resulted in a higher concentration of organic matter in the effluent (Daigger and Grady 1977, Zapf-Gilje and Mavinic 1982).
The purpose of this investigation was to study the biological treatability of a combined waste stream of domestic wastewater and leachate, and to study the performance of different reactor types. A continuous flow reactor and two differently fed fill-and-draw reactors were operated at room temperature (21–23°C). The difference in performance of these reactors was studied by comparing various parameters. The parameters investigated were effluent Chemical Oxygen Demand (COD), effluent solids, oxygen uptake rates, mixed liquor solids, Sludge Volume Index (SVI), pH and trace metals. All three reactors were studied for different organic loadings and different solids retention times (also called sludge age). The three systems were also operated briefly at lower temperatures, to study the temperature effects on the treatment efficiencies of the reactors.
2. LITERATURE REVIEW

2.1 COMPOSITION OF LANDFILL LEACHATES AND DOMESTIC WASTEWATERS

One of the most difficult aspects of a study involving leachate treatment is attempting to define the "characteristics" of the leachate which is to be treated. Leachate characteristics vary so widely that attempts to define a typical composition must include such broad concentration ranges of the various contaminants as to be virtually meaningless for treatability studies. Composition of typical leachates are shown in Table 2.1. This composition range is the result of several investigations done in the past (Chian and Dewalle 1976).

There are several known factors that contribute to the variation in leachate composition; factors like refuse characteristics, site hydrogeology, seasons, climate, height and moisture content of the refuse. These all determine the leachate quality leaving the refuse at any given site. These factors are extremely difficult to quantify due to their complexity (Boyle and Ham 1974). Age of the landfill, and thus the degree of solid waste stabilization, has a significant effect on the composition of leachate (Chian and Dewalle 1976). Other factors such as landfill geometry and interaction of leachate with its environment prior to sample collection, also contribute to the spread of data. Leachate frequently contains such high concentrations of a large variety of substances that many analytical techniques are in error because of interferences, and results are not necessarily comparable. Also, depending on the leachate flow and sampling systems, the apparent leachate quality may be changed appreciably.

COD concentrations in a landfill leachate are a major concern in terms of treatment. COD concentrations may reach as high as 89,520 mg/L (Chian and Dewalle 1974). COD is an indirect measure of the total organic matter in the leachate (Sawyer and McCarty 1978). Due to their biodegradable nature, the organic compounds decrease rapidly with increasing age of the landfill (Chian and Dewalle 1976). The COD of the
### TABLE 2-1
Composition of Typical Leachates
(Chian and Dewalle 1976)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of Concentrations *</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD</td>
<td>40 - 89,520</td>
</tr>
<tr>
<td>BOD$_5$</td>
<td>81 - 33,360</td>
</tr>
<tr>
<td>TOC</td>
<td>256 - 28,000</td>
</tr>
<tr>
<td>pH</td>
<td>3.7 - 8.5</td>
</tr>
<tr>
<td>Total Solids</td>
<td>0 - 59,200</td>
</tr>
<tr>
<td>Total Dissolved Solids</td>
<td>584 - 44,900</td>
</tr>
<tr>
<td>Total Suspended Solids</td>
<td>10 - 700</td>
</tr>
<tr>
<td>Specific Conductance</td>
<td>2,810 - 16,800</td>
</tr>
<tr>
<td>Alkalinity (CaCO$_3$)</td>
<td>0 - 20,850</td>
</tr>
<tr>
<td>Hardness (CaCO$_3$)</td>
<td>0 - 22,800</td>
</tr>
<tr>
<td>Total Phosphorus</td>
<td>0 - 130</td>
</tr>
<tr>
<td>Ortho Phosphorus</td>
<td>6.5 - 85</td>
</tr>
<tr>
<td>Ammonia - N</td>
<td>0 - 1,106</td>
</tr>
<tr>
<td>Nitrate + Nitrite - N</td>
<td>0.2 - 10.29</td>
</tr>
<tr>
<td>Ca</td>
<td>60 - 7,200</td>
</tr>
<tr>
<td>Cl</td>
<td>4.7 - 2,467</td>
</tr>
<tr>
<td>Na</td>
<td>0 - 7.70</td>
</tr>
<tr>
<td>K</td>
<td>28 - 3,770</td>
</tr>
<tr>
<td>Sulfate</td>
<td>1 - 1,558</td>
</tr>
<tr>
<td>Mn</td>
<td>0.09 - 125</td>
</tr>
<tr>
<td>Mg</td>
<td>17 - 15,600</td>
</tr>
<tr>
<td>Fe</td>
<td>0 - 2,820</td>
</tr>
<tr>
<td>Zn</td>
<td>0 - 370</td>
</tr>
<tr>
<td>Cu</td>
<td>0 - 9.9</td>
</tr>
<tr>
<td>Cd</td>
<td>0.03 - 17</td>
</tr>
<tr>
<td>Pb</td>
<td>less than 0.10</td>
</tr>
</tbody>
</table>

*All values in mg/L except pH in pH units and Specific Conductance in micromhos/cm.*
leachate, therefore, will tend to decrease with the age of the landfill. The Biochemical Oxygen Demand (BOD$_5$) test is predominantly a biological test and it reflects the biodegradability of the organic matter in leachate. It is, therefore, in itself a direct measure of the treatability of leachate by biological processes. The BOD$_5$/COD ratio decreases as the age of the landfill increases, thereby indicating that an older leachate is more difficult to treat by biological processes. As such, physical-chemical treatment may be the only feasible means.

In any biological process, a certain BOD$_5$:N:P ratio is required for treatability. For municipal wastewaters, the recommended ratio is 100:5:1 (Metcalf and Eddy 1972). Studies done by Temoin and Mavinic (1981) and Wong and Mavinic (1982) showed that for leachate treatment a 100:3.2:1.1 ratio is sufficient. Chian and Dewalle (1976) found that the Total Kjeldahl Nitrogen (TKN) values for leachate ranged from 0 to 1,106 mg/L. In a relatively young landfill, the COD is usually very high and the TKN is low. This can result in a nitrogen deficiency in the leachate for aerobic biostabilization. However, for an old landfill, the COD is low and the TKN is high. Such a situation can cause problems if nitrification-denitrification is desired, due to lack of a carbon source. A study conducted by Atwater and Mavinic (1983) on a low COD, high TKN leachate indicated that a carbon source is needed in order to achieve more complete nitrogen removal. The phosphorus concentrations in leachate has been shown to vary from 0 to 130 mg/L. The leachate used in the present investigation had very low phosphorus levels, 0.18 mg/L. However, on mixing the leachate with domestic wastewater, the phosphorus concentration in the combined feed was increased to 0.45 mg/L.

Most leachates have been known to contain high metal concentrations (Uloth and Mavinic 1977, Temoin and Mavinic 1981, Atwater and Mavinic 1983, Boyle and Ham 1974). Concentrations of iron may vary from 0 to 2,820 mg/L (Chian and Dewalle 1976). Zinc could also be present in high concentrations, as high as 370
mg/L. As such, these leachates may be difficult to treat.

Domestic wastewater, on the other hand, has been subjected to successful biotreatment for many years. A typical composition of domestic wastewater, as provided by Metcalf and Eddy (1972), is shown in Table 2.2. Although the COD values for sewage are considerably lower (compared to leachate), sewage can be significantly richer in phosphorus and contain a more favorable carbon:nitrogen:phosphorus ratio. Mixing the two types of waste, therefore, might prove to be advantageous from a treatment point of view.

2.2 AEROBIC BIOSTABILIZATION OF LEACHATE

2.2.1 GENERAL PROCESS DESCRIPTION

Removal of organic material from wastewater, by biological oxidation, proceeds via a conversion of the organic waste into biomass, energy and inert end products. In a normal aerobic biological treatment process, roughly two thirds, on an oxygen equivalent basis, of the influent organic waste is used for cell mass synthesis. The remaining one third is converted to energy which is then utilized for cell synthesis and maintenance.

While the bacteria are of primary importance, many other microorganisms take part in the stabilization of the organic waste. Biological treatment units are often composed of complex, interrelated, mixed biological populations, with each particular microorganism in the system having its own growth rate. The particular growth rate depends on the food and nutrients available and on environmental factors such as temperature, pH, and whether the system is aerobic or anaerobic.

Bacteria generally reproduce by binary fission. Bacterial growth pattern has four more or less distinct phases. The lag phase represents the time required for the organisms to acclimate to their new environment. Such a phase would be seen
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of Concentrations</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD</td>
<td>500</td>
</tr>
<tr>
<td>BOD₃</td>
<td>200</td>
</tr>
<tr>
<td>TOC</td>
<td>200</td>
</tr>
<tr>
<td>Total Solids</td>
<td>700</td>
</tr>
<tr>
<td>Total Dissolved Solids</td>
<td>500</td>
</tr>
<tr>
<td>Total Suspended Solids</td>
<td>200</td>
</tr>
<tr>
<td>Settleable Solids</td>
<td>10</td>
</tr>
<tr>
<td>Alkalinity (CaCO₃)</td>
<td>100</td>
</tr>
<tr>
<td>Total Nitrogen</td>
<td>40</td>
</tr>
<tr>
<td>Ammonia - N</td>
<td>25</td>
</tr>
<tr>
<td>Total Phosphorus</td>
<td>10</td>
</tr>
<tr>
<td>Chlorides</td>
<td>50</td>
</tr>
</tbody>
</table>

* All values in mg/L.
in a batch operation but not in a continuous operation. Log-growth phase is the period during which the cells divide at a rate determined by their generation time and their ability to process food. This phase is characterized by excess substrate available to the microorganisms. The stationary phase involves no net growth of the organisms; the total population remains constant. Reasons for this phenomena are (a) that the cells have exhausted the substrate or nutrients necessary for growth, and (b) that the growth of new cells is offset by the death of old cells. In the log death phase, the bacterial death rate is usually a function of the viable population and environmental characteristics. In some cases, the log death rate is the inverse of the log growth rate.

Growth patterns can also be interpreted in terms of the variation of the "mass" of microorganisms with time. Such a growth pattern consists of three phases: log growth phase, declining growth phase, and the endogenous phase. The log growth phase exists when the substrate is in excess. The latter two phases are characterized by limitations in the food supply. During the endogenous phase, a phenomena known as "lysis" can occur, in which the nutrients remaining in the dead cells diffuse out to furnish the remaining cells with food.

To ensure that the microorganism will grow, they must be allowed to remain in the system long enough to reproduce. This period depends on their growth rate, which is related directly to the rate at which they metabolize or utilize the waste.

Lawrence and McCarty (1970) proposed an empirical kinetic model, describing the assimilation of soluble organic matter. There are two basic equations which describe the relationship between biological growth and substrate utilization. Equation 1 describes the relationship between the net rate of growth and rate of substrate utilization:
\[
\frac{dX}{dt} = Y \frac{dF}{dt} - b X \tag{1}
\]

where

- \( \frac{dX}{dt} \) = net growth rate of microorganisms/reactor volume, mass/volume-time
- \( Y \) = growth yield coefficient, mass/mass
- \( \frac{dF}{dt} \) = rate of soluble substrate utilization/volume, mass/volume-time
- \( b \) = microorganism decay coefficient, time\(^{-1}\)
- \( X \) = microbial mass concentration, mass/volume

Monod (1949) proposed that the rate of substrate utilization is proportional to both the microorganism concentration and the substrate concentration:

\[
\frac{dF}{dt} = \frac{K S X}{K_s + S} \tag{2}
\]

where

- \( K \) = maximum substrate utilization/wt. of microorganisms, time\(^{-1}\)
- \( S \) = substrate concentration, mass/volume
- \( K_s \) = half-velocity coefficient (defined as the substrate concentration at which the substrate utilization rate is one-half the maximum), mass/volume

These two models form the basis for design and operation of most biological treatment units. The design of the activated sludge process is also based on these models.

2.2.2 Treatment Studies

2.2.2.1 Pure Leachate

The University of British Columbia has been extensively involved in the field of leachate treatment over the last 10 years (Temoin and Mavinic 1978, Uloth and Mavinic 1977, Zapf-Gilje and Mavinic 1981, Graham and Mavinic 1979,
Various other studies involving aerobic biological treatment of leachates have also been conducted (Boyle and Ham 1974, Cook and Foree 1974, Chian and Dewalle 1976, Palit and Qasim 1977).

The study conducted by Cook and Foree (1974) indicated that aerobic biological treatment was a very effective means of stabilizing sanitary landfill leachate. The best operational condition was a detention time of 10 days, with a mixed-liquor volatile suspended solids (MLVSS) concentration of 4,400 mg/L. With an influent COD of 15,800 mg/L, a COD stabilization efficiency of greater than 97 percent was accomplished. The mixed-liquor was characterized by very good settling properties; efficient nutrient removal of nitrogen (effluent TKN values as low as 13 mg/L) and phosphorus (effluent total phosphorus as low as 0.14 mg/L) was also accomplished.

Boyle and Ham (1974) also undertook a leachate treatment study using aerobic reactors. It was found that aerobic treatment of leachate was possible, with BOD$_5$ removal efficiencies of more than 90 percent. Organic loadings were kept lower than 0.48 kg BOD$_5$/day/cu m for an efficient performance. Foaming and poor solids-liquids separation occurred in the bench-scale units. The causes for the poor settling were attributed to high organic loadings and high food/microorganism (F/M) ratios.

Chian and Dewalle (1977) found that a high-strength leachate, with a COD of 57,900 mg/L, could be treated, with 93 to 96.8 percent organic matter removal. Completely mixed, fill-and-draw reactors with no cellular recycle, simulating aerated lagoons, were used with detention times varying from 7 days to 85.7 days. It was also concluded that higher detention times lead to a lower phosphorus requirement. For the 30 day units, COD:P ratios of at least 300:1 were required. Units with retention times of 60 to 85.7 days could have a COD:P ratio as low as 1540:1. Lower retention time units, with COD:P ratios less than
165:1, showed an increase in effluent organic matter, a decrease in the biological MLVSS and a deterioration of sludge settling rates. High metal removal rates were observed in all units for iron (>99.9%), zinc (99.9%), calcium (99.3%) and magnesium (75.9%).

Palit and Qasim (1977) used a bench-scale, continuous-flow activated sludge unit for treating leachate (365 mg/L COD). It was concluded that landfill leachate can be treated biologically in an activated sludge plant. However, sludge bulking problems were encountered several times during the experimentation. Nutrient deficiency in the leachate resulted in poorer plant efficiency.

Uloth and Mavinic (1977) found that leachate COD removal efficiencies from 96.8 to 99.2 percent could be obtained, with sludge ages from 10 days to 60 days, respectively. The influent COD concentrations ranged between 44,000 mg/L and 52,000 mg/L. Most of the metals in the mixed-liquor were removed by the settling biological floe; this removal was aided by high pH and high MLVSS concentrations. For the particular leachate used, a sludge age of at least 20 days was recommended and the F/M ratio to be kept below 0.15 kg BOD$_5$/ kg MLVSS/ day.

Zapf-Gilje and Mavinic (1981) studied the aerobic biostabilization of leachate (19,000 mg/L COD) at different temperatures. Removals better than 95 percent for COD and 99 percent for BOD$_5$ were achieved for all the temperatures investigated. The poor solids-liquid separation obtained throughout the study was attributed to the shock imposed by the intermittent feeding operation of a fill-and-draw system.

Another study on leachate treatment at the University of British Columbia was conducted by Wong and Mavinic (1982). The purpose of this project was to evaluate the treatability of a medium strength leachate (BOD$_5$ = 8090 mg/L) at a nutrient loading of BOD$_5$:N:P = 100:3.2:1.1, at different temperatures. BOD$_5$
removals of at least 99.4 percent and COD removals greater than 96.4 percent were achieved. The nutrient loading was found to be sufficient. Settling problems were also encountered in this study.

2.2.2.2 Combined Wastewaters

Very few studies have been conducted to study the effect of mixing leachate and domestic wastewater (Boyle and Ham 1974, Temoin and Mavinic 1981).

The study conducted by Boyle and Ham (1974) involved the use of an extended aeration process. The percentage of leachate in the domestic wastewater-leachate mixture was varied from 0 to 20 percent on a volume basis, with loadings varying from 5.7 to 77.6 lbs BOD₅/day /1000 cu ft. Effluent quality was not significantly affected up to 5 percent leachate addition by volume, approximately 24 lbs BOD₅/day /1000 cu ft. In excess of 5 percent volumetric additions, deterioration of sludge settleability resulted in poor effluent quality. The COD of the effluent and the SVI values for the sludge rose sharply above 5 percent additions. The authors concluded that leachate could be added to domestic wastewater in an extended aeration activated sludge plant at a level of at least 5 percent by volume (leachate COD=10,000 mg/L) without seriously impairing effluent quality. At greater than 5 percent by volume, leachate additions resulted in substantial solids production, increased oxygen uptake rates, and poorer mixed liquor separation.

Temoin and Mavinic (1981) found that a combination of high-strength leachate and domestic wastewater could be successfully treated in an aerated lagoon, simulated in the laboratory by a completely-mixed, no cellular recycle, single stage system, with a 20 day detention time. A good quality effluent was achieved with an influent consisting of 20 percent leachate addition, which corresponds to an influent BOD₅ of 3,650 mg/L. BOD₅ removal efficiencies greater than 99 percent
were achieved. When the BOD₃/P ratio in the feed dropped below 100:0.29, the effluent TKN concentrations rose to 13.4 mg/L, while the TKN values in all other instances never exceeded 2.8 mg/L. It was thought that the low phosphorus loading inhibited the ability of the mixed-liquor to assimilate nitrogen. Phosphorus, like nitrogen, is an essential nutrient for biological growth. Lack of phosphorus could inhibit growth and hence the microorganisms would not use up the nitrogen in the feed.

2.3 KINETIC PARAMETERS

2.3.1 LEACHATE

The main parameters of interest in understanding the kinetics of a biological growth system are the following - the maximum rate of substrate utilization (K), the half velocity coefficient (Kₛ), the microorganism decay coefficient (b), and the growth yield coefficient (Y).

A summary of all the kinetic parameters from various leachate treatment studies are presented in Table 2–3 (Mavinic 1984). These kinetic parameters are compared with the kinetic parameters for domestic wastewater. The maximum rate of substrate utilization, K, in all cases is lower than that for domestic wastewater, and seems to be decreasing with increasing leachate strength. This supports the conclusion of most authors that there is a certain degree of inhibition due, in part, to the presence of trace metals in the leachate (Neufeld 1976, Wong and Mavinic 1982, Uloth and Mavinic 1977).

Palit and Qasim (1977) carried out a study to obtain the values of the kinetic parameters for leachate. The value of the decay coefficient, b, was found to be considerably higher than that for domestic wastewater. In all probability, this was due to the deficiency of nutrients such as nitrogen and phosphorus in the
# TABLE 2-3
**Kinetic Parameters for Various Leachates**
(Mavinic 1984)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Feed Strength (mg/L)</th>
<th>Y (mg/mg)</th>
<th>b (days⁻¹)</th>
<th>K (days⁻¹)</th>
<th>Ks (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metcalf and Eddy 1972</td>
<td>Sewage BOD₅ - 250</td>
<td>0.67</td>
<td>0.07</td>
<td>5.6</td>
<td>22</td>
</tr>
<tr>
<td>Palit and Qasim 1977</td>
<td>COD - 365</td>
<td>0.59</td>
<td>0.1150</td>
<td>1.8</td>
<td>182</td>
</tr>
<tr>
<td>Lee 1979</td>
<td>BOD₅ - 1,000</td>
<td>0.59</td>
<td>0.04</td>
<td>4.5</td>
<td>99</td>
</tr>
<tr>
<td>Wong and Mavinic 1983</td>
<td>BOD₅ - 8,090</td>
<td>0.49</td>
<td>0.009</td>
<td>1.16</td>
<td>81.8</td>
</tr>
<tr>
<td>Zapf-Gilje and Mavinic 1981</td>
<td>BOD₅ - 13,640</td>
<td>0.39</td>
<td>0.022</td>
<td>0.77</td>
<td>20.4</td>
</tr>
<tr>
<td>Cook and Foree 1974</td>
<td>COD - 15,800</td>
<td>0.40</td>
<td>0.05</td>
<td>0.60</td>
<td>175</td>
</tr>
<tr>
<td>Uloth and Mavinic 1977</td>
<td>BOD₅ - 36,000</td>
<td>0.33</td>
<td>0.0025</td>
<td>0.75</td>
<td>200</td>
</tr>
</tbody>
</table>

# TABLE 2-4
**Kinetic Parameters for a Particular Leachate and a Combined Wastewater**
(Temoin 1980)

<table>
<thead>
<tr>
<th>Influent · Type</th>
<th>Y (mg/mg)</th>
<th>b (days⁻¹)</th>
<th>K (days⁻¹)</th>
<th>Ks (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leachate</td>
<td>0.525</td>
<td>0.0025</td>
<td>0.75</td>
<td>200</td>
</tr>
<tr>
<td>Combined Wastewater</td>
<td>0.525</td>
<td>0.0025</td>
<td>0.174</td>
<td>139</td>
</tr>
</tbody>
</table>
feed. Lack of the essential nutrients can prevent biological growth and cause microorganisms to die off. The value of the decay coefficient obtained by Palit and Qasim was also very high compared to other studies (Table 2-3). Uloth and Mavinic (1977) attribute the low value of the decay coefficient to the high substrate concentration available to the biomass. The authors concluded that no endogenous respiration took place and hence the low value of the decay coefficient. Wong and Mavinic (1982) also concluded that the low decay coefficient values were due to the presence of continuing log growth phase.

The growth yield coefficient for domestic wastewater is approximately 0.67 mg VSS /mg BOD$_5$. This value has been found to be lower for leachates. Uloth and Mavinic (1977) state that this may be due, in part, to biological inhibition caused by the trace metals. Wong and Mavinic (1982) also found that the growth yield coefficient is dependent on the strength of the leachate feed, as well as the complexity of the waste.

The half-velocity coefficient has been observed to vary with the type of waste (Uloth and Mavinic 1977). As the complexity of the waste increases or the biodegradability of the waste decreases, the half-velocity coefficient value increases. A very high value suggests that very high MLVSS concentrations are necessary to get reasonable reductions in the influent leachate BOD$_5$.

2.3.2 COMBINED WASTEWATERS

The only known study to evaluate kinetic parameters of a combined wastewater was done by Temoine (1980). The values of the parameters are provided in Table 2-4. According to the author, only one sludge age was used during the experiment and as such the data presented should not be construed as absolute in accuracy. It is simply indicative of a 'trend' in the kinetic evaluation of these reactors.
2.4 FACTORS AFFECTING AEROBIC STABILIZATION

2.4.1 TRACE METALS

A study was carried out by Barth et al. (1965) to determine the effects of trace metals on a conventional activated sludge process. The metals analyzed were chromium, copper, nickel and zinc. The biomass was acclimatized for two weeks before any analysis was done. A continuous dose of copper, with a concentration of 1 mg/L, was found to significantly reduce the treatment efficiency. It was observed that a total heavy metal concentration of 10 mg/L could be tolerated by the biomass.

Neufeld and Hermann (1975) studied the effects of mercury, cadmium and zinc on the activated sludge process. The threshold concentration for cadmium was about 25 mg/L and 8 mg/L for zinc. No threshold effect was observed for mercury and it was concluded that biological inhibition by mercury could be totally counteracted by increasing the concentration of the organic substrate.

Although various studies on the effects of metals have indicated an inhibitory effect on the biomass, several leachate treatment studies have shown that the activated sludge process can effectively remove trace metals (Cook and Foree 1974, Uloth and Mavinic 1977, Temoin and Mavinic 1981, Zapf-Gilje and Mavinic 1981).

The influent leachate feed used by Cook and Foree (1974) had an iron concentration of 240 mg/L. Most of the iron was removed from the 10-day units. This large iron removal, with the final effluent having less than 10 mg/L iron, was attributed mainly to chemical precipitation at the high pH that was maintained in the 10-day units. Significant removal of calcium and magnesium was also observed during the study.
Temoin and Mavinic (1981) used a leachate feed containing a wide range of metals. Aluminium, cadmium, chromium, iron, lead, manganese and zinc were studied. The 20-day sludge age was very effective in removing metals down to a base value, well below toxic levels. No correlation was found between metal removal and nutrient loading. However, there was good correlation between the total suspended solids level and the metal concentration in the settled effluent.

The removal of trace metals with aerobic treatment was also studied by Uloth and Mavinic (1977). It was found that most of the metals in the mixed liquors were removed by the settling biological floc. The high pH values (greater than 8.5) were found to aid metal removal, as did the high MLVSS concentrations. There was no indication of digester instability attributable to these metals. However, an analysis of the kinetic parameters indicated that the high metal concentrations in the mixed liquors probably helped to inhibit the actual biological removal of oxygen demanding material from this leachate.

Zapf-Gilje and Mavinic (1981) also studied the effects of metals on biological treatment. It was found that most metals were reduced in concentration by more than 90 percent. This was attributed to the precipitation of metal hydroxides with subsequent entrapment in biological flocs, sorption by organic solids, and consumption by biomass. Metal reduction was found to be independent of temperature and loading rates.

2.4.2 NUTRIENT REQUIREMENTS

The raw leachate used by Cook and Foree (1974) had a TKN concentration of 240 mg/L, with an ammonia-nitrogen concentration of 10 mg/L. This corresponded to a 43:1 ratio of BOD₅:N. The BOD₅:P ratio was found to be 430:1. Therefore, nitrogen and phosphorus were added in concentrations of 500 mg/L and 100 mg/L, respectively. However, the results from this study showed
that nutrient additions were not needed for successful biological treatment. Efficient nutrient removal was accomplished during the experiment.

Palit and Qasim (1977) found that the leachate they used was also nutrient deficient. The maximum COD of the feed was about 30,000 mg/L, while the TKN value was only 13 mg/L and the phosphorus concentration was approximately 1 mg/L. The kinetic parameters evaluated during the experiment indicated a high decay coefficient for the leachate. This was attributed to the deficiency of nutrients. The residual phosphorus was less than 0.25 mg/L, and the microbial growth was limited to some extent, due to this deficiency.

A study conducted specifically to evaluate the nutrient requirements for leachate was done by Temoin and Mavinic (1981). The study concluded that, for an extended aeration system with a sludge age of 20 days, the required nutrients can be significantly reduced to as low as 100:3.19:0.5, while still producing a good quality effluent. A lower nutrient loading resulted in a poorly settling, bulking sludge. However, at a lower volumetric BOD$_5$ loading, this nutrient ratio could be reduced further.

Wong and Mavinic (1982) also found that a BOD$_5$:N:P loading of 100:3.2:1.1 was "adequate" for treatment. Reactors under this loading compared favorably with a conventional nutrient loading of 100:5:1. Nutrients were added in all units in order to maintain the required loadings. The effect of temperature was not significant in this respect, except for the 5-day SRT, 5°C reactors.

Zapf-Gilje and Mavinic (1981) carried out a study for aerobic bio-treatment of leachate and used a standard nutrient loading of 100:5:1 for all the experiments. This was found to be sufficient at all times and no problems were encountered in this regard.

Uloth and Mavinic (1977) also conducted a study for leachate treatment using aerobic reactors. The BOD$_5$:N:P ratio of the feed was 100:3.3:0.55. Nutrients
were added to the feed, to provide a ratio of 100:6.4:3.1 during the "extended-aeration" study. This addition was found to be "excessive", as high effluent concentrations were observed for both nitrogen and phosphorus. A ratio of 100:5:1, which was provided during the later part of the study, improved the effluent quality without adversely affecting the biological efficiency.

2.4.3 TEMPERATURE EFFECTS

As mentioned earlier, most leachate treatment studies have been conducted at room temperatures. However, a few studies have also been done at lower temperatures (Wong and Mavinic 1982, Zapf-Gilje and Mavinic 1981).

Zapf-Gilje and Mavinic (1981) studied a temperature range from 9 to 25°C. This range seemed to have minimal effects on the biostabilization process of leachate. COD removal efficiency greater than 97 percent was observed during most of the experiments. The MLVSS concentrations increased when the temperature was decreased, and this was attributed to the slower biological activity at lower temperatures. The ideal operating temperature of the dominating biological community was speculated to be somewhere between 9°C and 25°C. The removal of metal ions was not affected by temperature. Iron, manganese, and zinc removal remained unchanged. Results obtained for other elements seemed to vary randomly.

The study conducted by Wong and Mavinic (1982) operated at temperatures ranging from 5°C to 25°C. Problems of poor sludge settling were encountered at the lower temperatures. The lowest sludge age reactors, at 5°C and 10°C, seemed to have a poor effluent quality, with a COD removal efficiency of 94 percent. It was also observed that the temperature had a minimal effect on the removal of most metals. However, chromium and nickel removals appeared very dependent on both sludge age and temperature. The study concluded that the removal of contaminants from leachate were only nominally dependent on the temperature.
2.5 SYSTEM PERFORMANCE

2.5.1 SETTLING CHARACTERISTICS

Most kinetic models proposed for microbial assimilation of organic matter do not indicate the efficiency with which biological solids may be separated from the liquid phase. In the design stage, it is often assumed that one hundred percent efficiency can be attained for solids-liquid separation. This, however, will seldom occur in practice (Bisogni and Lawrence 1971).

According to Pipes (1969), there are several different types of activated sludges which are difficult to separate from the effluent. The production of each specific type of sludge, which separates poorly, is caused by some specific deficiency in the composition of the waste. The poor separation may also be caused by certain environmental conditions like low dissolved oxygen or excess turbulence in the aeration tank.

There are different classifications for poorly settling sludges cited in the literature (Bisogni and Lawrence 1971, Pipes 1969, Neufeld 1976). Bisogni and Lawrence (1971) state that the factors which affect the settling characteristics can be divided into two categories; the first one is associated with changes in the bacterial or zoogaeal population’s physical or biochemical character, whereas the second category involves population shifts from the normal bacterial or zoogaeal types to a filamentous type population.

Bulking sludge is the most commonly occurring type of poorly settling activated sludge (Bisogni and Lawrence 1971, Pipes 1969, Biesinger et al. 1980, Frenzel 1977, Eikelboom 1977, Sezgin et al. 1978, Pitman 1980, Pipes 1979). Bulking sludge is defined as one which settles slowly and compacts poorly. Pipes (1969) and Sezgin et al. (1978) classify the two types of bulking as non-filamentous and filamentous. Non-filamentous bulking occurs in normal zoogaeal
activated sludge. Heukelekian and Weisburg (1956) state that this type of bulking occurs when the activated sludge organisms secrete an extracellular material with a high degree of hydration, thus producing a sludge with excessive amounts of bound water. Filamentous bulking occurs when there is an excessively large number of filamentous organisms in the activated sludge. In the vast majority of cases, the filamentous organism in the sludge has been identified as *Sphaerotilus* (Pipes 1969). In recent years, however, a variety of different filamentous organisms have also been identified (Eikelboom 1977). Eikelboom carried out his study to find out the most commonly occurring filamentous organisms (Table 2-5). *Microthrix parvicella* and Type 021N had been observed most frequently. It was observed that the population composition also depended on the wastewater quality. The same filamentous bacteria were seen in industrial plants as in plants receiving domestic wastewater. However, a clear difference existed between the population of filaments in the two types of plants.

According to Sezgin et al. (1978), in order to achieve a good settling sludge, one must have the correct microbially-mediated physical/chemical conditions. Unless the right conditions for microbial aggregation exists, proper activated sludge flocs cannot form. Filamentous and zoogloal microorganisms are both essential to the integrity of the macrostructure of the activated sludge floc. Filaments form a rigid backbone for the floc, to which flocculent zoogloal organisms attach like flesh on a bone. An absence of filaments leads to the formation of pinpoint floc - a weak floc that shears into small aggregates and particles that tend to contribute to secondary effluent turbidity. An excess of filaments causes the organisms to grow out of the confines of the bulk medium and this results in a slowly settling, poorly compacting sludge.

The authors also postulated that, at low DO concentrations, filamentous organisms grow more rapidly than the zoogloal ones, while at higher DO
TABLE 2-5
Commonly Occurring Filamentous Organisms (Eikelboom 1977)

<table>
<thead>
<tr>
<th>Name of Filamentous Organism</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Microthrix parvicella</em></td>
</tr>
<tr>
<td>Type 021N</td>
</tr>
<tr>
<td><em>Haliscomenobacter hydrossis</em></td>
</tr>
<tr>
<td>Type 0092</td>
</tr>
<tr>
<td>Type 1701</td>
</tr>
<tr>
<td>Type 0041</td>
</tr>
<tr>
<td><em>Sphaerotilus natans</em></td>
</tr>
<tr>
<td>Type 0581</td>
</tr>
<tr>
<td>Type 0803</td>
</tr>
<tr>
<td>Type 0961</td>
</tr>
<tr>
<td><em>Nostocoida limicola</em></td>
</tr>
<tr>
<td>Type 1851</td>
</tr>
<tr>
<td><em>Cyanophyceae</em></td>
</tr>
<tr>
<td><em>Nocardia spp.</em></td>
</tr>
<tr>
<td><em>Fungi spp.</em></td>
</tr>
<tr>
<td>Type 0914</td>
</tr>
<tr>
<td><em>Flexibacter spp.</em></td>
</tr>
<tr>
<td><em>Beggiatoa spp.</em></td>
</tr>
<tr>
<td><em>Thiothrix spp.</em></td>
</tr>
</tbody>
</table>
concentrations the reverse is true. The authors further concluded that a minimum level of 2.0 mg/L for most municipal wastewaters is required for a good settling sludge. Biesinger et al. (1980) also found that low DO is a principal factor in the excessive growth of filamentous organisms. Other factors which also increase the number of filamentous organisms in activated sludge are a low food/microorganism ratio (F/M) and the substrate type.

In a study conducted by Sezgin (1980), to explain the role of filamentous organisms in activated sludge settling, it was found that the settling characteristics, as presented by zone settling velocity, reflocculation time and height of the compacted volume, were related to the length of the filamentous organisms present in the sludge. The filaments were also the most important factor affecting the settling characteristics of activated sludge.

Deflocculation of the sludge is a state in which the sludge shows no tendency to separate. This produces a uniform turbidity in the supernatant above the settled sludge. Deflocculation is usually the result of a toxic shock such as a sudden temperature change (Dougherty and McNary 1958) or a slug of acid waste (Edwards and Nussberger 1947). Neufeld (1976) conducted experiments to study the toxic effects of mercury, cadmium and zinc on the settling characteristics of the sludge. Shock loadings, of these metals, to activated sludge resulted in the loss of significant quantities of biomass over the effluent weir. Maximum deflocculation seems to occur after 10 to 12 days of intimate contact. Pipes (1969) notes that if the toxic conditions are continuous or repeated, the deflocculated state may be established or all of the normal sludge may disappear, thus producing something that looks like dispersed growth. Low dissolved oxygen and low pH are also among the causes of deflocculation (Pipes 1979). Deflocculation has been found to occur at any F/M ratio (Pipes 1979). Bulking, on the other hand, occurs at low F/M ratios. However, bulking and deflocculation can occur simultaneously in an
activated sludge process at F/M ratios greater than 0.4 day\(^{-1}\).

Pinpoint floc results from a lack of sufficient filaments in the biomass (Sezgin et al. 1978). Pinpoint floc consists of small, yet visible, floc particles that are in the supernatant after the sludge has settled (Pipes 1979). There are at least two different types of pinpoint floc. One type appears to be normal activated sludge particles of very small size; the other type consists of white amorphous masses which do not exert an oxygen demand. Pipes (1969) postulates that pinpoint floc is more likely to occur when the temperature in the aeration tank is less than 15°C. Excess turbulence in the aeration tank can also contribute to the formation of a pinpoint floc (Pipes 1969, Sezgin et al. 1978). Pinpoint floc has been observed only in processes with low organic loadings, with an F/M ratio less than 0.2 day\(^{-1}\).

The detailed summary by Pipes (1969) also describes other types of activated sludges which separate poorly. Rising sludge is one which settles well and compacts well for 30 minutes or more. However, after a few hours or so, the sludge rises in a mass to the top of the cylinder. The mechanism of rising sludge depends on the occurrence of nitrification in the aeration tank, denitrification in the settling tank, and entrapment of nitrogen gas bubbles in the compacted sludge mass. Dispersed growth, another characteristic, shows no tendency to separate in a sedimentation tank. The whole biomass is seen as one with a uniform turbidity.

Yet another problem observed in sludge settleability is floating sludge. This means that the individual sludge particles have a density less than water (Pipes 1969). Floating sludge probably can be produced by a number of different biological phenomena. Overaerated sludge can result from violent agitation in the aeration tank. The air bubbles, broken up into very small particles, attach themselves to the sludge and float up to the surface. Overaerated sludge is more likely to occur in an activated sludge process using mechanical aeration (Pipes
For testing settling characteristics, heavy reliance has been placed on the suspended matter and settleability tests and on microscopic examination (Standard Methods 1980). Factors like sludge volume index (SVI), zone settling velocities and percent dispersion are used to define the settling characteristics of sludges. The SVI was originally devised as a quantitative measure of bulking (Pearse and Committee 1937). It measures the compactibility of the sludge.

Typical values of the SVI for good settling sludges, in diffused air aeration plants, operating with MLSS concentrations of 800 to 3500 mg/L, range from 150 to 35 (Metcalf and Eddy 1972). Sludge that is not of the conventional age (5-20 days) or which has a tendency to be fluffy and buoyant and thus to bulk, will have an index greater than 150. The value of SVI is of operational importance, since it reflects changes in the treatment system (Wang et al. 1977).

There are numerous papers on the importance of SVI measurements. Dick and Vesilind (1969) note that SVI has been used as the basic measure of sludge settleability in treatment plants. SVI is also used for comparing the settling characteristics of various sludges. However, the SVI defines only one point on the settling curve and therefore it is not a precise measure of settling characteristics.

There are various factors which influence the value of SVI. There is no consistent relationship between suspended solids concentration and SVI. However, the SVI of a sludge is highly dependent on its suspended solids concentration, with greater concentrations tending to decrease the SVI. Rheological characteristics like yield strength and plastic viscosity are not a direct reflection of the SVI value (Dick and Ewing 1969). No meaningful correlation was obtained either between the interface velocity and SVI (Roberts 1949). The cylinder diameter, in which the settling test is carried out, also affects the value of the SVI (Dick and Vesilind 1969). In comparing the SVI values of the different sludges, it is therefore
important to be consistent with the size of the test cylinder.

Temperature effects on the SVI values have also been shown to be significant (Dick and Vesilind 1969). SVI values tend to decrease with increase in temperature (Figure 2–1). Bisogni and Lawrence (1971) found that the SVI varies with the sludge age in a non-linear manner; this variation is shown in Figure 2–2. Another correlation cited in the literature by Hoepker and Schroeder (1979) is the variation of SVI with the organic loading. The relationship, as shown in Figure 2–3, is not direct and is likely to have significant variations from this representation.

A study conducted by Pitman (1980) also found that the settling characteristics of a sludge improved with increasing sludge age. The settling properties in this study were characterised by the interface settling velocities. Pitman also found that it is important to maintain aerobic conditions in the reactors to prevent excess filamentous growth. It was postulated that the nutrient removal activated sludge plants, incorporating anoxic zones, run a potential risk of developing slow-settling, filamentous sludges.

Sludge settling problems have also been encountered in leachate treatment studies. Boyle and Ham (1974) found that sludge bulking problems predominate at F/M ratios exceeding 1.5 day⁻¹.

Zapf–Gilje and Mavinic (1981), who conducted a study on the biostabilization of leachate, found that the settling characteristics were poor throughout the experiment, and deteriorated significantly with increased organic loadings and decreasing temperatures. The cause for the poor settling was speculated to be the severe loadings on the fill-and-draw systems. Both bulking and deflocculation were observed during the study. The high MLSS concentrations probably resulted in a slower settling sludge.
Figure 2-1: SVI as a function of temperature (Rudolfs and Lacy 1934)

Figure 2-2: SVI as a function of Sludge age (Bisogni and Lawrence 1971)

Figure 2-3: SVI as a function of feed strength. Batch and semibatch operation (Hoepker and Schroeder 1979)
Another leachate treatment study, carried out by Wong and Mavinic (1982), encountered problems due to poor settling. The excessive organic loading was thought to be a possible cause of sludge bulking. All reactors with bulking problems had a F/M ratio higher than 0.17 days$^{-1}$. Reactors with F/M ratios lower than this value did not have any settling problems. Wong and Mavinic also found that the sludge settleability grew progressively worse as the temperatures decreased.

2.5.2 OXYGEN UPTAKE RATES

To evaluate the aerobic treatability of a wastewater, it is necessary to devise a biological reactor which contains the waste, nutrients and the microorganisms and to follow some characteristic property of that system for a period of time. One of the easiest techniques is the observation of the Oxygen Uptake Rate (OUR) (Wang et al., 1977). Green and Shelef (1981) concluded that the viability of the sludge can be determined by observing the OUR values. Oxygen uptake rate increases with increasing growth rate under substrate saturation conditions. It was, however, assumed that any change in OUR is the result of changes in the sludge viability. It was also assumed that an increase in the VSS concentration is due to an increase in the viable cell concentration.

OUR data can be used to show an average, "relative" metabolic activity of the microorganisms at each value of the sludge age (Bisogni and Lawrence, 1971). The relationship between OUR and sludge age is shown in Figure 2-4. For a system in steady-state, the oxygen uptake rates tend to decrease with increasing sludge age.

In aerobic activated sludge systems, oxygen is used as an electron acceptor in the biological oxidation reaction. Thus, the OUR can also be used to represent the respiration rate of the system (Wang et al., 1977). OUR values can also be
Figure 2-4: Oxygen uptake rate Versus Sludge age (Bisogni and Lawrence 1971)

Figure 2-5: Oxygen uptake rate as a function of time for semibatch reactors (Hoepker and Schroeder 1979)
used to monitor the acclimatization of a sludge (Wang et al., 1977). When the OUR approaches a constant value, the sludge can be considered well acclimated.

Hoepker and Schroeder (1979) studied the effect of loading rate on the effluent quality of a batch activated-sludge system. High oxygen uptake rates were observed during the fill phase (as could be predicted intuitively) for a semibatch operation with an 8 hour fill cycle. At the end of the fill phase, the OUR values started to drop and gradually leveled out at the minimum value (Figure 2–5).

A leachate treatment study involving OUR activity was conducted by Boyle and Ham (1974) using an extended aeration process with a 23 hour detention time. This study showed that increased organic loading resulted in higher OUR values. It was speculated that a conventional activated sludge process may respond more severely to leachate inputs with a higher oxygen uptake rate.
3. EXPERIMENTAL METHODS AND ANALYSIS

3.1 EXPERIMENTAL SET UP

3.1.1 REACTOR TYPES

The purpose of this research was to study the treatability of a combined waste stream of leachate and domestic sewage. The two most common type of reactors used for biological treatment are the completely-mixed, continuous flow reactor and the plug flow reactor. The laboratory scale model of the complete-mix, continuous flow reactor was simulated by using a scaled downed version of the same, with a reactor volume of 5-L and a clarifier volume of 1-L. The plug flow system was simulated with a fill-and-draw reactor. The volume of this reactor was also chosen as 5-L. Since the operation of a plug flow system, on a laboratory scale, is difficult, most research work for a plug flow system is done with a fill-and-draw type of operation (Zapf-Gilje and Mavinic 1982, Daigger and Grady 1977). The kinetic model for a plug flow reactor is also similar.

Various related studies performed at the University of British Columbia have made use of fill-and-draw systems. However, the study conducted by Zapf-Gilje and Mavinic (1982) indicated the possible effects of shock loading in a fill-and-draw reactor. In this study, two different types of fill-and-draw reactors were set up, in order to study the possible effects of shock loadings on the system. One reactor was fed once a day while the other was fed the same amount of influent feed over two loadings, in a single day.

The performance of the fill-and-draw reactors was then compared with the complete-mix, continuous flow reactor. All three reactors were operated under similar conditions throughout the entire run.
3.1.2 APPARATUS USED

The two fill-and-draw systems were identical in all respects. Inverted 10-L glass jars were used as reactors. The necks of the glass jars were tightly fitted with rubber stoppers. The bottom of the glass jars was removed. Coarse bubble diffuser stones were fitted through the rubber stoppers at the bottom of the reactors. The reactors were kept completely mixed with the help of constant speed stirrers. Air was supplied through the diffuser by the laboratory's filtered, compressed air system. A schematic of the fill-and-draw system is shown in Figure 3–1.

The continuous flow reactor, unlike the fill-and-draw ones, was made of perspex. The reactor had a rectangular cross section and the bottom edges of the reactor were smoothed to avoid short-circuiting or dead spots in the reactor. The reactor was attached to a clarifier unit of 1-L volume. The clarifier was cylindrically shaped with a cone shaped bottom. A cylindrical influent chamber was also provided for the clarifier so as to direct the solids to the bottom. A constant speed stirrer was provided in the reactor to keep the biomass completely mixed. A coarse bubble air diffuser was also fitted in the reactor. Masterflex pumps, with silicon tubing were used for the influent line feed and the solids recycle. A 10-L tank was used for the influent feed. The feed was stirred intermitently to keep the solids in suspension. The continuous flow system is shown in Figure 3–2.

3.1.3 REACTOR OPERATION

3.1.3.1 Continuous Flow Reactor

The influent feed was prepared by mixing a certain proportion of domestic sewage and leachate, depending on the particular experimental run. The two waste streams were mixed on the basis of volume only. A constant influent flow rate of 5-L/day was maintained throughout the entire study. Since the pumps available
Figure 3-1: FILL-AND-DRAW SYSTEM.

Figure 3-2: CONTINUOUS FLOW SYSTEM.
were not able to pump at a low flow rate of 5-L/day, the influent feed pump was set on a timer. The timer was operated on an on/off cycle of approx. 10 minutes. The 'On' period for one cycle was 6.5 minutes. The influent feed pump was operated at its slowest flow rate of 8.6-L/day.

The recycle pump was operated either continuously or on a timer, depending on the solids build up in the clarifier. The reason for doing this was to ensure complete solids recycle to the reactor. Since the recycle rate varied from run to run, the hydraulic retention time in the clarifier also varied. For this reason, it was decided to evaluate the effluent quality of the continuous flow reactor by performing 1 hour settling tests on the biomass.

The SRT in the continuous flow system was maintained by wasting the appropriate amount of mixed liquor directly from the aerobic reactor. Wastage was done on a once a day basis. The volume of mixed liquor wasted was replaced by distilled water. This procedure involved the removal of some soluble organic food along with the biomass. The amount of food wasted was accounted for in the organic loadings to the reactor. Also, it was anticipated that settling problems would be encountered during some of the runs. Such a problem would make it difficult to replace the organic food that is wasted along with the mixed liquor. In order to maintain uniformity during the entire experimental run, it was decided to waste according to the above mentioned procedure during all steady-state runs.

Completely-mixed conditions were obtained with the help of constant speed stirrers and the air flow. The air flow was kept sufficiently high in the reactor so as to keep the biomass aerobic (DO 2 ppm). Due to the stirring, some water was lost due to evaporation. However, in a continuous flow system, there is no need to replace this lost water since the continuous feed would bring the level in the reactor up to volume. The amount of water lost due to evaporation was calculated by taking the difference between the influent volume and the effluent volume.
From past experience, it was anticipated that domestic sewage used in this experiment would contain nutrients in excess. The leachate, however, was expected to be nutrient deficient in either one or both of the essential nutrients, nitrogen and phosphorus. Since domestic sewage was added to leachate in significantly large proportions, it was decided not to add any nutrients to the influent feed. The nutrient levels were spot checked during the entire study and influent and effluent nutrient levels were monitored for the worst condition.

3.1.3.2 Fill-and-Draw Reactors

Fill-and-draw reactors are commonly used for experimental work due to their ease of operation and their ability to simulate a plug flow reactor. Two reactors of this kind were operated with the intention of studying the effect of different organic loadings on the reactors. One reactor was fed once a day only, whereas the other reactor was fed twice a day. The two reactors were fed the same amount of substrate.

Wastage from the fill-and-draw reactors was done by wasting a certain volume of the mixed liquor, depending on the SRT required. A constant volume, 1-L, of influent feed was added daily during the entire run. Since the volume to be wasted varied according to the SRT required, maintaining a constant total volume of 5-L in the reactor proved to be complicated. To get around this problem, the following elaborate method was adopted:

Firstly, to maintain the required SRT, the volume to be wasted was removed from the reactor. Removal of mixed liquor from all the reactors was done by using a vacuuming system. For the 5 day SRT runs, the volume to be wasted was 1-L, and therefore the influent feed of 1-L could be added to make up the total volume in the reactor. For the twice-a-day reactor, the influent feed was added in two doses of 500 mls. each. For the 10 day and 20 day SRT runs, the wasted volume was less than 1-L. Therefore, during these runs an additional
1-L (approximately) of mixed liquor was removed from the reactor and allowed to settle. The solids were poured back into the reactor while an appropriate amount of the supernatant was wasted. The COD of the supernatant was accounted for in the organic loading calculations. The influent feed of 1-L was then added to the reactor. The above mentioned procedure is schematically shown in Figure 3-3.

Water was also lost to evaporation in the fill-and-draw reactors. This loss of water was adjusted in the supernatant wastage described above. At the end of each feeding operation, the level in the reactors was kept at 5-L.

The dissolved oxygen levels in the fill-and-draw reactors were kept sufficiently high (DO 2 ppm) so as to keep the biomass aerobic at all times. The airflow was kept constant with time and it was not varied over a feeding cycle.

3.2 EXPERIMENTAL RUNS AND START UP PROCEDURES

3.2.1 RUNS CONDUCTED

Based on previous research conducted in this field (Boyle and Ham 1974, Cook and Foree 1974, Zapf-Gilje and Mavinic 1981, Uloth and Mavinic 1977, Palit and Qasim 1977), it was decided to operate the three reactors with SRT's of 5, 10 and 20 days. This would cover the range of conventional activated sludge processes.

The continuous flow reactor was operated at all times with a 24 hour nominal hydraulic retention time (HRT). Nominal HRT is defined as the reactor volume divided by the influent flow. This is a fairly high retention time for conventional activated sludge processes (Metcalf and Eddy 1972). The reasons for keeping a high nominal HRT in the continuous flow reactor were the following:
- leachate is often found to contain high metal concentrations, which may inhibit the biological activity and subsequent uptake of the organic matter.
Figure 3-3: SCHEMATIC OPERATION OF A FILL-AND-DRAW SYSTEM.
- the high organic strength of the feed would restrict the influent flow rate to a low value of 5-L/day, so as to maintain "acceptable" organic loadings to the system. This in turn would require that the reactor size be small, to keep the nominal HRT in the reactor to a reasonable value. An aerobic reactor of 5-L capacity was chosen for this purpose.
- a laboratory scale model would normally require a reactor of at least 5-L capacity. During a steady-state run, a significant amount of mixed liquor is removed for analysis and it would be undesirable to have a much smaller reactor.
- a conventional activated sludge process would not have a high strength organic feed and as such a lower nominal HRT would be sufficient to remove the organic matter.

In the fill-and-draw reactors, the hydraulic retention time was very high due to the very nature of its operation. In this experiment, 1-L of the influent was added every day, to maintain a constant HRT of 5 days. The total volume in the reactor was maintained at 5-L, by wasting the appropriate amount of mixed-liquor and supernatant from the reactor.

Each sludge age was studied for two different ratios of domestic wastewater and leachate. The leachate used had an initial COD of 3530 mg/L. The domestic wastewater used, from the UBC pilot plant's influent feed tank, has a COD value in the range of 200–300 mg/L. The ratios of sewage:leachate used were 80:20 and 60:40, by volume. This resulted in approximate influent COD concentrations of 906 mg/L and 1562 mg/L, respectively. The feed concentrations, however, varied throughout the study period (but not significantly). The COD values for the influent feed were analysed during every steady-state run.

After the room temperature (21–23°C) runs were completed, the reactors were operated under lower temperatures. SRT of 10 days was maintained in all three reactors, during both cold temperature studies. The first cold temperature run
had a sewage:leachate ratio of 80:20. This corresponded to an average influent COD of 905 mg/L. The room temperature maintained for this run was 10°C, with a 8°C liquid temperature. This temperature was selected due to the environmental constraints existing in the laboratory. Perhaps a slightly higher temperature of 12 – 14°C would have been more desirable for this first cold temperature run, but the logistics of this were not attainable. The second cold temperature run involved a further drop in the room temperature to 6°C, with a corresponding 5°C liquid temperature. However, since this drop in temperature was not a significant one, it was decided to increase the organic loading in the reactors to a 60:40 sewage:leachate ratio. The average influent COD for this steady-state run was 1830 mg/L.

A preliminary run was also conducted with no leachate additions to the influent domestic wastewater. Problems of low MLVSS were observed at the 5 day and 10 day SRT's, while serious settling problems were encountered at the 20 day SRT run. The low MLVSS values were a direct result of the low organic loadings to the three systems. The nominal HRT was fixed at 24 hours, and this was too long for the low organic feed. The bulking sludge in the 20 day SRT run was a result of the denitrification taking place in the clarifier. Poor clarifier operation, during the early stages of the experimentation, prevented quick removal of the sludge from the bottom of the clarifier. This further enhanced the problem of denitrification, due to the anaerobic conditions created in the clarifier. Limited results are presented in the later chapters to help serve as a basis for comparison with other steady-state runs.

3.2.2 START UP AND ACCLIMATIZATION

Activated sludge was collected from the UBC pilot plant aerobic reactor. The MLSS of the activated sludge was 1990 mg/L at the time of collection. Since
the preliminary run was operated with only domestic sewage as the influent feed, there was no need to seed or acclimatize the biomass. The three reactors were filled with 5-L of the activated sludge and the operation was started as described earlier. The solids level in the reactor was checked daily, to keep track of the stability of the system. The biomass in all three reactors dropped sharply, due to the low organic loadings on the reactors. The reactors were operated under the same conditions for a duration of approximately 6 weeks; the SRT for the first run was kept at 20 days. Steady-state conditions were assumed when the solids level in the reactors became fairly constant. The MLSS from all three reactors was checked at the time of wasting.

In the follow-up studies, domestic sewage, collected on a weekly basis from the UBC pilot plant, was mixed with the leachate before being used as influent feed. The leachate for the entire study was collected from the Premier Landfill in North Vancouver, B.C.. All the leachate was collected at the start of the experiment and stored at 4°C for future use.

The second set of steady-state runs was conducted with a sewage:leachate ratio of 80:20. Three experimental runs were studied at SRT's of 5, 10 and 20 days. The first steady-state run, at an SRT of 5 days, required acclimatization of the biomass to the leachate component in the feed. Initially, 10% leachate was added with the sewage. This was done for a period of 10 days. After 10 days, the leachate component in the feed was increased to 20%. The reactors were then operated for an additional 4 weeks. The MLSS in all the reactors reached a fairly constant value within 3 weeks. The analyses were then conducted on the various parameters for a further 1 week duration. At least 3 days of analyses were done for each parameter.

The 10 days and 20 days SRT runs, with a 80:20 feed ratio, were operated for 4 weeks and 6 weeks, respectively. As explained earlier, the duration
of each run was governed by the solids level in the reactors. At the end of each steady-state run, the mixed-liquor from all three reactors was mixed together to eliminate any biases developed during a particular run.

The next experimental sequence was operated at 20 days SRT, with a 60:40 sewage:leachate feed ratio. This run showed the highest MLSS levels encountered during the entire study, approximately 8320 mg/L for the continuous flow reactor. The first two weeks of this run were spent acclimatizing the biomass to the higher-strength, organic feed. The run was then conducted for an additional 4 weeks.

The last two steady-state runs, with a 60:40 feed ratio and SRT's of 5 and 10 days, were operated for a total of 4 weeks, at the end of which the solids level had fully stabilized and analyses were completed.

A summary of all experimental runs conducted is provided in Table 3-1.

Table 3-1
Steady State Experimental Program

<table>
<thead>
<tr>
<th>SRT (days)</th>
<th>Leachate:Sewage Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>0:100</td>
</tr>
</tbody>
</table>
3.3 ANALYTICAL PROCEDURES

3.3.1 SOLIDS AND CHEMICAL OXYGEN DEMAND

The mixed-liquor suspended solids (MLSS) and volatile suspended solids (MLVSS) were measured daily during the entire run. The solids level was used as the basis for checking the steady-state conditions. When the biomass reached a fairly steady value, it was assumed that the system was in steady-state. All analysis of solids was done conforming to the procedure outlined in Standard Methods (1980). During a steady-state run, effluent suspended solids and volatile suspended solids were also analysed. All effluent samples were taken after allowing the biomass to settle for 1 hour in a 1-L graduated cylinder. Solids levels, of the wasted supernatant from the fill-and-draw reactors, were also analysed.

Chemical Oxygen Demand (COD) values were analyzed daily during a steady-state run. This test was also in accordance to the Standard Methods procedure. Mercuric sulfate was not added to the sample, as chloride levels in both leachate and domestic wastewater were very low. The COD test was performed on influent and effluent samples.

3.3.2 OXYGEN UPTAKE RATE

This test was used as a means of determining the viability of the biomass. The value of the Specific Oxygen Uptake Rate (SPOUR) was used for comparing the performance of different reactors and the various steady-state runs. The OUR meter used was a Yellow Springs Instruments Co. Ltd., Model 5301 meter. A sample volume of 3 ml was used for each reading. OUR values were analyzed for all steady-state conditions. For every individual steady-state situation, OUR values were also analyzed over a 24 hour period. This was done purposefully to study the difference in the performance of the two fill-and-draw reactors.
3.3.3 DISSOLVED OXYGEN AND pH

Both dissolved oxygen and pH values were spot checked during the entire study. The dissolved oxygen levels were kept more than 2 mg/L at all times in all reactors. There was no strict monitoring of the dissolved oxygen levels, but care was taken to prevent the reactors from going anaerobic. For a few steady-state runs, dissolved oxygen values were observed over a 24 hour period for the two fill-and-draw reactors. A Yellow Springs Instruments Co. Ltd., Model 54A Oxygen meter was used for measuring the dissolved oxygen levels.

The pH meter used for the analysis was a Fisher Accumet Model 320 Expanded Scale Research pH meter.

3.3.4 SLUDGE VOLUME INDEX AND SETTLING

The Sludge Volume Index (SVI) was measured by allowing the biomass to settle for half an hour and observing the ml of sludge settled in the cylinder. Settling was carried out in a 1-L graduated cylinder. The SVI is defined as the volume in ml occupied by 1 gm of activated sludge after settling the aerated liquor for 30 minutes.

The biomass was then allowed to settle for a further half hour and the supernatant from the settling was decanted as the effluent sample. The one hour settling procedure was used as a standard for comparison between steady-states.

3.3.5 TOTAL KJELDAHL NITROGEN AND TOTAL PHOSPHORUS

Total Kjeldahl Nitrogen (TKN) and Total Phosphorus (TP) were also analysed from time to time, during a steady-state run. Analysis for these two parameters was done on the influent and the effluent samples. The main purpose for doing TKN and TP was to check for any nutrient limitations during the steady-state runs. The tests were carried out according to the Technicon Manual
(1974), and the instrument used was a Technicon Auto Analyser II S.C. Colorimeter.

3.3.6 TRACE METALS

For each steady-state run, metal analyses were performed on the sludge samples from each reactor. The metals analyzed were - Iron, Copper, Chromium, Zinc, Cadmium, and Lead. These metals have been known to inhibit the activity of activated sludge microorganisms (Neufeld 1976). An attempt was made to correlate the bioaccumulation of metals in the sludge to the process efficiency. Firstly, the sludge samples were centrifuged and dried; then they were ground and 'wet-ash' digested according to the recommended EPA procedure (March 1979). An Atomic Absorption (AA) Spectrophotometer, a Jarrell Ash AA (Model 810), was used for all metal analyses.
4. RESULTS AND DISCUSSION

4.1 FEED CHARACTERISTICS

Leachate used in this investigation was collected from the Premier Street Landfill situated in North Vancouver, British Columbia. The Premier Landfill leachate is the subject of several investigations at the University of British Columbia; current work involves studying the biological treatability of this leachate using on-site rotating biological contactors, and the anaerobic treatment of leachate using an upflow filter.

Approximately 350-L of leachate were collected from the site at the start of the experiment. This was stored in 20-L polyethylene containers, with airtight caps, at 4°C, throughout the study. The investigation was carried out for a duration of ten months.

The characteristics of the leachate are shown in Table 4-1. The COD of the leachate was checked from time to time and no significant decrease in COD value was observed during the experiment. Initially, BOD₅ tests were carried out but the variation in the BOD₅ values indicated that this could not be used as a reliable measure of organic matter. The use of BOD₅, as a parameter was, therefore, discontinued in the experimental runs.

The domestic sewage used in this experiment was obtained from the influent feed tank of the pilot-plant, at the University of British Columbia. Sewage was collected on a weekly basis and stored at 4°C. The variation in the domestic sewage quality was reflected in the combined influent feed COD concentrations. However, this variation was not found to be significant (detailed later). COD values for each batch of domestic sewage collected were obtained, thus keeping track of the variation in the influent feed. Average characteristics of the domestic sewage are shown in Table 4-2.
TABLE 4-1
Leachate Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Concentration *</th>
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</thead>
<tbody>
<tr>
<td>COD</td>
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</tr>
<tr>
<td>BOD₅</td>
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</tr>
<tr>
<td>pH</td>
<td>6.1</td>
</tr>
<tr>
<td>Total Solids</td>
<td>3246</td>
</tr>
<tr>
<td>Specific Conductance</td>
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</tr>
<tr>
<td>Alkalinity (as CaCO₃)</td>
<td>3258</td>
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<tr>
<td>Total Phosphorus</td>
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<tr>
<td>Total Kjeldahl Nitrogen</td>
<td>53</td>
</tr>
<tr>
<td>Ca</td>
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<tr>
<td>Cd</td>
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</tr>
<tr>
<td>Cr</td>
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<td>Cu</td>
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<tr>
<td>Fe</td>
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</tr>
<tr>
<td>Zn</td>
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</tbody>
</table>

* All concentrations in mg/L, except pH in pH units and Specific Conductance in micromhos/cm.

TABLE 4-2
Sewage Characteristics

<table>
<thead>
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<tbody>
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<td>COD</td>
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<tr>
<td>BOD₅</td>
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<tr>
<td>pH</td>
<td>7.2</td>
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<tr>
<td>Total Kjeldahl Nitrogen</td>
<td>24</td>
</tr>
<tr>
<td>Total Phosphorus</td>
<td>4.2</td>
</tr>
</tbody>
</table>

* All concentrations in mg/L, except pH in pH units.
4.2 RESULTS FROM THE PRELIMINARY EXPERIMENT

A preliminary experiment was conducted to develop an idea of sewage characteristics and system performance. This experiment involved the use of only domestic sewage as influent feed. It was also expected to serve as a basis for comparison with the other experimental runs. All runs were performed at room temperature (21–23°C).

Initially, the bioreactors were operated at a SRT of 5 days. The mixed-liquor suspended solids (MLSS) levels in the fill-and-draw reactors dropped to less than 100 mg/L. In order to build up the biomass, it was decided to increase the SRT to 20 days. However, this increase in SRT caused a decrease in the food/microorganism (F/M) ratio to less than 0.2 days⁻¹, which corresponded to an endogenous phase in the system. Therefore, the biomass at 20 days SRT was also very low (Table 4-3). The biomass levels in the fill-and-draw reactors were considerably lower than the continuous-flow reactor due to the low organic loadings to these systems. Values of various parameters obtained for this run are also provided in Table 4-3. All three reactors indicated average effluent COD's in the range of 25 to 35 mg/L, corresponding to treatment efficiencies from 83.1 percent to 87.6 percent. Settling characteristics for all three systems were poor and pin-point floc was observed throughout the graduated cylinder. This could have been due to the very low MLSS values, thus resulting in a poorly settling floc.

Specific oxygen uptake rate (SPOUR) values taken over a 24-hour period (Figure 4-1) showed that a maximum SPOUR value was reached in each fill-and-draw reactor a few hours after feeding. It was also noted that the maximum SPOUR value in the once-a-day reactor occurred 2 to 3 hours after the twice-a-day system. This seems to indicate that the twice-a-day reactor took up the substrate more efficiently. However, due to the unstable nature of the systems, it was difficult to ascertain any definite relationship or trend from this set of data. The SPOUR
<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Influent Feed (mg/L COD)</th>
<th>Organic Loading (kg COD/m$^3$-day)</th>
<th>MLSS (mg/L)</th>
<th>Effluent COD (mg/L)</th>
<th>% Treatment</th>
<th>Sludge Settling (mls)</th>
</tr>
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<td>0.210</td>
<td>253</td>
<td>35</td>
<td>83.1</td>
<td>20 - 25</td>
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<tr>
<td>Once-a-day Feed</td>
<td>210</td>
<td>0.042</td>
<td>85</td>
<td>33</td>
<td>84.5</td>
<td>5 - 5</td>
</tr>
<tr>
<td>Twice-a-day Feed</td>
<td>210</td>
<td>0.042</td>
<td>96</td>
<td>26</td>
<td>87.6</td>
<td>5 - 5</td>
</tr>
</tbody>
</table>
Figure 4-1: SPOUR Vs Time for the Fill-and-Draw Systems - Preliminary Experiment

Figure 4-2: SPOUR Vs Time for the Continuous-Flow System - Preliminary Experiment
values for the continuous-flow reactor were also obtained. Samples from the continuous-flow system were taken daily. A plot of SPOUR against days, in steady state operation, showed that the variation was quite significant and the system was unstable (Figure 4–2).

The data obtained from this experimental run clearly indicated that this run did not perform well. It is felt that for such a weak influent, the SRT should not have been increased to 20 days. Perhaps, at an SRT of 10 days or less, the system would have performed better. Another important factor, as mentioned earlier, was the significantly high hydraulic retention time (HRT) in the bioreactors (24 hours for the continuous-flow reactor). Metcalf and Eddy (1972) recommend an HRT of 4 to 8 hours in a conventional activated sludge plant. This high HRT probably resulted in the substrate being used up very quickly and the subsequent dieoff of the microorganism in the endogenous phase. Although such a high HRT was required for the aerobic biological treatment of a high strength waste like leachate (discussed earlier), it was felt, that this particular experimental set-up was not feasible for a domestic sewage influent feed. In order to have a significantly higher biomass for the 20 days SRT, either the flow rate had to be increased (thereby increasing the organic loading) or the reactor size had to be reduced (to decrease the HRT). The flow rate, however, could not be increased since there was limited amount of feed available. A reactor size of 5 L is considered to be the minimum recommended size for laboratory work (discussed earlier), and hence a smaller reactor size also was not used.

4.3 RESULTS FROM THE 80:20 EXPERIMENTAL RUNS

4.3.1 MIXED-LIQUOR CHARACTERISTICS

The purpose of conducting this experiment was to study the treatability of a landfill leachate by using different reactor types. Leachate was mixed in varying
proportions with the domestic sewage. The 80:20 run corresponds to 20 percent leachate, by volume, in the domestic wastewater. The influent feed strength (as COD) throughout this entire run varied from 804 mg/L to 952 mg/L. This variation was observed due to the fluctuations in the domestic wastewater quality. The day-to-day variation of the influent feed is provided in Figure 4-3.

Influent feed strengths and the corresponding loadings are shown in Table 4-4. The organic loadings for the continuous-flow reactor varied from 0.781 to 0.888 kg COD/m$^3$-day (48.6 to 55.3 lb COD/1000 cu ft-day). This is within the recommended range of organic loadings for a completely-mixed, activated sludge process (Boyle and Ham 1974, Metcalf and Eddy 1972, Zapf-Gilje and Mavinic 1981). Organic loadings on the fill-and-draw systems ranged from 0.156 to 0.177 kg COD/m$^3$-day (9.7 to 11.0 lb COD/1000 cu ft-day). These values are also within the recommended range (Zapf-Gilje and Mavinic 1981).

In the continuous-flow reactor, food/microorganism (F/M) values during a particular steady-state run are relatively constant and the F/M value can be used to represent the state of the system at all times. The F/M ratio in a fill-and-draw reactor, however, varies at all times. This is due to the nature of the fill-and-draw operation. Two different fill-and-draw reactors should therefore be compared, on the basis of F/M ratios, only if the F/M values have been calculated at a particular time during the feed cycle. In a fill-and-draw system, the initial F/M values, corresponding to the time of feeding, are extremely high and they decrease to their lowest value with time. In this experiment, all F/M values are calculated just before feeding, i.e. at the end of a daily feed cycle. As such, the F/M values obtained for the fill-and-draw reactors are their lowest values. These values do not indicate the system's state at all times. However, in most of the steady-state runs, the 'base' value was reached within 4-5 hours of feeding and it is reasonable to assume that this value is perhaps the single most
Figure 4-3: Variation of Influent Feed COD with Time

5 Days SRT
80:20 Experimental Run
### TABLE 4-4
Operational Characteristics for the 80:20 Experimental Run

(a) Continuous Flow Reactor

<table>
<thead>
<tr>
<th>SRT (days)</th>
<th>Influent Feed (mg/L COD)</th>
<th>Org. Loading (kg COD/m³-day)</th>
<th>Organic Loading (lb COD/1000 cu ft-day)</th>
<th>MLSS (mg/L)</th>
<th>F/M Ratio (kg COD/kg MLSS -day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>888</td>
<td>0.888</td>
<td>55.30</td>
<td>331</td>
<td>2.46</td>
</tr>
<tr>
<td>10</td>
<td>812</td>
<td>0.812</td>
<td>50.60</td>
<td>1899</td>
<td>0.43</td>
</tr>
<tr>
<td>20</td>
<td>781</td>
<td>0.781</td>
<td>48.60</td>
<td>3975</td>
<td>0.20</td>
</tr>
</tbody>
</table>

(b) Once-a-day Reactor

<table>
<thead>
<tr>
<th>SRT (days)</th>
<th>Influent Feed (mg/L COD)</th>
<th>Org. Loading (kg COD/m³-day)</th>
<th>Organic Loading (lb COD/1000 cu ft-day)</th>
<th>MLSS (mg/L)</th>
<th>F/M Ratio (kg COD/kg MLSS -day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>888</td>
<td>0.177</td>
<td>11.00</td>
<td>282</td>
<td>0.63</td>
</tr>
<tr>
<td>10</td>
<td>812</td>
<td>0.162</td>
<td>10.10</td>
<td>513</td>
<td>0.32</td>
</tr>
<tr>
<td>20</td>
<td>781</td>
<td>0.156</td>
<td>9.70</td>
<td>987</td>
<td>0.16</td>
</tr>
</tbody>
</table>

(c) Twice-a-day Reactor

<table>
<thead>
<tr>
<th>SRT (days)</th>
<th>Influent Feed (mg/L COD)</th>
<th>Org. Loading (kg COD/m³-day)</th>
<th>Organic Loading (lb COD/1000 cu ft-day)</th>
<th>MLSS (mg/L)</th>
<th>F/M Ratio (kg COD/kg MLSS -day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>888</td>
<td>0.177</td>
<td>11.00</td>
<td>250</td>
<td>0.71</td>
</tr>
<tr>
<td>10</td>
<td>812</td>
<td>0.162</td>
<td>10.10</td>
<td>532</td>
<td>0.30</td>
</tr>
<tr>
<td>20</td>
<td>781</td>
<td>0.156</td>
<td>9.70</td>
<td>1103</td>
<td>0.14</td>
</tr>
</tbody>
</table>
representative F/M value for the particular system. A more representative F/M value for the system might have been an average value calculated over the daily feed cycle. However, it was found difficult to monitor the F/M values at various times during a feed cycle, mainly due to the limited quantity of mixed-liquor available.

In all three reactors, it was expected that the F/M ratio would decrease as the SRT increases. A definite trend towards this was indicated. The relationship between F/M ratio and SRT, for the continuous-flow reactor, is shown in Figure 4-4 (a). The F/M value for the 5-day SRT was 2.46 kg COD/kg MLSS-day. This high F/M value is attributed to the low mixed-liquor suspended solids (MLSS) in the reactor, due to the loss of solids in the effluent and improper clarifier operation. The 5-day SRT was the first steady-state run carried out; a few operational problems were encountered, such as solids accumulating in the clarifier. This led to anaerobic conditions for the biomass in the clarifier and subsequently to some gas formation; this, in turn, resulted in rising sludge and solids loss in the effluent. This problem was corrected by changing the operation of the recycle pump to an intermittent 'on-off' basis. A slow speed stirrer (1 rpm) was also installed in the clarifier to prevent the sludge from clogging the opening of the recycle line. These modifications worked fairly well and no further operational problems were encountered during the rest of the study.

The F/M ratios at different SRT's, for the two fill-and-draw reactors, are compared in Figure 4-4 (b). These 'minimum' F/M values indicate that the 'base' F/M ratio in both fill-and-draw reactors was approximately the same. As expected, both reactors experienced a drop in the F/M ratio with increase in SRT, thereby agreeing with the kinetic model proposed by Lawrence and McCarty (1970).

Since the organic loadings did not vary much with the SRT's, for a particular system, it was anticipated that a change in the F/M ratio would also
Figure 4-4: F/M Ratio Vs SRT - 80:20 Experimental Run
lead to a change in the MLSS of the system. A decrease in the F/M ratio with increasing SRT implies that the MLSS in the reactors would increase, the organic loading being approximately constant. The variation of the MLSS with SRT is shown in Figure 4–5 (a). MLSS values varied slightly during each steady-state run. This variation, however, was much less during the 20–day SRT run (Figure 4–6), thereby indicating a more stable operation. Average values obtained for a particular steady-state run have been used for comparison and calculation purposes.

An interesting trend was indicated in the relationship between percent mixed-liquor volatile suspended solids (MLVSS) and the SRT's. The MLVSS percentage is known to vary with the SRT in any biological reactor (Metcalf and Eddy 1972, Zapf–Gilje and Mavinic 1981). The variation, however, seems to be a complex one. On the one hand, percent MLVSS tends to decrease as the SRT is increased, due to the drop in the F/M ratio (leading to endogenous respiration); this is a result of the limited substrate available to the biomass. The biodegradable portion of the feed is used up completely, whereas the non-biodegradable and inert fractions keep accumulating. The consequence of this is a drop in the percent MLVSS at a higher SRT. This argument holds as long as the feed strength remains the same. However, an increase in the feed strength also increases the total inert content. The increase in the biodegradable fraction results in an increase in the activity of the microorganisms and, at a long SRT, this fraction is completely used up. The net result of this is a decrease in the percent MLVSS in the reactor. For a complex waste like leachate, the inert fraction may be a significant amount. In such a case, the drop in percent MLVSS with an increase in SRT may not be as large as one might expect, since the inert fraction is already quite high.

The percent MLVSS is plotted against the SRT, for all the steady-state runs, in Figure 4–5 (b). For the continuous-flow reactor, the percent MLVSS
Figure 4-5: Mixed-Liquor Solids - 80:20 Experimental Run
Figure 4-6: MLSS Vs Days in Steady State - 80:20 Experimental Run
dropped from 72.8 percent, at a 5-day SRT, to 59.3 percent at a 20-day SRT. A similar pattern, with larger differences, however, was also observed for the two fill-and-draw reactors (Table 4-5 (a)).

The Specific Oxygen Uptake Rate (SPOUR) values (expressed as mg/gm VSS-hr) are used to determine the metabolic activity of the microorganisms (Bisogni and Lawrence 1971). In a fill-and-draw system, the SPOUR value varies with time during a feed cycle. This variation, however, is different from the F/M ratio. SPOUR values reach a maximum after a short time period and then decline to their 'base' value, which also corresponds to their lowest value during a feed cycle. In this study, SPOUR values were also obtained just before feeding. Therefore, the SPOUR values in the fill-and-draw systems are their lowest values and the average values would perhaps be higher. However, in most cases, the 'base' values were reached within 4-5 hours, thereby indicating this value to be the single most representative value for the system. Since the procedure for obtaining SPOUR data requires only 3 ml. of the mixed-liquor, it was also possible to obtain SPOUR values over the entire feed cycle.

SPOUR values were expected to decrease with an increase in SRT. This was confirmed by the data obtained (Table 4-5 (b)). Variations of SPOUR with SRT, for the three reactors, are shown in Figure 4-7. As the amount of food available to the biomass decreases, due to a longer sludge age, the activity of the biomass is likely to drop. The same trend was observed in all three reactors. This also indicates that, at longer sludge ages, the log growth phase was virtually non-existent, since SPOUR values were quite low. This conforms well to published theory (Metcalf and Eddy 1972).

SPOUR values were also monitored on a day-to-day basis, during each steady-state run, for all three reactors. Significant variations were observed in the 5-day SRT run. However, in the 10-day and 20-day SRT runs, SPOUR values
TABLE 4-5
(a) Effect of SRT on Suspended Solids for the 80:20 Run

<table>
<thead>
<tr>
<th>SRT (days)</th>
<th>Cont. Flow Reactor</th>
<th>Once-a-day Reactor</th>
<th>Twice-a-day Reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MLSS (mg/L)</td>
<td>MLVSS (mg/L) (%)</td>
<td>MLSS (mg/L)</td>
</tr>
<tr>
<td>5</td>
<td>331</td>
<td>241</td>
<td>72.8</td>
</tr>
<tr>
<td>10</td>
<td>1899</td>
<td>1178</td>
<td>62.0</td>
</tr>
<tr>
<td>20</td>
<td>3975</td>
<td>2355</td>
<td>59.3</td>
</tr>
</tbody>
</table>

(b) Effect of SRT on SPOUR Values for the 80:20 Run

<table>
<thead>
<tr>
<th>SRT (days)</th>
<th>Cont. Flow Reactor (mg/gm VSS-hr)</th>
<th>Once-a-day Reactor (mg/gm VSS-hr)</th>
<th>Twice-a-day Reactor (mg/gm VSS-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>179</td>
<td>29.2</td>
<td>16.9</td>
</tr>
<tr>
<td>10</td>
<td>18.6</td>
<td>16.0</td>
<td>14.2</td>
</tr>
<tr>
<td>20</td>
<td>12.1</td>
<td>10.7</td>
<td>8.3</td>
</tr>
</tbody>
</table>
Figure 4-7: SPOUR Vs SRT - 80:20 Experimental Run
Figure 4-8: SPOUR Vs Days in Steady State - 80:20 Experimental Run
were found to be much more consistent (Figure 4-8). This indicates that an increase in the biomass of the system tends to stabilize the activity of the microorganisms, thereby creating a more uniform system, with a lower probability for 'plant upset'. The SPOUR values also conform well with the variation in MLSS values during a particular steady-state operation (Figure 4-6).

Values for pH in the reactors were noted for all three steady-state systems, and it was found that at higher SRT's, the pH values were more uniform. pH, however, did not depart at any time out of an acceptable range (6.5 to 8.5) (Figure 4-9).

4.3.2 EFFLUENT CHARACTERISTICS

The effluent characteristics for this experimental series are summarized in Table 4-6.

The average effluent COD, for each of the three reactors, dropped when the SRT was increased from 5 days to 10 days. In the continuous-flow reactor (the system performing most efficiently at the 5-day SRT), the average effluent COD dropped from 73 mg/L to 58 mg/L at the 10-day SRT (Figure 4-10 (a)). This resulted in a marginal improvement in treatment efficiency from 91.8 percent to 92.8 percent COD removal (Figure 4-10 (b)). This decrease in the effluent COD could be expected due to the decrease in the F/M ratio at the 10-day SRT and, as such, there was less substrate available to the biomass. The fill-and-draw reactors also performed in a similar fashion, with the average effluent COD in the once-a-day reactor dropping from 83 to 72 mg/L; the twice-a-day reactor had its average effluent COD reduced from 83 to 62 mg/L.

The same trend was expected when the SRT was increased further to 20 days. However, the effluent COD for all three reactors increased, thereby leading to a reduction in the treatment efficiency. The continuous-flow reactor was the
Figure 4-9: pH Vs Days in Steady State - 80:20 Experimental Run
TABLE 4-6
Effluent Characteristics for the 80:20 Experimental Run

(a) Continuous Flow Reactor

<table>
<thead>
<tr>
<th>SRT (days)</th>
<th>F/M Ratio (kg COD/kg MLSS-day)</th>
<th>Influent COD (mg/L)</th>
<th>Effluent COD (mg/L)</th>
<th>% Eff.</th>
<th>Effl. Susp. Solids (mg/L)</th>
<th>SVI (ml/gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2.46</td>
<td>888</td>
<td>73</td>
<td>91.8</td>
<td>25</td>
<td>312</td>
</tr>
<tr>
<td>10</td>
<td>0.43</td>
<td>812</td>
<td>58</td>
<td>92.8</td>
<td>23</td>
<td>71</td>
</tr>
<tr>
<td>20</td>
<td>0.20</td>
<td>781</td>
<td>112</td>
<td>85.7</td>
<td>17</td>
<td>42</td>
</tr>
</tbody>
</table>

(b) Once-a-day Reactor

<table>
<thead>
<tr>
<th>SRT (days)</th>
<th>F/M Ratio (kg COD/kg MLSS-day)</th>
<th>Influent COD (mg/L)</th>
<th>Effluent COD (mg/L)</th>
<th>% Eff.</th>
<th>Effl. Susp. Solids (mg/L)</th>
<th>SVI (ml/gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.63</td>
<td>888</td>
<td>83</td>
<td>90.7</td>
<td>57</td>
<td>118</td>
</tr>
<tr>
<td>10</td>
<td>0.32</td>
<td>812</td>
<td>72</td>
<td>91.1</td>
<td>53</td>
<td>60</td>
</tr>
<tr>
<td>20</td>
<td>0.16</td>
<td>781</td>
<td>78</td>
<td>90.0</td>
<td>13</td>
<td>56</td>
</tr>
</tbody>
</table>

(c) Twice-a-day Reactor

<table>
<thead>
<tr>
<th>SRT (days)</th>
<th>F/M Ratio (kg COD/kg MLSS-day)</th>
<th>Influent COD (mg/L)</th>
<th>Effluent COD (mg/L)</th>
<th>% Eff.</th>
<th>Effl. Susp. Solids (mg/L)</th>
<th>SVI (ml/gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.71</td>
<td>888</td>
<td>83</td>
<td>90.6</td>
<td>51</td>
<td>120</td>
</tr>
<tr>
<td>10</td>
<td>0.30</td>
<td>812</td>
<td>62</td>
<td>92.4</td>
<td>46</td>
<td>61</td>
</tr>
<tr>
<td>20</td>
<td>0.14</td>
<td>781</td>
<td>96</td>
<td>87.6</td>
<td>19</td>
<td>46</td>
</tr>
</tbody>
</table>
Figure 4-10: Effluent Characteristics Vs SRT - 80:20 Experimental Run
least efficient, with an average effluent COD increasing from 58 mg/L to 112 mg/L; this represented a change in treatment efficiency from 92.8 percent to 85.7 percent. The once-a-day and twice-a-day reactors also experienced a deterioration in effluent COD, with increases from 72 to 78 mg/L and 62 to 96 mg/L, respectively (the reasons for this trend will be discussed later in this section).

The effluent suspended solids levels, which are also indicative of effluent quality, however, continued to drop in all reactors. The continuous-flow, once-a-day and twice-a-day reactors had average effluent suspended solids levels of 17, 13 and 19 mg/L, respectively for the 20-day SRT run. This was an improvement over the effluent suspended solids level for the 5-day and 10-day SRT runs (see Table 4-6). Analyses of these two effluent quality parameters lead to the conclusion that there must have been a release of soluble organics at an SRT of 20 days. The F/M ratios for all three reactors indicate that the bioreactors were operating under endogenous respiration, at a 20-day SRT; this is typically characterized by an F/M ratio of less than 0.2 day\(^{-1}\). It is quite possible, and indeed probable, that cell lysis took place at the low F/M values, resulting in the release of soluble organics to the effluent and thus a lower COD removal efficiency. Since BOD, values were not determined, it is not known, however, what fraction of these organics were biodegradable.

As mentioned earlier, the Sludge Volume Index (SVI) is one of the most common parameters used for estimating effluent quality. SVI values were monitored throughout the entire study. A sludge with a SVI value between 35 and 150 is considered to be a properly settling sludge (Dick and Vesilind 1969). In this set of experiments, the only exception to this range of values was the continuous-flow reactor, during the 5-day SRT run. The SVI value for that particular steady-state system was 312 (see Table 4-6). The reason for this high value was improper clarifier operation (explained earlier), eventually leading to rising sludge and a
solids loss in the effluent. All the other reactors, under different steady-state conditions, indicate the presence of a properly settling sludge. SVI values, for all three systems, dropped with increasing SRT. This conforms well with the effluent suspended solids level which also dropped with increasing SRT. It can therefore be concluded that the settling properties of the biomass improved with sludge age. However, due to endogenous respiration, cell lysis occurred during the 20-day SRT experimental run and caused the effluent COD to increase.

4.3.3 COMPARISON OF DIFFERENT REACTOR TYPES

One of the main objects of this study was to compare the performance of different reactor types while treating the combined waste. All three reactors were operated under similar environmental conditions, at all times. The mixed-liquors were intermixed, to ensure for randomness, before each experimental run.

The organic loadings in the two fill-and-draw reactors were kept the same at all SRT's. However, the organic loading in the continuous-flow reactor was approximately 5 times higher. For example, for the 10-day SRT, the fill-and-draw reactors had an organic loading of 0.162 kg COD/m$^3$-day, while the continuous-flow reactor had a loading of 0.812 kg COD/m$^3$-day. This difference resulted from the operational characteristics of the two reactor types. Even though the difference in the organic loadings between the continuous-flow system and the fill-and-draw systems was 5 times, observed MLSS values were only 4 times higher in the continuous-flow reactor. This might be expected since, at very high substrate concentrations, the ability of the microorganisms to metabolize the substrate in the log growth phase is restricted by their own growth rate.

The variation in the percent MLVSS for the different reactor types was also studied in detail (see Table 4-5). As noted earlier, all three reactors indicated a drop in the percent MLVSS with increase in SRT, and the cause was attributed
to the limited substrate available per unit of biomass, i.e. a low F/M ratio. However, it is interesting to compare the percent MLVSS, for the same SRT, in the three different reactor types. For example, at the 5-day SRT, the continuous-flow reactor had a MLVSS percentage of 72.8 percent, which is somewhat lower than the percent MLVSS for the two fill-and-draw systems (Figure 4-11). At the 10-day and 20-day SRT's, however, the fill-and-draw systems had a lower MLVSS percentage. This phenomenon can be partially explained by studying the variation in the Specific Oxygen Uptake Rate (SPOUR) over a feed cycle. For the 5-day SRT (Figure 4-12), the 'base' SPOUR value for the once-a-day reactor was reached approximately 21 hours after feeding (for a 24-hour feed cycle). Similarly, the twice-a-day reactor reached its 'base' value approximately 9 hours after feeding (for a 12-hour feed cycle). Thus, the biomass exhibited a higher activity, as compared to its 'base' value, during most of the feed cycle. It is, therefore, inferred that there was sufficient food (but not excess) available to the biomass, for the 5-day SRT, at most times of the fill-and-draw feed cycle.

In the continuous-flow reactor, at a 5-day SRT, the amount of substrate available was also very high (as indicated by the much higher F/M ratio), but the value of the percent MLVSS in the continuous-flow reactor, although very high at 72.8 percent, was slightly lower than the percent MLVSS in the fill-and-draw system (Table 4-5). It appears then that the biomass, in the continuous-flow reactor, was unable to metabolize the excess substrate, thus suppressing the production of new biomass, and hence lowering the value of the percent MLVSS. The fill-and-draw systems, did not experience "excess substrate" conditions, even at the 5-day SRT, and were therefore able to convert most of the available food into new biomass.
Figure 4-11: Percent MLVSS Vs SRT - 80:20 Experimental Run
Figure 4-12: SPOUR Vs Time (5 Days SRT) - 80:20
Experimental Run
The uptake of food in the 10 and 20-day SRT systems, however, was quite different compared to the 5-day SRT. Figure 4–13 shows the variation of SPOUR with time, for the 20-day SRT (similar for a 10-day SRT). In this case, the 'base' value was reached after approximately 1 hour of feeding. The F/M ratios, during the 20-day SRT, for the once-a-day and twice-a-day reactor were 0.16 and 0.14 day\(^{-1}\), respectively. This implies that the two fill-and-draw reactors were in the endogenous respiration state for most of the feeding cycle; this, in turn, would lead to a decrease in the percent MLVSS, since most of the biodegradable fraction is used up. The continuous-flow reactor, however, had an F/M ratio of 0.20 day\(^{-1}\), for the 20-day SRT, throughout the feed cycle; this means more available substrate, greater biomass activity and a percent MLVSS higher than the fill-and-draw systems. A similar explanation would follow the 10-day SRT data.

The difference in the average solids levels of the two fill-and-draw reactors was also observed. Since the 5-day and 10-day SRT systems had very low MLSS values (see Table 4–4), it was difficult to ascertain any difference between the solids levels of the two reactors. Wide fluctuations were observed in the MLSS values during the steady-state operation of the 5-day SRT unit (see Figure 4–6), thereby indicating an unstable operation. Variations in the SPOUR values (Figure 4–8) also support the above observations. However, as the SRT was increased to 20 days and the biomass also increased, a definite trend was indicated. At the 20-day SRT, the twice-a-day reactor was found to have a higher average solids level, 1103 mg/L, as compared to the once-a-day reactor, 987 mg/L, approximately 12 percent higher (Figure 4–5 (a)). This higher solids level might be due, in part, to a more efficient conversion of the available substrate over a twice-a-day feeding cycle.
Figure 4-13: SPOUR Vs Time (20 Days SRT) - 80:20
Experimental Run
The F/M ratios in the continuous-flow reactor were higher than the fill-and-draw systems, for all SRT's. As explained earlier, this was to be expected since the observed F/M values in the continuous-flow reactor were indicative of the average F/M ratio in the system, whereas F/M values in the fill-and-draw reactors were the 'minimum' F/M values for that system. The "average" value of the F/M ratio for the fill-and-draw reactors would be higher, however, although this average value was not monitored during this study. As such, it was difficult to compare the F/M values between the continuous-flow reactor and the fill-and-draw systems; however, the 'base' F/M values for the two fill-and-draw reactors were compared and they were found to be approximately equal (see Figure 4-4 (b)).

The main basis for comparing the two fill-and-draw systems were the Specific Oxygen Uptake Rate (SPOUR) values. Samples from the mixed-liquor were taken after every few minutes, over a 24-hour period, during each steady-state set of experiments. The variation of SPOUR over 24 hours for both fill-and-draw reactors, is shown in Figures 4-12 & 4-13. Plots are shown for the 5-day and 20-day SRT's, for comparison. During the 20-day SRT run, SPOUR values for the twice-a-day reactor reached a maximum value of 110 mg/gm VSS/hr, whereas the once-a-day reactor attained a maximum of only 85 mg/gm VSS/hr. This clearly indicates that the biomass in the twice-a-day reactor was more active and probably less susceptible to any form of 'shock' loading. Also, at the 20-day SRT (Figure 4-13), the decline in the SPOUR values (after the maximum value was reached), was fairly steep for both reactors, indicating that the substrate was taken up very quickly. The biomass was subsequently in endogenous respiration for the remainder of the cycle; this would eventually result in cell lysis, thereby deteriorating the effluent quality (in terms of effluent COD).
The 5-day SRT run, in turn, was characterized by a more gradual decline in the SPOUR values (see Figure 4-12). This indicates that there was excess food available, for the level of biomass, through most of the feeding cycle. At the 5-day SRT, the maximum SPOUR value for the once-a-day reactor, 175 mg/gm VSS-hr, was lower as compared to the twice-a-day reactor, 250 mg/gm VSS-hr. Therefore, in both the 5-day and 20-day SRT runs, the twice-a-day system indicated a more 'active' biomass as compared to the once-a-day system.

It was also interesting to note that, in the 5-day SRT, the maximum SPOUR values in both the fill-and-draw reactors were reached anywhere from 1 to 4 hours after feeding. Contrary to this, during the 20-day SRT run, both fill-and-draw reactors showed an almost immediate oxygen demand (see Figure 4-13). Because of the low F/M ratios observed in the 20-day SRT systems, the biomass would be in the endogenous respiration state at the start of the feeding cycle; in the 5-day SRT systems, however, the endogenous respiration state would not likely be reached. As such, the oxygen demand of the two regimes would be expected to be different.

The DO levels in the bioreactors were kept greater than 2 ppm at all times. However, during feeding, the DO level in the fill-and-draw systems fell steeply to a very low level. For example, in the 20-day SRT system, the DO level went below 0.2 ppm in the twice-a-day reactor for a duration of few minutes (Figure 4-14). However, aerobic conditions with DO greater than 2 ppm were re-established after a duration of 1 hour. The corresponding DO drop upon feeding, in the once-a-day reactor, was not as great. This again confirms the earlier conclusion, based on SPOUR values, that the twice-a-day reactor was more 'active' than the once-a-day system.

According to Zapf-Gilje and Mavinic (1982), the DO levels in a fill-and-draw system are characterized by two significant drops during a leachate
Figure 4-14: D.O. Vs Time (20 Days SRT) - 80:20
Experimental Run
feed cycle. The first drop is an immediate one and it takes place due to zero-order metal oxidation in the leachate. The DO levels recover after an hour or so and then a less significant drop takes place; this is attributed to a population shift of the microorganisms from anaerobic to aerobic.

In this experiment, the sewage:leachate feed was pre-aerated before being fed into the reactor. Hence it can be assumed that metal oxidation had taken place before feeding. For example, iron would be present in ferrous form in the absence of oxygen; however, oxidation would result in the conversion of ferrous to ferric. The DO drop in this study was thus attributed more to microbial growth. Furthermore, a DO drop, due to metal oxidation, would have resulted in even a higher DO drop for the once-a-day reactor (the maximum SPOUR value for the once-a-day reactor should also have been higher), since the once-a-day system was fed twice the amount of feed at one time as compared to the twice-a-day system. This was not the case, however, and it can be concluded that the biomass in the twice-a-day reactor was basically in a more active state.

The effluent characteristics of the three reactors were also compared. The biomass in the continuous-flow reactor did not settle well at the 5-day SRT; however, the settling properties of this particular biomass did improve with SRT, and at a 20-day SRT, the performance of this reactor was better than the other two systems (in terms of SVI values). The average effluent solids levels in the three reactors were comparable (for the 20-day SRT), with each system having an average effluent solids level less than 20 mg/L (see Table 4-6).

As mentioned earlier, the continuous-flow reactor experienced the largest increase in effluent COD, when the SRT was increased from 10 to 20 days. The reason for this was probably the existence of an endogenous respiration state (F/M ratio less than 0.2 day\(^{-1}\)) during the 20-day SRT reactor operation; essentially, cell lysis took place almost continuously. In the fill-and-draw reactors, however, the
endogenous respiration state was achieved only during part of the feed cycle (near the end), the result being much less cell lysis occurring. The twice-a-day reactor proved to be the most active one from all the data obtained. As a result, this system reached an endogenous state earlier, in comparison to the once-a-day system. Cell lysis, therefore, was more prevalent in the twice-a-day system, with corresponding higher COD values (see Table 4-6). The net result of this appears to be that at very high SRT's (or low F/M ratios), the once-a-day feed system might be expected to produce the best quality effluent for a combined leachate/sewage feed mix.

4.4 RESULTS FROM THE 60:40 EXPERIMENTAL RUN

4.4.1 MIXED-LIQUOR CHARACTERISTICS

The 60:40 experimental run corresponds to the presence of 40 percent leachate, by volume, in the influent feed. The feed strengths in this set of steady-state runs were approximately 1200 mg/L. Variations in the influent feed COD concentrations, for the different SRT's, were not significant (Table 4-7). This run was therefore characterized by a higher organic loading, as opposed to the 80:20 experimental run. The main purpose of setting up this experiment was to study the effect of a higher organic loading on the treatability of the different reactor types. It is, however, important to note that a change in the sewage:leachate ratio also resulted in an 'effective' change in the composition (in terms of concentrations) of the influent feed. This led to significant changes in the performance of the three reactors, as discussed later.

The values of the organic loadings and the influent COD's are provided in Table 4-7. In the continuous-flow system, the influent COD varied from 1156 mg/L to 1323 mg/L, which corresponds to organic loadings of 1.16 kg
<table>
<thead>
<tr>
<th>SRT (days)</th>
<th>Influent Feed (mg/L COD)</th>
<th>Org. Loading (kg COD/m³-day)</th>
<th>Organic Loading (lb COD/1000 cu ft-day)</th>
<th>MLSS (mg/L)</th>
<th>F/M Ratio (kg COD/kg MLSS-day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
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<td>1.238</td>
<td>77.0</td>
<td>3088</td>
<td>0.40</td>
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<tr>
<td>10</td>
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<td>72.0</td>
<td>4939</td>
<td>0.23</td>
</tr>
<tr>
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<td>1323</td>
<td>1.323</td>
<td>82.40</td>
<td>8322</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRT (days)</td>
<td>Influent Feed (mg/L COD)</td>
<td>Org. Loading (kg COD/m³-day)</td>
<td>Organic Loading (lb COD/1000 cu ft-day)</td>
<td>MLSS (mg/L)</td>
<td>F/M Ratio (kg COD/kg MLSS-day)</td>
</tr>
<tr>
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<td>1297</td>
<td>0.259</td>
<td>16.1</td>
<td>1029</td>
<td>0.25</td>
</tr>
<tr>
<td>10</td>
<td>1160</td>
<td>0.232</td>
<td>14.4</td>
<td>1402</td>
<td>0.17</td>
</tr>
<tr>
<td>20</td>
<td>1304</td>
<td>0.260</td>
<td>16.20</td>
<td>1899</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRT (days)</td>
<td>Influent Feed (mg/L COD)</td>
<td>Org. Loading (kg COD/m³-day)</td>
<td>Organic Loading (lb COD/1000 cu ft-day)</td>
<td>MLSS (mg/L)</td>
<td>F/M Ratio (kg COD/kg MLSS-day)</td>
</tr>
<tr>
<td>5</td>
<td>1273</td>
<td>0.254</td>
<td>15.8</td>
<td>1124</td>
<td>0.23</td>
</tr>
<tr>
<td>10</td>
<td>1140</td>
<td>0.228</td>
<td>14.2</td>
<td>1547</td>
<td>0.15</td>
</tr>
<tr>
<td>20</td>
<td>1304</td>
<td>0.260</td>
<td>16.20</td>
<td>2296</td>
<td>0.11</td>
</tr>
</tbody>
</table>
COD/m³-day to 1.32 kg COD/m³-day. This variation was attributed mainly to the fluctuations in the domestic sewage quality. A similar variation in the influent feed COD's was also observed for the fill-and-draw systems. Due to the nature of the fill-and-draw operation, these reactors had an organic loading 5 times less than the continuous-flow system, varying from 0.228 to 0.260 kg COD/m³-day. A study conducted by Zapf-Gilje and Mavinic (1981) recommended the use of a maximum organic loading of 3.2 kg COD/m³-day, for a fill-and-draw system. Therefore, all organic loadings during this experimental run were well below this upper limit.

Food/microorganism (F/M) ratios for the different steady-state runs are also given in Table 4-7. In the continuous-flow reactor, F/M values ranged from 0.16 days⁻¹, at the 20-day SRT, to 0.40 days⁻¹, at the 5-day SRT. This indicated again that this system was in endogenous phase during the 20-day SRT operation. The F/M values obtained for the fill-and-draw reactors were less than 0.20 days⁻¹ for the 10-day and 20-day SRT's, also indicating an endogenous phase. However, the F/M values for the fill-and-draw reactors were obtained just before feeding, and as such, they represent only the 'base', lowest values in the systems.

According to the kinetic model of Lawrence and McCarty (1970), an increase in the SRT is characterized by a decrease in the F/M ratio. The plots of F/M ratios against SRT, for all three reactors, are given in Figure 4-15. As expected, the three reactors showed a decrease in the F/M ratio with increasing SRT.

In the previous 80:20 experimental run, it was observed that the difference between the mixed-liquor suspended solids (MLSS) values, for the two fill-and-draw reactors, increased with increasing SRT. At a 20-day SRT, for the 80:20 run, the twice-a-day reactor showed a 12 percent higher MLSS value. However, this difference, in the 60:40 run, was found to be approximately 21 percent at the 20-day SRT, with the twice-a-day reactor having the higher
Figure 4-15: F/M Ratio Vs SRT - 60:40 Experimental Run
average value of 2296 mg/L (Table 4-7). The continuous-flow reactor indicated an almost linear increase in MLSS with SRT for the three steady-states (Figure 4-16 (a)). For the 20-day SRT, the average MLSS concentration in the continuous-flow reactor was 8322 mg/L. The linear increase in the MLSS with increase in SRT indicates that biological growth was not inhibited at any SRT during the experimental runs.

The MLSS values for the different reactors were obtained daily during a steady-state operation. The variation in the MLSS values during steady-state operations are given in Figure 4-17. The systems showed fairly stable operation, at all SRT's, and the variations in the MLSS values were, for the most part, not significant. Average values were computed for a particular steady-state and these values were used for comparison and calculation purposes.

The nature of the fill-and-draw operation did allow for a more stable operation, on a day-to-day basis; there was no loss of solids over the effluent weir and there was no problem of recycling the solids. This stability is reflected in the MLSS values for the fill-and-draw systems (Figure 4-17). For example, at the 5-day SRT, the once-a-day system experienced a variation from 919 mg/L to 1124 mg/L in the MLSS values, a maximum variation of 10.6 percent from the average computed value of 1028 mg/L. On the other hand, the continuous-flow system, at the 5-day SRT, had a variation from 2839 mg/L to 3568 mg/L in its MLSS value, which corresponds to a maximum variation of 16 percent from the average value of 3080 mg/L.

Another significant aspect of this experiment was to study the relationship between percent mixed-liquor volatile suspended solids (MLVSS) and SRT. In the 80:20 experimental run, the percent MLVSS in all three reactors dropped with an increase in SRT. Such a trend, however, could not be predicted for this set of steady-state runs since the organic loadings were significantly higher. As mentioned
Figure 4-16: Mixed-Liquor Solids - 60:40 Experimental Run
Figure 4-17: MLSS Vs Days in Steady State - 60:40 Experimental Run
earlier, a complex waste like leachate contains a significant inert fraction and this could reduce the percent MLVSS in all three systems. The values of percent MLVSS obtained for this set of steady-state runs are provided in Figure 4–16 (b) and Table 4–8 (a). Due to the increased organic loadings, the percent MLVSS during the different SRT's, for all three reactors, were much lower as compared to the 80:20 run (see Tables 4–5 (a) and 4–8 (a)). In the continuous-flow reactor, the variation in percent MLVSS with SRT was not significant; this indicates that the inert fraction exerted a significant influence on the resulting reactor characteristics.

The fill-and-draw reactors had an organic loading 5 times less than the continuous-flow system. This lower organic loading implies that the inert content in the reactor might be less. At the 5-day SRT, the fill-and-draw reactors did have a higher percent MLVSS as compared to the continuous-flow system (Table 4–8 (a)). However, as the SRT was increased from 5 days to 10 days, and the inert fraction accumulated in the biomass due to the longer sludge age, this inert fraction became significant in all three reactors. As a result, the percent MLVSS were practically the same, albeit at much lower levels. The low F/M ratios support this argument, with the lack of substrate indicating a decrease in the volatile content of the biomass.

The examination of the data in this case indicates a somewhat interesting phenomenon. On increasing the SRT further to 20 days, the percent MLVSS values in all three reactors were not expected to change by any significant amount. The fill-and-draw reactors were already in endogenous phase at the 10-day SRT and therefore the percent MLVSS was perhaps at its lowest value. As shown in Table 4–8 (a), all three reactors had percent MLVSS values similar to the 10-day SRT systems, thereby confirming the assumption that the inert portion governed at longer sludge ages. Thus, in the continuous-flow reactor, this
### (a) Effect of SRT on Suspended Solids for the 60:40 Run

<table>
<thead>
<tr>
<th>SRT (days)</th>
<th>Cont. Flow Reactor</th>
<th>Once-a-day Reactor</th>
<th>Twice-a-day Reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MLSS (mg/L)</td>
<td>MLVSS (mg/L)</td>
<td>MLVSS (%)</td>
</tr>
<tr>
<td>5</td>
<td>3088</td>
<td>1371</td>
<td>44.4</td>
</tr>
<tr>
<td>10</td>
<td>4939</td>
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</tr>
<tr>
<td>20</td>
<td>8322</td>
<td>3981</td>
<td>47.8</td>
</tr>
</tbody>
</table>

### (b) Effect of SRT on SPOUR Values for the 60:40 Run

<table>
<thead>
<tr>
<th>SRT (days)</th>
<th>Cont. Flow Reactor (mg/gm VSS-hr)</th>
<th>Once-a-day Reactor (mg/gm VSS-hr)</th>
<th>Twice-a-day Reactor (mg/gm VSS-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>6.9</td>
<td>4.9</td>
<td>3.9</td>
</tr>
<tr>
<td>10</td>
<td>8.1</td>
<td>6.4</td>
<td>6.7</td>
</tr>
<tr>
<td>20</td>
<td>3.9</td>
<td>5.6</td>
<td>4.5</td>
</tr>
</tbody>
</table>
inert fraction was significant even at the 5-day SRT, due to the high organic loading; in the fill-and-draw systems, however, this fraction became more significant only at the higher SRT's.

Variation of the SPOUR values against SRT is shown in Figure 4–18 (and presented in Table 4–8 (b)), for the three reactors. All three reactors showed a decrease in the average SPOUR values when the SRT was changed from 10 days to 20 days. This was expected since the F/M decreases and the substrate available per unit of biomass decreases as well. However, the average SPOUR values increased when the SRT was increased from 5 days to 10 days. The low SPOUR values for the 5-day systems could be due to the high organic loading to the system, coupled with a relatively low level of biomass, thereby resulting in excess substrate in the system. This argument is supported by the high average effluent COD's observed for the 5-day SRT systems (Table 4–9). High COD values in the effluent implies that total and efficient conversion of the substrate did not take place.

pH values in the reactors were spot checked from time to time and they were found to be within the acceptable range of 6.5 to 8.5 pH units.

4.4.2 EFFLUENT CHARACTERISTICS

The effluent characteristics for this experimental run are summarized in Table 4–9.

The 5-day SRT systems had higher average effluent COD concentrations, than the 10 or 20-day SRT units, for all reactor types. The continuous-flow reactor had the highest average value, 152 mg/L, for the 5-day SRT. The two fill-and-draw reactors showed lower average effluent COD's. As noted previously, these high COD values for the 5-day SRT systems could be due, in part, to the high organic loading imposed on these systems. The recommended range of organic
Figure 4-18: SPOUR Vs SRT - 60:40 Experimental Run
**TABLE 4-9**

Effluent Characteristics for the 60:40 Experimental Run

(a) Continuous Flow Reactor

<table>
<thead>
<tr>
<th>SRT (days)</th>
<th>F/M Ratio (kg COD/kg MLSS-day)</th>
<th>Influent COD (mg/L)</th>
<th>Effluent COD (mg/L)</th>
<th>% Eff.</th>
<th>Effl. Susp. Solids (mg/L)</th>
<th>SVI (ml/gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.40</td>
<td>1238</td>
<td>152</td>
<td>89.1</td>
<td>31</td>
<td>304</td>
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<td>10</td>
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<td>52</td>
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<tr>
<td>20</td>
<td>0.16</td>
<td>1323</td>
<td>67</td>
<td>95.0</td>
<td>10</td>
<td>102</td>
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</tbody>
</table>

(b) Once-a-day Reactor

<table>
<thead>
<tr>
<th>SRT (days)</th>
<th>F/M Ratio (kg COD/kg MLSS-day)</th>
<th>Influent COD (mg/L)</th>
<th>Effluent COD (mg/L)</th>
<th>% Eff.</th>
<th>Effl. Susp. Solids (mg/L)</th>
<th>SVI (ml/gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
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<td>1297</td>
<td>93</td>
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<tr>
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<td>0.17</td>
<td>1160</td>
<td>70</td>
<td>94.3</td>
<td>21</td>
<td>31</td>
</tr>
<tr>
<td>20</td>
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<td>1304</td>
<td>86</td>
<td>93.9</td>
<td>35</td>
<td>50</td>
</tr>
</tbody>
</table>

(c) Twice-a-day Reactor

<table>
<thead>
<tr>
<th>SRT (days)</th>
<th>F/M Ratio (kg COD/kg MLSS-day)</th>
<th>Influent COD (mg/L)</th>
<th>Effluent COD (mg/L)</th>
<th>% Eff.</th>
<th>Effl. Susp. Solids (mg/L)</th>
<th>SVI (ml/gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
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<td>38</td>
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<td>90</td>
<td>92.7</td>
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</tr>
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<td>20</td>
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<td>85</td>
<td>94.0</td>
<td>41</td>
<td>38</td>
</tr>
</tbody>
</table>
loadings for a conventional activated sludge plant are 20 to 40 lb BOD₅/1000 cu ft-day (Metcalf and Eddy 1972). The continuous-flow reactor had an organic loading of 77 lb COD/1000 cu ft-day (Table 4-7). This indicates that the biomass was not able to completely utilize the available substrate and this resulted in a higher effluent COD value. However, as the SRT was increased from 5 days to 10 days and the biomass also increased, the substrate was used up more efficiently and a lower average effluent COD was observed for all three systems.

The decrease in the F/M ratio also indicates that more substrate was used up during the 10-day SRT. On increasing the SRT further to 20 days, it was expected that the average effluent COD in all three reactors would drop even further. However, this did not take place. The F/M ratios at the 20-day SRT were lower than 0.20 days⁻¹ for all three systems; therefore, some cell lysis would be expected to occur in the reactors, thus affecting effluent quality. In the continuous-flow reactor, at the 20-day SRT, the F/M ratio was the highest, 0.16 days⁻¹, and it showed only a minor improvement in the treatment efficiency (Figure 4-19 and Table 4-9). The once-a-day reactor observed an actual drop in the treatment efficiency while the twice-a-day reactor had only a marginal improvement in its treatment efficiency. As before, the data seems to indicate a need for 'optimization' of the treatment systems, in terms of organic loadings and F/M ratios.

No significant changes in the settling characteristics for all three systems were observed, with the biomass showing good settling properties. However, the continuous-flow system, due to its high organic loading, indicated the presence of a poorly settling sludge at the 5-day SRT. The biomass settled very well, however, during the 10-day and 20-day SRT's.

The effluent suspended solids level, in the continuous-flow system, continued to drop with increasing SRT (see Table 4-9). The 20-day SRT had an average
Figure 4-19: Effluent Characteristics Vs SRT - 60:40
Experimental Run
effluent suspended solids level of only 10 mg/L. The fill-and-draw systems, showed a decrease in the average effluent suspended solids levels when the SRT was increased to 10 days; however, a slight deterioration in the average effluent suspended solids level was observed at the 20-day SRT run.

SVI values were used as a measure of sludge settleability. All three reactors had a decrease in their SVI values as the SRT was increased from 5 to 10 days (Table 4-9). However, on increasing the SRT further to 20 days, an increase in the SVI values, for all three sludges, was observed. It is speculated that this may be due to the low F/M ratios encountered at the 20-day SRT, thereby resulting in bulking sludge.

4.4.3 COMPARISON OF DIFFERENT REACTOR TYPES

The 60:40 run was operated under similar conditions to the 80:20 run, with the exception of a higher organic loading.

The organic loadings in the fill-and-draw systems were 5 times less than the continuous-flow reactor. The MLSS values, however, were approximately 4 times lower than the continuous-flow system. This trend was similar to the one observed in the 80:20 run. As noted earlier, this was attributed to the higher organic loadings in the continuous-flow system.

The MLSS levels in the two fill-and-draw reactors were also compared. The 80:20 experimental run had suggested a trend of the twice-a-day reactor having a higher biomass. This trend was also indicated in the 60:40 experimental run. For the 5-day SRT runs, the difference in the MLSS values was 9.2 percent, and this difference was increased to 21 percent for the 20-day SRT run.

The percent MLVSS obtained for the different reactors was also compared (Figure 4-20). As mentioned earlier, this steady-state run had significantly higher organic loadings in the reactors. As such the inert content in the feed was also
Figure 4-20: Percent MLVSS Vs SRT - 60:40 Experimental Run
significantly higher. The continuous-flow reactor, with 5 times higher organic loadings, showed the same percent MLVSS for all three SRT's, approximately 45 percent. At each particular SRT, the two fill-and-draw reactors had similar percent MLVSS. However, at the 5-day SRT, the percent MLVSS in the fill-and-draw systems was both higher than the continuous-flow system and the 10-day and 20-day SRT fill-and-draw systems.

F/M ratios for the continuous-flow reactor were higher in comparison to the fill-and-draw system, at all SRT's. However, the reported F/M ratios for the fill-and-draw systems were their minimum values, and, as such, they do not indicate the state of the system at all times. The fill-and-draw reactors showed a marginal difference between their F/M values, with the once-a-day reactor showing a slightly higher value at all SRT's. This difference was attributed to the lower MLSS levels in the once-a-day reactor.

SPOUR values for the fill-and-draw systems were obtained over a 24-hour period. These were used as a basis for comparing the two fill-and-draw systems. For the 5-day SRT, the once-a-day reactor reached a maximum value of 64 mg/gm VSS-hr, approximately 1 hour after feeding (Figure 4-21). The twice-a-day system reached a maximum of 62 mg/gm VSS-hr, but only 0.5 hours after feeding. This time difference, which is consistent with the other steady-state runs, clearly indicated that the twice-a-day system was more efficient and faster at utilizing the substrate. Also, the decline in the SPOUR value, for the once-a-day reactor, was gradual. However, the twice-a-day system had a fairly steep decline after the maximum value was reached, indicating, again, a greater affinity for substrate and a higher level of activity.

As the SRT was increased further to 20 days, the decline in the SPOUR values, after the maximum was reached, was fairly steep for both the fill-and-draw systems (Figure 4-22). This indicated that, at the 20-day SRT, the
Figure 4-21: SPOUR Vs Time (5 Days SRT) - 60:40 Experimental Run
Figure 4-22: SPOUR Vs Time (20 Days SRT) - 60:40 Experimental Run
substrate was taken up more quickly due to the lower F/M ratio in these systems. Maximum values were reached just a few minutes after feeding, indicating a high substrate demand. In both fill-and-draw systems, the 'base' value was reached approximately 2 hours after feeding, which shows that the biomass was in the endogenous state for most of the time.

The average effluent COD level in the continuous-flow reactor was higher than the two fill-and-draw systems, at all SRT's (Table 4-9). This is attributed to the higher F/M ratios in the continuous-flow system, indicating that the biomass could not metabolize all of the available substrate, thereby producing a higher effluent COD. As expected, the corresponding treatment efficiencies in the continuous-flow system were also lower. The two fill-and-draw systems performed equally well at all SRT's, with the 20-day SRT showing the most efficient performance (in terms of COD removal).

An interesting trend was observed in the settling characteristics of these systems. The average effluent solids dropped in all three reactors as the SRT was increased from 5 days to 10 days. This was expected as the increase in biomass helps improve the settling characteristics. The corresponding SVI values also dropped in all three systems (Table 4-9). However, when the SRT was increased from 10 days to 20 days, the three reactors behaved differently. In the continuous-flow reactor, the average effluent solids levels dropped further, but the SVI value increased. It was speculated that, at a low F/M ratio, sludge bulking took place, thereby increasing the SVI value. Limited sludge bulking is often characterized by a good effluent solids level (Pipes 1969); however, if excessive bulking takes place, due to a still lower F/M ratio, then the effluent quality also deteriorates. This phenomena was observed in the fill-and-draw systems. Both the fill-and-draw systems showed increases in the SVI values and effluent suspended solids levels, when the SRT was increased further to 20 days.
Results obtained from this experimental run indicate that aerobic treatment of the combined leachate/sewage waste, at a high organic loading, is feasible. The growth of the biomass in all systems was extensive and a stable operation was achieved. The continuous-flow reactor performed better at the 10-day and 20-day SRT's; at a 5-day SRT, the once-a-day system produced the best quality effluent. The difference in the MLSS levels of the two fill-and-draw systems was more significant in this 60:40 run. It was speculated that, at higher MLSS levels, this difference could be large enough to affect the effluent quality; however, in reality, the two fill-and-draw systems performed equally well (in terms of effluent quality) at all SRT's.

4.5 RESULTS FROM THE COLD TEMPERATURE STUDY

4.5.1 RESULTS FROM THE 10°C TEMPERATURE RUN

After operating the different reactors, under varying conditions, at room temperatures (21–23°C), it was decided to study the effect of lower temperature on the performance of these reactors. The reactors were moved into a temperature controlled room and a temperature of 10°C was set for the study. It would have been desirable to keep the temperature at 12–15°C for the first run. However, this was not possible since the 10°C temperature was required for another experiment being carried out, in the same temperature controlled room, at that time. The SRT for this run was chosen as 10 days. This SRT was chosen due to the 'acceptable' MLSS levels that were encountered during the room temperature runs. This experiment was carried out for a duration of approximately four weeks.

The temperature in the room varied from 9°C to 10°C. However, this resulted in a liquid temperature from 7.5 to 8.5°C in the reactors. Ordinarily, one would expect the liquid temperature in the reactors to be higher than the room
temperature; however, cold air used for aeration caused a drop in the liquid temperatures. Evaporation from the reactors might also have contributed to the lower liquid temperature values. The liquid temperature was monitored over a 24-hour period and no significant variation was observed in either of the three reactors. Therefore, it was decided to observe the liquid temperature in each reactor just before feeding. Variations in the temperature on a daily basis are shown in Figure 4-23.

The organic loading in the reactors corresponded to 20 percent leachate additions, by volume, in the influent feed. The average influent COD in this steady-state run was observed at 905 mg/L. Therefore, the organic loading in the continuous-flow reactor was 0.905 kg COD/m$^3$-day (56.4 lb COD/1000 cu ft-day), which is in acceptable range according to Zapf-Gilje and Mavinic (1982). The fill-and-draw reactors had organic loadings 5 times less than the continuous-flow system, 0.181 kg COD/m$^3$-day (11.3 lb COD/1000 cu ft-day) (Table 4-10).

The variation in the mixed-liquor suspended solids (MLSS) was observed during the steady-state operation, as shown in Figure 4-24. The variation in the values was not significant at any time and this indicated a fairly stable operation. The continuous-flow reactor showed an average MLSS value of 2066 mg/L (Table 4-10). This value is somewhat higher than the MLSS for the same steady-state run, at room temperature (21-23°C). However, the fill-and-draw reactors showed MLSS levels twice as high as the previous room temperature runs.

The F/M ratios, at room temperature, were found to be fairly high in the fill-and-draw systems (see Table 4-4). As mentioned earlier, these F/M values for the fill-and-draw systems represent their lowest values. Therefore it appears that the microorganisms did not convert the organic substrate into biomass efficiently at room temperatures. At the 10°C temperature run, because of the higher solids
Figure 4-23: Liquid Temperature Vs Days in Steady State - 10°C Temperature Run
TABLE 4-10
Characteristics from the 8°C Liquid Temperature Run

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cont. Flow Reactor</th>
<th>Once-a-day Reactor</th>
<th>Twice-a-day Reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRT (days)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Influent COD (mg/L)</td>
<td>905</td>
<td>905</td>
<td>905</td>
</tr>
<tr>
<td>Organic Loading (kg COD/m^3-day)</td>
<td>0.905</td>
<td>0.181</td>
<td>0.181</td>
</tr>
<tr>
<td>Organic Loading (lb COD/1000 cu ft-day)</td>
<td>56.4</td>
<td>11.3</td>
<td>11.3</td>
</tr>
<tr>
<td>F/M Ratio (kg COD/kg MLSS-day)</td>
<td>0.44</td>
<td>0.16</td>
<td>0.17</td>
</tr>
<tr>
<td>MLSS (mg/L)</td>
<td>2066</td>
<td>1169</td>
<td>1082</td>
</tr>
<tr>
<td>MLVSS (mg/L)</td>
<td>960</td>
<td>566</td>
<td>539</td>
</tr>
<tr>
<td>Percent MLVSS (%)</td>
<td>46.3</td>
<td>48.4</td>
<td>49.8</td>
</tr>
<tr>
<td>SPOUR (mg/gm VSS-hr)</td>
<td>38.1</td>
<td>29.8</td>
<td>33.6</td>
</tr>
<tr>
<td>Effluent COD (mg/L)</td>
<td>220</td>
<td>118</td>
<td>112</td>
</tr>
<tr>
<td>Treatment Efficiency (%)</td>
<td>72.7</td>
<td>85.3</td>
<td>86.1</td>
</tr>
<tr>
<td>Effl. Susp. Solids (mg/L)</td>
<td>58</td>
<td>37</td>
<td>23</td>
</tr>
<tr>
<td>SVI (ml/gm)</td>
<td>75</td>
<td>177</td>
<td>322</td>
</tr>
</tbody>
</table>
Figure 4-24: MLSS Vs Days in Steady State - 10°C Temperature Run
levels, the fill-and-draw systems had much lower F/M values, thereby indicating that at the end of the feed cycle, most of the substrate had been converted to biomass. Also, the 'base' SPOUR values in the fill-and-draw systems, at 10°C, were much higher, thus supporting the argument that a higher level of activity existed in the 10°C systems over the 24-hour feed cycle. It is possible that a different group of microorganisms (probably psychrophilic) dominated at this temperature, thereby resulting in a more efficient system. However, definitive proof is unavailable from this experimental work.

The percent MLVSS levels in all three reactors were almost equal (see Table 4-10). However, these values were lower than the corresponding room temperature run at the 10-day SRT (Table 4-5 (a)). The continuous-flow reactor experienced a sharp decrease in the percent MLVSS from 62.0 to 46.3 percent. This could be explained by the much higher SPOUR value in the 10°C system, 38.1 mg/gm VSS-hr. The room temperature run had a SPOUR value of 18.6 mg/gm VSS-hr. This implies that a more "active" biomass, albeit slower responding due to the colder temperature, existed in the continuous-flow system at 10°C, resulting in a lower percent MLVSS value overall. A similar explanation also holds for the two fill-and-draw systems, which also had much higher 'base' SPOUR values (see Tables 4-5 (b) and 4-10).

The food/microorganism (F/M) ratios for this steady-state run are also given in Table 4-10. In the continuous-flow system, a high F/M ratio of 0.44 days⁻¹ was observed. In the fill-and-draw reactors, however, the F/M ratios were less than 0.2 days⁻¹, which indicates an endogenous phase operation. The F/M values in the fill-and-draw reactors were obtained just before feeding; therefore, they represent the minimum F/M values in the system. In the low temperature study, the uptake of substrate was expected to take longer, due to the slower response by the microorganisms; hence, it was expected that the substrate would
be used up over most of the feed cycle, and not in the initial part, as shown previously. This type of response, if true, would be reflected in the SPOUR values for each system.

SPOUR values were obtained for all three reactors during the steady-state operation (see Table 4-10). For the fill-and-draw systems, these values were also obtained over a 24-hour period (Figure 4-25). SPOUR values were also used as a basis for comparing the two fill-and-draw systems. The maximum SPOUR values were also expected to be lower, compared to the room temperature runs, due to the slower response time of the microorganisms.

Oxygen uptake was indeed gradual with time (Figure 4-25) and the base values were reached only near the end of the feed cycle. The once-a-day reactor had a maximum SPOUR value of 65 mg/gm VSS-hr, while the twice-a-day system had a maximum value of 84 mg/gm VSS-hr. The twice-a-day reactor showed a maximum value higher than the once-a-day system, as was the case in previous runs. Again, this was attributed to the microorganisms being able to metabolize the substrate faster and more efficiently, thus increasing the maximum SPOUR value. Also, the maximum value for the once-a-day system was reached after approximately 4 hours, as compared to only 2 hours in the twice-a-day system.

As expected, the average effluent COD values showed an increase in all three reactors. The continuous-flow system had a high F/M ratio of 0.44 days\(^{-1}\) and the effluent COD value for this system was expected to be the highest. This reactor had an average effluent COD of 220 mg/L. This resulted in a treatment efficiency of only 72.7 percent. The fill-and-draw reactors had organic loadings 5 times less than the continuous-flow system; therefore, the F/M ratio in the fill-and-draw systems was much lower (Table 4-10). The average effluent COD for the once-a-day system was only 118 mg/L, corresponding to a 85.3 percent
Figure 4-25: SPOUR Vs Time for the Fill-and-Draw Systems - 10°C Temperature Run
treatment efficiency, while the twice-a-day system had a treatment efficiency of 86.1 percent. It is possible, though, that some cell lysis also occurred in the fill-and-draw reactors thereby deteriorating the effluent quality. However, it is speculated that, on the basis of SPOUR values, the endogenous phase occurred only during a small part of the feed cycle and the effect of cell lysis, in this low temperature run, would not be as significant.

An interesting part of this steady-state run were the settling characteristics. The three reactors showed different characteristics, although each individual system exhibited a uniform pattern. The average effluent suspended solids level in the continuous-flow reactor was 58 mg/L, indicating a relatively poor quality effluent. The sludge volume index (SVI) was, however, within the acceptable range of 35 to 150. This indicated that the sludge compacted fairly well. The deterioration in the effluent suspended solids (compared to the room temperature study) levels was probably due to the formation of a pinpoint floc. According to Pipes (1969), pinpoint floc occurs when the temperature in the aeration tank is less than 15°C, and there is a lack of sufficient filamentous growth in the system. A pinpoint floc was observed in this system at these lower temperatures. The two fill-and-draw reactors, on the other hand, experienced a decrease in the effluent suspended solids levels, compared to the corresponding room temperature run (see Tables 4–6 and 4–10). However, SVI values for both systems showed a sharp increase (greater than 150), indicating that bulking took place in the fill-and-draw systems.

As mentioned earlier, filamentous growth is controlled by two important parameters: F/M ratio and temperature. Since the F/M ratios in the fill-and-draw systems were low, it appears that some filamentous growth took place in the reactors. However, the low temperature probably restricted the extent of the filamentous growth and hence average effluent suspended solids levels were lower. The continuous-flow system, though, did not have a low F/M ratio. It was
also characterized by a lack of filamentous growth and the formation of pinpoint floc. It appears then that at the 10°C temperature run, the F/M ratio had a more significant effect on filamentous growth, and subsequent settling performance, than did the temperature.

The above data also indicates that at lower temperatures, treatment efficiencies in the reactors started to drop. At an operating temperature of 10°C, even though the microorganisms were active, there was a significant reduction in treatment efficiency for all three systems. Since the metabolic activity of the microorganisms is slower, the organic loadings should be lowered for efficient operation, especially when treating leachate. Settling performance also deteriorates with a decrease in temperature, predominantly due to the formation of a pinpoint floc. A system with a F/M ratio less than 0.2 days⁻¹ could also be expected to experience sludge bulking problems at 10°C.

4.5.2 Results from the 6°C Temperature Run

The performance of all three reactors was evaluated at 10°C. After that, it was decided to decrease the temperature further to 6°C. Liquid temperatures varied from 5.0 to 5.5°C, while the air temperatures varied from 6 to 6.5°C. The SRT for this particular run was also maintained at 10 days, so as to serve as a basis for comparison with other temperatures. Since the temperature reduction from the previous run was not as great as hoped for, it was decided to increase the organic loading in this system, in order to study the effect of a higher organic loading at a low temperature.

Leachate was added to the domestic wastewater in a ratio of 60:40 sewage:leachate. The average influent COD for this steady-state was calculated as 1830 mg/L (Table 4-11). Minor variations were observed due to the changes in the domestic wastewater quality. The corresponding organic loading on the
### TABLE 4-11
Characteristics from the 5 °C Liquid Temperature Run

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cont. Flow Reactor</th>
<th>Once-a-day Reactor</th>
<th>Twice-a-day Reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRT (days)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Influent COD (mg/L)</td>
<td>1830</td>
<td>1830</td>
<td>1830</td>
</tr>
<tr>
<td>Organic Loading (kg COD/m³-day)</td>
<td>1.830</td>
<td>0.370</td>
<td>0.370</td>
</tr>
<tr>
<td>Organic Loading (lb COD/1000 cu ft-day)</td>
<td>114</td>
<td>22.8</td>
<td>22.8</td>
</tr>
<tr>
<td>F/M Ratio (kg COD/kg MLSS-day)</td>
<td>0.47</td>
<td>0.19</td>
<td>0.20</td>
</tr>
<tr>
<td>MLSS (mg/L)</td>
<td>3856</td>
<td>1919</td>
<td>2006</td>
</tr>
<tr>
<td>MLVSS (mg/L)</td>
<td>1890</td>
<td>917</td>
<td>987</td>
</tr>
<tr>
<td>Percent MLVSS (%)</td>
<td>49.0</td>
<td>47.8</td>
<td>49.2</td>
</tr>
<tr>
<td>SPOUR (mg/gm VSS/hr)</td>
<td>23.6</td>
<td>16.8</td>
<td>17.2</td>
</tr>
<tr>
<td>Effluent COD (mg/L)</td>
<td>572</td>
<td>515</td>
<td>506</td>
</tr>
<tr>
<td>Treatment Efficiency (%)</td>
<td>68.6</td>
<td>71.7</td>
<td>72.2</td>
</tr>
<tr>
<td>Effl. Susp. Solids (mg/L)</td>
<td>63</td>
<td>106</td>
<td>93</td>
</tr>
<tr>
<td>SVI (ml/gm)</td>
<td>55</td>
<td>64</td>
<td>46</td>
</tr>
</tbody>
</table>
continuous-flow reactor was 1.83 kg COD/m³-day (114 lb COD/1000 cu ft-day). This was considered to be a fairly high organic loading at a temperature of only 6°C. However, the fill-and-draw systems had 5 times lower organic loadings, 0.37 kg COD/m³-day (22.8 lb COD/1000 cu ft-day). This loading was within the acceptable range suggested by Zapf-Gilje and Mavinic (1982).

Due to the higher organic loadings (compared to the 10°C temperature run), F/M ratios for all three reactors were within the normal range of 0.2 to 0.5 days⁻¹ (Table 4-11). The F/M value of 0.47 days⁻¹ for the continuous-flow system was fairly high, and this resulted in a poorer effluent quality. Again, the F/M values for the fill-and-draw reactors were their minimum values and therefore, these systems were not in an endogenous phase at any time during the feeding cycle.

The mixed-liquor suspended solids (MLSS) were observed during the steady-state operation, as shown in Figure 4-26. The solids variation in the continuous-flow reactor was significant and it appears that this system never stabilized. The fill-and-draw systems, on the other hand, seemed to be fairly stable, with insignificant variation in their MLSS values. The average value in the continuous-flow reactor was 3856 mg/L. This was approximately twice as much as the MLSS in the fill-and-draw systems. The once-a-day reactor had an average value of 1919 mg/L, while the twice-a-day reactor had an average value of 2006 mg/L. The continuous-flow system, at the room temperature and same SRT, had a higher MLSS value compared to the 6°C run. It appears that, at this low temperature, biological activity slowed considerably and therefore the microorganisms were not able to use up the organic substrate, especially at such a high loading rate. However, the organic loading in the fill-and-draw systems was 5 times less, and the biomass had sufficient time to use up the organic substrate, thereby resulting in a relatively higher MLSS value. Also, the influent feed strength, at
Figure 4-26: MLSS Vs Days in Steady State - 6°C Temperature Run
the 6°C, was significantly higher, and this may also have led to the higher solids levels in the reactors.

The percent MLVSS values in all three reactors were low, due to the high inert content in the influent feed (Table 4-11). However, these values were marginally higher than the values for the room temperature run (Table 4-8 (a)). This indicates that there was a slower utilization of the organic substrate at 6°C.

The SPOUR values were monitored on a daily basis, as well as over a 24-hour period for the fill-and-draw systems. The variation of SPOUR with time for the two fill-and-draw systems is shown in Figure 4-27. A pattern similar to the 10°C run was observed. The maximum SPOUR values were much lower, however, in comparison to the previous run. The once-a-day reactor had a maximum SPOUR value of 42 mg/gm VSS-hr, while for the twice-a-day reactor the maximum value was also 42 mg/gm VSS-hr. In the previous temperature run, the twice-a-day reactor had a maximum SPOUR value of 84 mg/gm VSS-hr, which was greater than the once-a-day value of 65 mg/gm VSS-hr. Even though the high organic loading appeared to adversely affect the metabolic rate in the twice-a-day reactor, all else being equal, the twice-a-day reactor was still as efficient (or more so) at utilizing the substrate as compared to the once-a-day reactor. The maximum value in the once-a-day system was reached approximately 2.5 hours after feeding, while the twice-a-day system reached its maximum value after just 1.5 hours (see Figure 4-27).

Perhaps the most conspicuous effect of the lower temperatures was the significant deterioration in the effluent quality for all three systems (see Table 4-11). As mentioned earlier, settling characteristics can be affected either by the F/M ratio or the temperature. The F/M ratios in all three reactors were higher than the previous run (see Tables 4-10 and 4-11). Therefore, it appears that filamentous growth was not extensive in any system. Also, the still lower
Figure 4-27: SPOUR Vs Time for the Fill-and-Draw Systems - 6°C Temperature Run
temperature in this experiment would further inhibit filamentous growth. As such, at the 6°C temperature, formation of a pinpoint floc was visually observed in all three reactors. High effluent suspended solids were observed in the systems, with the once-a-day reactor having the highest value of 106 mg/L. Since the environmental conditions were not conducive for filamentous growth, no sludge bulking was observed. The SVI values were found to be acceptable for the three systems (Table 4–11). Unlike the 10°C temperature run, it appears that the combination of higher F/M ratios and lower temperatures resulted in the formation of a pinpoint floc (by inhibiting filamentous growth) in all systems, thereby producing a poorer quality effluent.

The average effluent COD in the continuous-flow system was 572 mg/L. This clearly indicated that, at this low temperature and high organic loading, the biomass was not able to metabolize as much of the available substrate. Therefore, it appears that a significantly lower organic loading would perhaps be more suitable at this low temperature. The effluent COD value corresponded to a treatment efficiency of only 68.6 percent. The fill-and-draw reactors also had very high effluent COD values; the once-a-day reactor had an average effluent COD of 515 mg/L, for a treatment efficiency of 71.7 percent, and the twice-a-day system had an average effluent COD of 506 mg/L, for a 72.2 percent treatment efficiency. The high effluent suspended solids levels in these two reactors probably contributed, in part, to the high COD value.

The 6°C temperature run clearly indicated that all three systems failed to treat the influent feed in an effective manner. High values of effluent COD and suspended solids were observed in each reactor. Therefore, at such low operating temperatures, aerobic biotreatment of a combined sewage/leachate mix would require reduced organic loadings on the system, with 'optimization' necessary to maintain the lowest possible effluent levels of organic carbon and suspended solids.
5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

1. Combined treatment of the two waste streams, domestic sewage and leachate, is feasible under various different environmental conditions. Efficient treatment was achieved for most of the steady-state runs using 80:20 and 60:40 mixtures of sewage and leachate. The treatment efficiencies for all three reactors (once-a-day, twice-a-day and continuous feed) were comparable at all times. However, the reactors performed better at the higher organic loadings. The overall best performance, at room temperatures of 21–23°C, was observed in the continuous-flow system, at the 20-day SRT, and an organic loading of 1.323 kg COD/m³•day, with an average effluent COD of 67 mg/L. This corresponded to a treatment efficiency of 95 percent COD removal, and effluent suspended solids of 10 mg/L. The lowest treatment efficiency of 85.7 percent COD removal was also observed in the continuous-flow reactor, for a 20-day SRT, but at the lower organic loading of 0.781 kg COD/m³•day.

Since the influent feed contained a significant portion of domestic sewage, acclimatization of the sewage-fed activated sludge (obtained from the UBC pilot plant) did not take more than 3–4 weeks. The first week was operated with a 10 percent leachate mix, and in the later weeks 20 percent leachate was added to the feed.

2. The most efficient performance of the continuous-flow reactor, at room temperature (21–23°C), was observed at a SRT of 20 days, and an organic loading of 1.323 kg COD/m³•day. However, at the lower organic loading of 0.781 kg COD/m³•day, the 10-day SRT was found to be the most efficient, for the continuous-flow system. Therefore, it appears that an optimization of the continuous-flow system, in terms of the organic loading and SRT (or F/M ratio), would be required to obtain the most
efficient operation.

3. The once-a-day feed system performed most efficiently (in terms of COD removal) at the 10-day SRT's and 21-23°C temperature, for both the organic loadings, 0.162 and 0.232 kg COD/m³-day. A SRT of 20 days was found to be too long at such low organic loadings. However, the longer SRT resulted in higher MLSS values and this improved the sludge settleability, as indicated by the lower effluent suspended solids values. It seems that the once-a-day system could also be optimized in terms of the organic loadings and the SRT. A still higher organic loading would perhaps require a SRT longer than 10 days for the most efficient operation.

4. The twice-a-day system performed differently as compared to the once-a-day system. The best performance was observed at the 20-day SRT (21-23°C) and the higher organic loading. The higher organic loaded system performed better, as was the case in the once-a-day system. At the lower organic loading, the low F/M ratios probably resulted in cell lysis, further deteriorating the effluent quality.

5. On the basis of SPOUR values, the twice-a-day system was found to be more efficient (21-23°C room temperature) and faster at utilizing the substrate. This was quite significant at the lower SRT of 5-days. At the 20-day SRT, however, both fill-and-draw systems exhibited a similar uptake. Due to the faster utilization of substrate, the microorganisms in the twice-a-day system were in an endogenous respiration state for a longer duration and hence cell lysis was probably more significant in this system.

6. The performance of the two fill-and-draw reactors, in terms of COD removal, was comparable for most of the steady-state runs at room temperatures (21-23°C). At the
lower SRT's, the once-a-day system was found to be marginally better. However, at the longer SRT's, there was no noticeable difference in performance. The MLSS values in the two reactors, however, showed a definite trend with SRT and organic loadings. As the organic loading increased, the difference in the MLSS values of the two fill-and-draw systems also increased, with the twice-a-day reactor indicating a higher value. This difference also increased with increasing SRT's. For example, at the 5-day SRT and an organic loading of 0.177 kg COD/m$^3$-day, there were wide variations in the extremely low MLSS values and in fact, the once-a-day system showed an average higher MLSS value of 282 mg/L (a 13 percent higher average value than the twice-a-day system). However, as the SRT was increased to 20 days, the twice-a-day system had a 12 percent higher MLSS value. An organic loading of 0.260 kg COD/m$^3$-day resulted in a 21 percent difference in MLSS values, at the 20-day SRT. It appears that, at higher organic loadings and higher MLSS values, this difference could be large enough to affect the effluent quality and a significant difference in the performance of the two systems could result.

7. The percent MLVSS values showed interesting trends during the experiments. At low organic loadings and 21–23°C room temperature, percent MLVSS decreased with increasing SRT. However, this variation was not observed at the higher organic loading, presumably due to the high inert content in the influent feed.

8. The cold temperature, steady-state runs clearly indicated a decrease in treatment efficiency with temperature, for all three reactors. The continuous-flow system showed the maximum deterioration in average effluent COD and treatment efficiency, probably due to the higher organic loading. At the 6°C temperature run, however, all three reactors showed a significant decrease (compared to the room temperatures of 21–23°C) in their treatment efficiencies and an increase in their average effluent
suspended solids.

9. Even though the metabolic activity of the microorganisms was lower at the decreased operating temperatures, the biomass in all three systems was fairly 'active', with no decrease in MLSS values. It seems that a higher treatment efficiency could be achieved at low temperatures by reducing the organic loadings.

10. The settling characteristics were studied in detail during the experiment. The settling properties of a sludge were found to be dependent on various parameters: F/M ratio or SRT, organic loading, MLSS and temperature. For most of the steady-state runs, however, settling characteristics were found to be "acceptable".

11. The continuous-flow system, at the 5-day SRT and 0.781 kg COD/m³-day organic loading (21–23°C), experienced sludge settling problems due to the low MLSS values. However, at the 20-day SRT and 1.323 kg COD/m³-day organic loading, the continuous-flow system had an average MLSS value of 8322 mg/L, with hindered settling indicated at this high MLSS value. Therefore, it appears that for a still higher organic loading, settling problems may be encountered at long SRT's. Again, there seems to be a need for optimization of the system with respect to organic loadings, SRT and MLSS values.

12. Sludge bulking was encountered during a few steady-state runs. All such systems were characterized by a low F/M ratio, which also corresponds to a long SRT. It appears that filamentous growth dominated during low F/M ratios. However, bulking sludge did not necessarily affect the effluent suspended solids levels.

13. The low temperature runs encountered frequent problems with sludge settleability.
Due to the low temperatures, filamentous growth was inhibited, but the formation of a pinpoint floc was predominant. This was observed in the continuous-flow system, for both the 10°C and 6°C temperature runs. On the other hand, the fill-and-draw systems had low F/M ratios, which enhances filamentous growth. In these systems, at the 10°C temperature run, filamentous growth dominated and no pinpoint floc was observed; sludge bulking occurred in these fill-and-draw systems. At the lower 6°C temperature run, however, the filamentous growth appears to have been inhibited and pinpoint floc was again observed in all three systems; no sludge bulking occurred at this low temperature. It can therefore be concluded that, at lower temperatures, a low F/M ratio would result in a properly settling sludge.

5.2 RECOMMENDATIONS

This experiment was carried out to study the feasibility of combined sewage:leachate treatment, and in particular, to study settling characteristics under different conditions. Certain aspects of the study which require further work are:

1. The difference in the MLSS levels of the fill-and-draw systems, at higher organic loadings, could be large enough to significantly affect effluent quality. Therefore, fill-and-draw reactors should be operated with higher MLSS values to study this effect.

2. Sludge settling properties are dependent on the particular microorganisms. A study of the microorganisms speciation, for a few steady-state runs, would further enhance conclusions derived from this experiment.

3. Operation of fill-and-draw systems clearly indicated that oxygen requirements vary considerably with time. This is of great practical importance, as significant cost
reductions could be achieved in terms of oxygen requirements. Oxygen requirements, with time, should be studied in greater detail so as to provide an efficient method of aerating fill-and-draw systems.

4. A study should be undertaken to optimize the treatment system, using parameters like organic loadings, SRT or F/M ratio, and temperature.

5. Specific Oxygen Uptake Rate (SPOUR) was used in this experiment as a measure of activity of the microorganisms. A study should be carried out using both SPOUR and ATP measurements to assess biological activity in the system. Also, measurement of factors such as $^{14}\text{C}$-glucose uptake/unit ATP would provide information on the relative energetics of microorganisms at different times under different conditions.

6. The MLSS levels, in the fill-and-draw systems, at cold temperatures were found to be higher than the corresponding room temperature runs. This phenomena should be studied in greater detail and a study of the microorganisms dominating at different temperatures should also be carried out.


8. Monitoring of effluent to look at trace metals and removal of trace organic contaminants by this process would also be useful since it helps eliminate the toxicity of the leachate prior to discharge to the environment.
BIBLIOGRAPHY


