

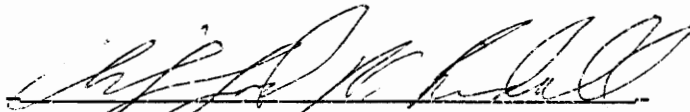
EFFECT OF COPPER AND NICKEL ON THE PERFORMANCE  
OF AN ACTIVATED SLUDGE SYSTEM TREATING  
CELLULOSE ACETATE WASTEWATER

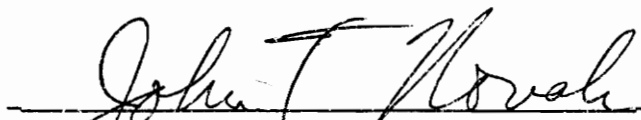
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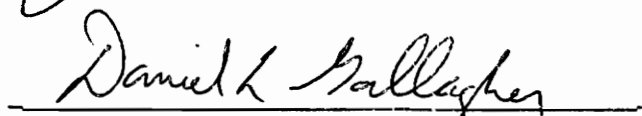
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**Effect of Copper and Nickel on the performance  
of an Activated Sludge System using  
Cellulose Acetate Wastewater**

by

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**(ABSTRACT)**

This research investigated the effect of copper and nickel on the performance of a laboratory scale activated sludge system. The wastewater used for this research was the influent to the activated sludge process at the Hoechst Celanese cellulose acetate manufacturing plant, located at Narrows, Virginia. The influent wastewater to the experimental unit was pretreated with lime and then selected amounts of copper and nickel were added separately or together to evaluate their effects on the performance of the system.

The Specific Uptake of Metal (SUM), Dissolved Metal (DM), Total Metal Loading Rate (TMLR), and Specific Total Metal Loading Rate (STMLR) were useful parameters for analysis of the effects of the metals on activated sludge performance. No significant changes in effluent COD, SS, and OUR were observed for the acclimated activated sludge when the

selected amounts of metals were added but not when either was added separately. The settling characteristics of the activated sludge deteriorated when a combination of copper and nickel were added. The SUM increased at a faster rate at higher metal loading rates than at lower metal loading rates to the reactor. The increases in dissolved metal concentrations in the mixed liquor were a linear function of the metal loading rates.

## ACKNOWLEDGEMENTS

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## TABLE OF CONTENTS

	<u>PAGE</u>
TITLE	i
ABSTRACT	ii
ACKNOWLEDGEMENTS	iv
TABLE OF CONTENTS	v
LIST OF FIGURES	viii
LIST OF TABLES	xii
CHAPTER 1.	
INTRODUCTION	1
General	1
Scope of research	2
CHAPTER 2.	
LITERATURE REVIEW	3
General	3
Presence of heavy metals in the influent feed of the activated sludge system	4
Removal of metals through the activated sludge process	11
Physical trapping of precipitated metals in the sludge floc matrix	11
Binding of soluble metal to extracellular polymers	12
Accumulation of soluble metal by the cell	13
Volatilization of metal to the atmosphere	13
Acclimation	16
	v

## TABLE OF CONTENTS (CONTINUED)

	Factors affecting behavior of toxic metals	17
	Indirect measures of toxicity	19
CHAPTER 3.	Materials and methods	22
	Wastewater pretreatment	22
	Experimental equipment and system operation	26
	Influent feed	28
	Preparation for the Control Unit	30
	Preparation for the Experimental Unit	33
	Sample collection and analysis	37
CHAPTER 4.	RESULTS	43
	General	43
	Wastewater variation	44
	Metals variation	44
	COD variation	47
	SS variation	50
	pH variation	54
	Metal Analysis Elements	54
	Performance of control unit	59
	COD removal	59
	pH variation	59
	MLVSS/MLSS and F:M variation	62
	Effluent SS variation	62

**TABLE OF CONTENTS (CONTINUED)**

	<u>PAGE</u>
OUR and SOUR variation	66
SVI and ZSV variation	66
Accumulation of metals in the mixed liquor	72
Performance of experimental unit	73
Accumulation of metals in the mixed liquor	73
Effect of metals on COD removal	73
Effect of metals on OUR and SOUR	79
Effect of metals on effluent SS	82
Effect of metals on settling properties	85
CHAPTER 5. DISCUSSION	91
Accumulation of metals in Mixed Liquor	91
Modeling of Effluent Characteristics	97
Metal Analysis Parameters - DM, TMLR, STMLR, and SUM	98
Relationship between the different Metal Analysis Parameters	103
Metal analysis elements and their effects on effluent COD, effluent SS SOUR and settling properties of the activated sludge	109
CHAPTER 6. CONCLUSIONS	129
BIBLIOGRAPHY	131
DATA TABLES	140
VITA	164
	vii



## LIST OF FIGURES

<u>TITLE</u>	<u>FIGURE NO.</u>	<u>PAGE</u>
1. Flow diagram for Lab. Scale Activated Sludge Process	3.1	29
2. Comparison of Total Copper in the Influent Feed for the Celco and Experimental Units	4.1	45
3. Comparison of Total Nickel in the Influent Feed for the Celco and Experimental Units	4.2	46
4. Comparison of Influent COD for the Celco and Experimental Units	4.3	48
5. Variation of Influent COD Ratio (Celco: Experimental)	4.4	49
6. Comparison of Influent SS for the Celco and Experimental Units	4.5	51
7. Variation of Influent pH for the Celco and Experimental Units	4.6	55
8. COD Removal by the Celco Unit	4.7	60
9. Variation in Mixed Liquor pH for the Celco Unit	4.8	61
10. Variation of Influent and Effluent pH for the Celco Unit	4.9	63
11. Variation in MLSS and MLVSS for the Celco Unit	4.10	64
12. Variation in F:M ratio for the Celco Unit	4.11	65
13. Variation of Effluent SS and VSS for the Celco Unit	4.12	67
14. Variation in OUR for the Celco Unit	4.13	68
15. Variation in SOUR for the Celco Unit	4.14	69

**LIST OF FIGURES (CONTINUED)**

	<u>TITLE</u>	<u>FIGURE NO.</u>	<u>PAGE</u>
16.	Variation in SVI for the Celco Unit	4.15	70
15.	Variation in ZSV for the Celco Unit	4.16	71
16.	Variation of Total and Soluble Copper in Mixed Liquor for the Celco Unit	4.17	74
17.	Variation of Total Influent and Effluent Copper for the Celco Unit	4.18	75
18.	Variation of Total and Soluble Nickel in Mixed Liquor for the Celco Unit	4.19	76
19.	Variation of Total Influent and Effluent Nickel for the Celco Unit	4.20	77
20.	COD Removal by the Experimental Unit	4.21	78
21.	Variation of the Effluent COD concentration for the Experimental Unit	4.22	80
22.	Variation in OUR for the Experimental Unit	4.23	81
22.	Variation in SOUR for the Experimental Unit	4.24	83
23.	Variation in Effluent VSS for the Experimental Unit	4.25	84
24.	Variation in SVI for the Experimental Unit	4.26	86
25.	Variation in ZSV for the Experimental Unit	4.27	87

**LIST OF FIGURES (CONTINUED)**

<u>TITLE</u>	<u>FIGURE NO.</u>	<u>PAGE</u>
26. Variation of Total and Soluble Copper in Mixed Liquor for the Experimental Unit	5.1	92
27. Variation of Total Influent and Effluent Copper for the Experimental Unit	5.2	93
28. Variation of Total and Soluble Nickel in Mixed Liquor for the Experimental Unit	5.3	94
29. Variation of Total Influent and Effluent Nickel for the Experimental Unit	5.4	95
30. Variation of Loading Rate for the Experimental Unit	5.5	99
31. Variation of Specific Loading Rate for the Experimental Unit	5.6	100
32. Variation of Specific Uptake of Metal for the Experimental Unit	5.7	101
33. Correlation between SUM and TMLR	5.8	105
34. Correlation between SUM and DM	5.9	106
35. Correlation between TMLR and DM	5.10	107
36. Correlation between STMLR and DM	5.11	108
37. Correlation between SUM and STMLR	5.12	110
38. Variation of Effluent COD with DM concentration	5.13	111
39. Variation of Effluent COD with SUM	5.14	112
40. Variation of Effluent COD with STMLR	5.15	113

**LIST OF FIGURES (CONTINUED)**

<u>TITLE</u>	<u>FIGURE NO.</u>	<u>PAGE</u>
41. Variation of Effluent COD with TMLR	5.16	114
42. Variation of Effluent VSS with DM concentration	5.17	116
43. Variation of Effluent VSS with SUM	5.18	117
44. Variation of Effluent VSS with STMLR	5.19	118
45. Variation of Effluent VSS with TMLR	5.20	119
46. Variation of SOUR with DM Concentration	5.21	120
47. Variation of SOUR with SUM	5.22	121
48. Variation of SOUR with STMLR	5.23	122
49. Variation of SOUR with TMLR	5.24	123
50. Variation of SVI with DM Concentration	5.25	125
51. Variation of SVI with SUM	5.26	126
52. Variation of SVI with STMLR	5.27	127
53. Variation of SVI with TMLR	5.28	128

## LIST OF TABLES

	<u>TITLE</u>	<u>TABLE NO.</u>	<u>PAGE</u>
1.	Concentration of Copper and Nickel toxic to game fish	2.1	5
2.	Comparison of the relative magnitude of microorganisms present in the mixed liquor	2.2	7
3.	Environmental Extremes of Microorganism survival	2.3	9
4.	Summary of Metal Removal Efficiency in an Activated Sludge Plant	2.4	14
5.	% COD removal Efficiency	2.5	20
6.	Jar Test No. 1	3.1	24
7.	Jar Test No. 2	3.2	25
8.	Time Line of change in operating conditions for the Experimental Unit	3.3	38
9.	Experimental Unit Metal Loading by Phase	4.1	58

# CHAPTER 1

## INTRODUCTION

### 1.1 General

This research was carried out with the wastewater from the treatment plant of Hoechst Celanese Corporation (CELCO), located at Narrows, Virginia. The wastewater produced during the operation of the Celco Plant is a cellulose acetate manufacturing wastewater. This wastewater is treated by an activated sludge plant consisting of screens, equalization basin, aeration basin, clarifier, sludge thickener and aerobic digester.

One of the basic operational requirements of an activated sludge plant is the maintenance of an adequate number of microorganisms, primarily bacteria. These bacteria accomplish the assimilation of the organic pollutants in the wastewater. Like any other living creature the bacteria have basic needs. The basic needs include food, oxygen, and a suitable environment. A suitable environment among other things includes the presence/absence of heavy metals. The presence of heavy metals have been considered to be a major

obstacle in the effective use of biological treatment systems for some wastewaters. The purpose of this research was to study the effects of heavy metals on the treatment efficiency of a laboratory scale activated sludge unit when the heavy metal concentration in the influent feed was varied. The heavy metals considered for this research were copper as  $\text{Cu}^{2+}$  and nickel as  $\text{Ni}^{2+}$ .

## 1.2 SCOPE OF RESEARCH

The metals copper and nickel were chosen for this research because these metals were known to be present in the influent wastewater. The CELCO treatment plant was experiencing some problems such as poor sludge settlement and high effluent concentrations of total suspended solids (TSS) and chemical oxygen demand (COD). High concentrations of heavy metals like copper and nickel in the influent wastewater are known to be highly toxic to the microorganisms present in activated sludge mixed liquor but the chronic effects of these metals are not thoroughly understood. Therefore, it was decided to determine if the presence of relatively low concentrations of the metals in the influent wastewater had any effect on the activated sludge COD removal efficiency, oxygen uptake rate (OUR), sludge settling characteristics, and effluent SS.

## CHAPTER 2

# LITERATURE REVIEW

### 2.1 GENERAL

The presence of heavy metals in wastewater has long been a concern for the regulators and the regulated. Different researchers over the past three decades have conducted research on heavy metals to understand their impact on the performance of activated sludge systems, but the results obtained by any two researchers is difficult to compare. This is because in the running of an activated sludge unit, a number of parameters are involved, and one or more of them is usually different when two studies are compared. The parameters include hydraulic retention time, mean cell residence time, recycle ratio, source (domestic or industrial), type of influent feed, influent feed concentration of metals, oxidation state of metals etc. Hence the use of different values for the parameters, by different researchers, makes it very difficult to draw definite conclusions from their work. Nevertheless, since the nature of research is the same, general conclusions can



be drawn from the studies of the various researchers. They are discussed below :

## **2.2 Presence of heavy metals in the influent feed of the activated sludge system**

The heavy metals that have been generally considered by researchers are : aluminum, bismuth, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, molybdenum, nickel, silver, thallium, and zinc. The metals copper and nickel will be given importance in this literature survey.

The heavy metals have been traditionally a concern to the regulatory agency and the treatment plant manager. The concern to the regulatory agency stems from the fact that the discharge of heavy metals to the receiving stream may be toxic to a variety of aquatic life. Table 2.1 gives an idea of the concentration of Copper and nickel that may be toxic to game fish. Treatment plant managers are concerned about metals in their wastewaters because they might result in reduction of treatment efficiency by their activated sludge plants. Hence, over the past decades, research has been done to study the fate of heavy metals in the activated sludge process.

Table 2.1 : Concentration of Copper and Nickel toxic to game fish

Cu	0.04 mg/L
Ni	0.80 mg/L

Source : Reference #3.

Heavy metals may enter the treatment system in a continuous concentration or may vary with time i.e. as a slug dose. More research has been done on the slug dose as compared to a continuous dose. In the CELCO activated sludge plant this variation is minimized due to the presence of the equalization basin.

The presence of heavy metals in the influent wastewater raises two important questions i.e.

- What is the effect of metals on the treatment efficiency?
- How efficient is the activated sludge in removing metals?

The treatment of the wastewater in the activated sludge process is carried out by a number of microorganisms, so an understanding of the interaction between the metals and the microorganism is useful. But there are a number of factors which make the understanding of the interaction between the metal and the microorganism a complicated one<sup>25</sup>.

First, the activated sludge is the home of millions of microorganisms. Table 2.2 gives an idea of the magnitude of the different types of microorganisms present in the mixed

//

Table 2.2 Comparison of the relative magnitude of microorganism present in the mixed liquor //

Process	Phylum	Genera	Species
Aerobic	Several	Hundreds	Thousands
Anaerobic	One	One to Ten	One to Ten

Source : Reference #45.

liquor of such an aerobic system.

Gerardi<sup>21</sup> reported that an aerobic activated sludge system can withstand a higher level of metal load when compared to an anaerobic system due to the reduced solubility of many metals under aerobic conditions. This is probably due to the thousands of species that may be available in the aerobic system when compared to a few (< 10) species available in an anaerobic system. Table 2.3 gives an idea of the extreme environment the microorganisms can survive.

When one or more metals is introduced into the wastewater stream, this metal may affect only certain species without affecting the others. So, a true understanding of the interaction between the metals and the microorganisms requires knowing the species affected and suitable measurement techniques. But, due to the sheer magnitude of the number of species involved in an aerobic activated sludge system, the species are usually unknown. Hence, only a general picture of what happens to the system is obtainable<sup>25</sup>. In spite of the above difficulties numerous researchers have studied metal toxicity effects on activated sludge microorganisms.

The overall cellular activity of the microorganisms has been

Table 2.3 Environmental extremes of microorganism survival

Factor	Lower Limit	Upper Limit
Temperature	-18° C (Fungi and Bacteria)	104° C (Sulfate reducing bacteria in hot springs)
pH	0 (Thiobacillus)	13 (Plectonema nostocurum)
Hydrostatic Pressure	0 Atm (Spores)	1400 atm (deep sea bacteria)
Salinity	Distilled water (Pseudomonas)	Saturated Brine (halophilic bacteria)
Oxygen	0 saturation (anaerobes)	Supersaturated (Algae)
eH Potential	-500 (clostridium)	+ 500 (nitrosomonas)

Source : Reference #47

suggested as a control parameter for the measurement of toxic effects due to metals<sup>24</sup>. The reason for preferring the overall cellular activity over that of the measurement of individual enzymes is the heterogeneity of substrates utilized by activated sludge microorganisms<sup>24</sup>. Brezonik and Patterson suggested adenosine triphosphate (ATP) as a measure of microbial activity. Slug doses of the metals were introduced for one hour. They concluded that for up to 2.5 mg/L of copper there was no decrease in ATP; but in the case of nickel there was a constant decrease in ATP. They also reported that for temperature changes up to 37 deg. centigrade, ATP is a sensitive indicator of the toxicity to the activated sludge. Another measure used was the measurement of the specific growth rate of certain species<sup>6</sup>. Sudo et. al. found that the concentrations of copper required to reduce the specific growth rate to one half of that of a control were as follows:

0.25 mg/L -- (V. microstoma)  
0.32 mg/L -- (C. Campylum)  
0.27 mg/L -- (Opercularia sp.)

The authors pointed out that after acclimation of the protozoa to the metal for at least 96 hours, the specific growth rate was 1.2 to 2.2 times that of the control. The

above were the two common methods used to get a direct measure of toxicity. The indirect methods are discussed later in this section.

### **2.3 Removal of metals through the activated sludge process**

In an activated sludge, the metals may be removed at two different stages in the activated sludge process. The two outlets for the metal removal are the primary sludges and the secondary sludges. The mechanism of metal removal in an activated sludge is discussed in detail by Brown and Lester<sup>29</sup>. There are four different mechanisms by which the metals may be removed. They include :

- physical trapping of precipitated metals in the sludge floc matrix;
- binding of soluble metal to extracellular polymers;
- accumulation of soluble metal by the cell; and
- volatilization of metal to the atmosphere.

#### **2.3.1 Physical trapping of precipitated metals in the sludge floc matrix :**



The microorganisms present in the mixed liquor helps in the conversion of dissolved or suspended organic matter in the wastewater into carbon dioxide, water and cellular material. The bacteria and other microorganisms form flocs. The mixed liquor along with the flocs then passes to the clarifier. These flocs have the ability to absorb or adsorb the metals. This capacity to absorb or adsorb varies widely with different sludges and different metals. In the clarifier the settling of the sludge along with the metals occur. The removal of this secondary sludge leads to the removal of metals.

### 2.3.2 Binding of soluble metal to extracellular polymers

Wilkinson<sup>58</sup> and Sutherland<sup>59</sup> have shown that many species of bacteria that are present in the activated sludge produces extracellular polymers. These polymers may be in the form of loose slime, or capsules or microcapsules<sup>58</sup>. Nitrogen, sulphur and phosphorous were not required for the extracellular polymer synthesis. If excess carbon source was present then these were converted to extracellular polymers. Novak et al<sup>60</sup> showed the importance of dissolved oxygen concentration in influencing the concentration of extracellular polymers. Many researchers have reported the adsorption of soluble metal to the extracellular

polymers<sup>62,63,64,65</sup>. At the same time Bitton and Freihofer<sup>64</sup> have suggested that the toxicity of a metal dose (copper) to bacteria is reduced due to the protective mechanism of the capsule.

### 2.3.3 Accumulation of soluble metal by the cell

The cells of the microorganisms have been observed to have the capacity to adsorb the metals<sup>67,66</sup>. This adsorption by the cells of microorganisms is generally said to occur when the microorganisms do not have the capacity to produce capsules or microcapsules. The extent to which the accumulation takes place is not well documented.

### 2.3.4 Volatilization of metal to the atmosphere

This is associated generally with mercury and is not applicable to other metals<sup>67,68</sup>.

Another point brought out by Nelson et. al. was the rate of uptake of metal was fastest during the first couple of hours after the new dosage of the metal<sup>36</sup>. In the literature different researchers have reported different levels of metal removals. These are shown in Table 2.4.

Table 2.4 Summary of Metal Removal Efficiency in an Activated Sludge Plant

Metal/Plant	Activated sludge effluent (ug/L)	Range of removal efficiency(%)	Avg. Removal efficiency (%)	Reference
Copper				
FS	60		25	48
FS	12		33	49
FS	92	0-95	57	50
FS	40-660		60	39
FS	170		61	35
FS			68	37
FS	110-130	69-85	77	40
FS	0-160		81	51
FS	90		81	52
PP	920		33	33
PP	171		38	53
PP	98		43	54
PP	160		72	37
PP	9000		75	3
PP	10000-25000	75-79	78	56
LS	106	0-42	24	38
LS	129	17-42	28	11
LS	150		35	55
LS	2100-25200	85-91	89	9
Nickel				
FS	42		<0	49
FS	30-1600		1	39
FS	50		15	48
FS	163	0-80	20	50
FS		25	11	
FS	77		30	52
FS	191		41	40
PP	715		<0	53
PP	77-200		9	54
PP	73		21	33
PP	2000-10000		28	3
PP	1000	28-42	33	5
PP	180		33	37
LS	114	0-26	11	38
LS	96	3-26	13	11
LS	140-25300		14	55
LS	2100	53-65	58	9

LS = Lab. Simulation; PP = Pilot Plant; FS = Full Scale  
 Ref # 44 and others as indicated on the table

One problem with the data presented in Table 2.4 is the lack of information on the different operating parameters (like MCRT, HRT etc.) in the activated sludge system run by the different researchers. In general, it can be observed from the table, that there is no "consistent value" for the removal efficiency. The range of removal efficiency is wide, ranging from 0% to 95% for copper and 0% to 80% for nickel. A study of the table shows the average removal efficiency for copper was greater than that for nickel. Also the removal efficiency was found to be directly proportional to the metal loading<sup>31,58,35</sup>.

The reason cited for the low metal removal in certain systems was due to the *fixed demand* for these metals by the microorganisms<sup>33</sup>. Petrasek and Kugelman<sup>37</sup> pointed out that higher removal efficiencies of the metals were obtained when the concentration of the metals in the influent were high.

From the above discussion it can be said that the microorganisms may have a certain ability to retain the metals. This ability to retain metals varies widely from species to species. It is this ability of the microorganisms to retain the metals and survive in the activated sludge makes them develop a resistivity to certain concentration of the metals.

## 2.4 Acclimation

The metals are considered to be in toxic concentrations when the microorganisms present in the mixed liquor dies or the enzymes are completely damaged. Generally, when a small continuous dose of the metal concentration is fed into the reactor, one or more enzymes are inactivated or damaged<sup>2,69</sup>. When this happens the microorganisms have the ability to replace the damaged enzymes, or an alternate metabolic pathway may be provided for the metabolic activities. For the above readjustments to take place by the microorganisms, it takes a certain amount of time. Once the above readjustments are made, the microorganisms are now ready to perform at a higher level of efficiency than at the time when the metal concentration in the feed was increased. This ability of the microorganisms to adopt to the new concentration of the metal is called *acclimation*. This time period for acclimation is different for different sludges.

A two (2) week time period for acclimation (measured as BOD removal) was reported by Mowat<sup>30</sup>. A 5 day acclimation period was reported by Lester et. al.<sup>13</sup>. when a slug dose of 50 mg/L of copper was added. In their research they found reduction of the bacterial population in the sludge from an initial population of about  $4.5 \times 10^8$  to  $3.5 \times 10^5$  within 2 hours.

But within a period of 5 days they found the concentrations of microorganisms to be similar to that of the control. When lead was used at concentrations of 5 and 10 mg/L the acclimation period was the same for both i.e. 6 days. An acclimated sludge has shown to take shock loads of metals better than an unacclimated sludge<sup>29</sup>.

Once the sludge is acclimated for a small dosage of metal (1 to 2 mg/L), it has been reported that the sludge can withstand concentrations upto 10 to 20 mg/L with just about 5% reduction in treatment efficiency<sup>45,2,31</sup>. The acclimation of the sludge also depends on the form of the metal added<sup>3</sup>.

Barth et. al. have reported that when copper was added in the cyanide form, it required more time for acclimation when compared to that of sulphate form. But once the system was acclimatized to cyanide it appears that the form of metal does not matter. Evidence of this can be found in Adams et. al.<sup>28</sup> work. They found that after the system was acclimatized to the effect of cyanide, there was no difference in treatment efficiency when copper was applied as copper cyanide or as copper sulphate.

## **2.5 Factors affecting the behavior of toxic metals**

The toxicity of the metal in the mixed liquor is not only

related to the concentration of the metal in the mixed liquor but also to the ratio of the metal conc./MLVSS<sup>1,12,21,23,27,38</sup>. The degree of toxicity for copper and nickel have been reported to be in the following order<sup>30</sup>.

Cu > Ni

Metal toxicity is dependent on the type of species present<sup>6</sup>. Sudu and Shuichi found that the toxicity of copper was increasing in the following order for the following species.

V. microstoma > Opercularia sp. > C. Campylum

Sludge age was also found to affect the degree of metal toxicity to the microorganisms<sup>1,2,8</sup>. Higher sludge age mixed liquor showed an overall greater suppression of toxicity of the metal to the microorganisms. The higher sludge age leads to an increase in microorganisms, and this leads to more organisms which are not complexed with the metal. The presence of more than one metal present in the mixed liquor is not clear from the literature if there is synergistic or antagonistic effect. Barth et. al.<sup>3</sup> found that copper, nickel, chromium and zinc behaved independently when present in the mixed liquor.

## 2.6 Indirect measures of Toxicity

The indirect measures of the measurement of toxic effects have been studied by a number of researchers. The indirect measures include measurements of BOD, COD, MLVSS, OUR, SVI, and nitrification. The reduction in COD removal efficiency as reported by some investigators is shown in Table 2.5. From the data it can be seen that there is no reduction in treatment efficiency for a metal concentration of 1 mg/L; a concentration of 10 mg/L causes a reduction in COD by about 5 %. It has been reported<sup>28</sup> that the activated sludge system can withstand up to 45 mg/L of continuous dosage of copper without the failure of the system.

Neufield<sup>7</sup> has reported increases in the effluent suspended solids after the metal dosage. Such increases appeared to be directly proportional to the metal concentration in the reactor. The SVI was reported to drop with the addition of the metal to the mixed liquor, indicating better settling characteristics<sup>19</sup>. Yetis and Gokcay also reported a better sludge settleability when 5 mg/L of Ni (II) was added. The general trend when a metal dose was added was a reduction or maintenance of the same level of total biomass. One exception found in the literature was in the Yetis and Gokay report<sup>19</sup>, where they reported a doubling of biomass when 5



Table 2.5 % COD removal efficiency

METAL	CONC. (mg/L)	% REDUCTION	REFERENCE
Copper	10	5	3
Nickel	1	0	1
	5	3	1
	10	5	3
	10	3	5
	5	1	5
	2.5	5	5
	1	0	5

mg/L of Ni (II) was added.

Hartz et. al.<sup>26</sup> reported that an increase in biomass does not lead to a proportional increase in oxygen demand. They reported that the toxic effects of the metal are decreased when there is an increase in biomass. Tyagi and Couillard<sup>16</sup> reported that a decrease in pH leads to an increase in inhibition of the growth of the microorganisms. The reason was attributed to the increase in free metal ions at lower pH.

## CHAPTER 3

# MATERIALS AND METHODS

### 3.1 Wastewater Pretreatment

One of the important requirements of this research was the removal of heavy metals, particularly copper and nickel, from the influent feed before it entered the biological reactor. The reasons for the removal of the heavy metals were as follows :

- to allow study of effects of "no metals" on system performance.
  
- enable operation with a known concentration and type of metal.

The removal of the heavy metals i.e. copper and nickel, was accomplished with the help of lime. The principle for removal of the heavy metals was to raise the pH to a point such that their solubility products were exceeded and

precipitation of metals took place. To determine the pH to which the influent feed had to be raised, jar tests were conducted in the laboratory. The jar tests were conducted using both lime and ferric chloride. When lime was used, the pH was raised to 9, 10, 11, and 12. In the case of ferric chloride, a 20 mg/L concentration was used. The jar tests were conducted using a flash mix time of 1 minute, a slow mix time of 30 minutes and a settling time of 45 minutes. After this, supernatant samples were taken and analyzed for Total Metal concentration for both copper and nickel as explained in the "Sample collection and analysis" section. The results are shown in Tables 3.1 and 3.2.

From the Tables it can be seen that when ferric chloride was used, the removal efficiency of copper was about 65%. In the case of nickel, there was practically no removal. When lime was used the best removal efficiency occurred at pH 10.5 - 11. For copper, the removal efficiency was greater than 95% while for nickel, the removal efficiency was about 55%. So ferric chloride was not very effective for precipitation of the metals (copper and nickel), when compared with lime. Hence lime was used for pretreatment of the influent feed.

Table 3.1 : Jar Test No 1

Jar No.	Type	pH	Cu (mg/L)	Ni (mg/L)
1	Control	4.37	0.27	0.29
2	Lime	9.03	0.10	0.19
3	Lime	10.1	0.03	0.15
4	Lime	10.99	0.04	0.16
5	Lime	12	0.05	0.18
6	20 mg/L FeCl <sub>3</sub>	-	0.11	0.28

Table 3.2: Jar Test No 2

Jar No.	Type	pH	Cu (mg/L)	Ni (mg/L)
1	Control	4.84	0.20	0.23
2	Lime	9.00	0.08	0.20
3	Lime	9.96	0.07	0.14
4	Lime	11.01	0.03	0.16
5	Lime	12.06	0.04	0.15
6	20 mg/L FeCl <sub>3</sub>	-	0.07	0.23

### 3.2 Experimental equipment and system operation

The research involved comparison between two activated sludge systems, i.e., one where metal was added to pretreated influent feed and the other where no changes were made to the influent feed. Two (2) lab scale activated sludge systems were used. In this thesis, the reactor to which no metal was added will henceforth be identified as the *Celco unit*. The other reactor which received metal additions will henceforth be identified as the *experimental unit*.

#### Operating conditions

Both reactors were operated under the following set of conditions:

- A common reactor volume of 8 Liters.
- A common Hydraulic Retention Time (HRT) of 2 days and hence a common influent flow rate of 4 liters per day.
- A common Mean Cell Residence Time of 12 days.
- A constant temperature of 20±1 deg. centigrade.
- A common seed sludge from the aeration basin of the wastewater plant at CELCO.
- Adequate aeration in both the reactors to provide

complete mixing of the mixed liquor suspended solids (MLSS) in the aeration basin.

### Experimental equipment

The following is a description of the equipment used, which was applicable for both the Celco and the experimental unit. The reactors and clarifiers were made of glass. The influent was pumped from calibrated carboys with the help of a Sigmamotor (Middleport, New York) model T-6 pump. The excess mixed liquor flowed from the reactor into the clarifier by gravity. The recycle from the clarifier to the reactor was accomplished with a Sigmamotor pump which used #14 tygon tubings. Again by gravity, the supernatant overflow of the clarifier flowed to an effluent carboy. The influent lines were rinsed approximately once every 10 days with a solution of bleach. The tygon tubings were replaced approximately once every twenty days. The recycle lines were washed first with hot water and then with cold water. Bleach was not used for washing the recycle lines in order to prevent any accidental killing or inhibition of the microorganisms that were recycled.

Air from compressed air lines was regulated by a valve and was released into the reactors with the help of two diffuser



stones. The purpose of the air was two fold :

- To supply oxygen to the microorganisms in the reactor.
- To keep the reactor in a well mixed state.

Sometimes there was buildup of foam in the reactor. In order to destroy this foam, a foam suppressing liquid was obtained from the Celco plant. A drop or less was used for this purpose. An average of a drop was used once in two weeks.

The clarifier had a scraper which helped reduce the solids attached to the walls of the clarifier. The flow diagram for the lab scale activated sludge process is shown in Figure 3.1.

### **3.3 Influent feed**

The influent wastewater for the reactors were obtained from the equalization basin of the Celco wastewater treatment plant. Floating leaves and other debris were removed when the carboy was filled. The influent was stored in a refrigerator at the Environmental Engineering laboratory. The time period for the storage varied from 2 to a maximum of 7 days.

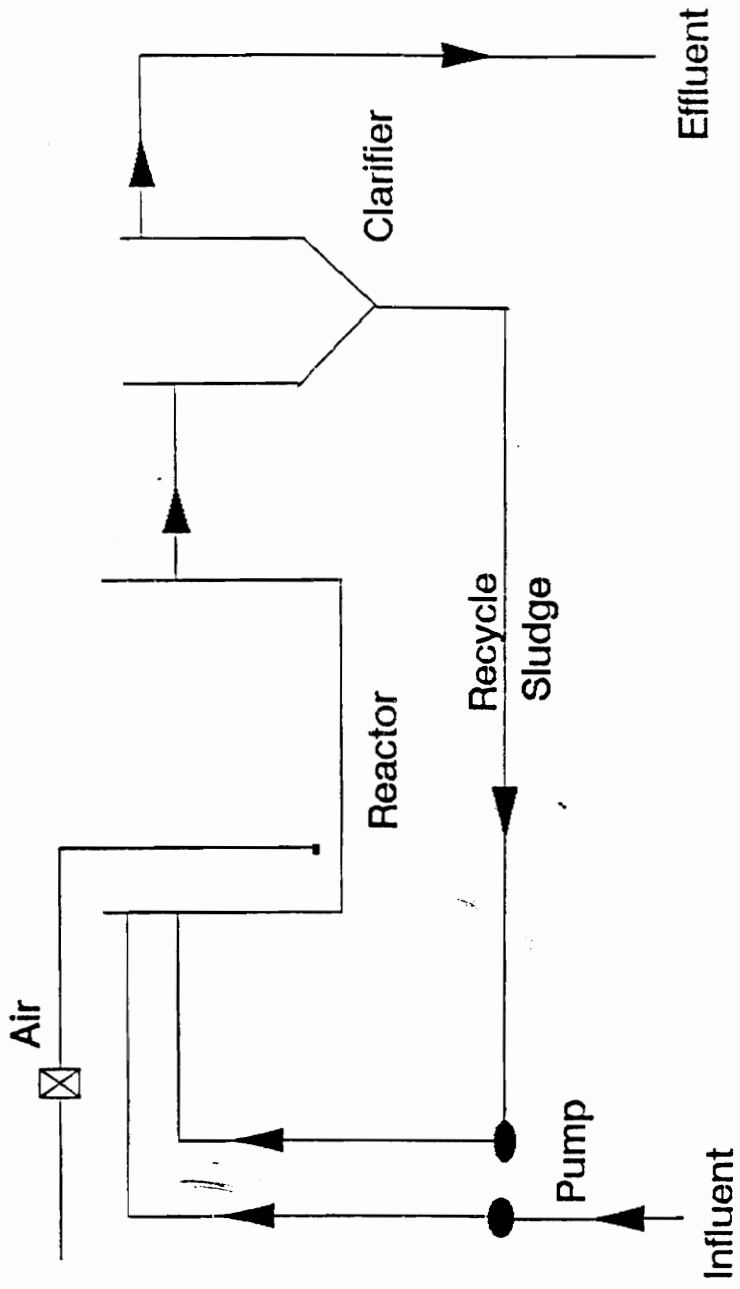


Figure 3.4 Flow Diagram for Lab Scale Activated Sludge Process

### 3.3.1 Influent feed preparation for the Celco unit

Nutrients are important for the microbial organisms in the activated sludge reactors. To provide the organisms with the required amounts, it was necessary to add nutrients to the influent feed. After going through the plant records, it was decided that nitrogen, potassium and iron were limiting compared to the COD. From a study of the plant records from January to May 1990, it was found that there was an average of 18 mg/L of nitrogen in the influent feed.

The requirements for the nutrients were calculated as follows:

#### *Nitrogen*

The amount of biomass to be wasted was calculated using the following equation.

$$Q_{waste} = [Vol_{reactor} \times MLVSS/MCRT - (Q_{feed} \times Eff_{vss})] / (MLVSS - Eff_{vss}) \dots (1)$$

where

$Q_{waste}$  = Quantity wasted from the reactor (L/day)

$Vol_{reactor}$  = Volume of the reactor (L)

MLVSS = Mixed Liquor Volatile Solids (mg/L)

MCRT = Mean Cell Residence Time (days)

$Q_{\text{feed}}$  = Influent feed quantity (L/day)

$\text{Eff}_{\text{VSS}}$  = Effluent suspended solids (mg/L)

$$\text{If } X = [(Q_{\text{waste}} \times \text{MLVSS}) + (Q_{\text{feed}} - Q_{\text{waste}}) \times \text{Eff}_{\text{VSS}}] \dots (2)$$

then

$$\text{Required Nitrogen} = 0.12 \times X / Q_{\text{feed}} \dots (3)$$

The value of 0.12 was used after a discussion with Dr. Randall and from Gaudy and Gaudy<sup>72</sup>. Since there is an average of about 18 mg/L nitrogen present in the influent feed, the nitrogen that was added was :

$$N_{\text{added}} = \text{Required Nitrogen (mg/L)} - 18 \text{ mg/L} \dots (4)$$

This nitrogen was added in the form of urea ( $\text{NH}_2\text{CONH}_2$ ). Since urea contains 0.46 % nitrogen the amount of urea added was :

$$\text{Urea added} = N_{\text{added}} / 0.46 \dots (5)$$

The amount of potassium (K) to be added was determined as follows:

From Gaudy and Gaudy<sup>72</sup> the elemental cell composition has a potassium content of 1/14 of the required nitrogen. Hence

$$K = (1/14) \times \text{required nitrogen} \dots (6)$$

Potassium was added in the form of KOH. Hence KOH required was

$$\text{KOH} = \text{K}/0.697 \quad \dots (7)$$

Again from Gaudy and Gaudy, the elemental cell composition has a iron (Fe) content of 0.2/14 of the required nitrogen.

Hence

$$\text{Fe required} = (0.2/14) \times \text{Required nitrogen} \quad \dots (8)$$

The iron was added as Ferric Chloride. Hence the required Ferric Chloride was :

$$\text{FeCl}_3 = \text{Fe}/0.344 \quad \dots (9)$$

The above equations were the general calculations on which addition of nutrients was based. But changes were made in the amounts of nutrients added during the research. From day 36,  $\text{FeCl}_3$  was limited to 1 mg/L, in order to avoid precipitation. From day 34, a potassium concentration of 25 mg/L was added to the influent feed, as per Dr. Randall's recommendation. This was to be certain potassium was not a limiting nutrient. Also from day 58, the  $\text{FeCl}_3$  concentration was further reduced to 0.5 mg/L, since some precipitation was still observed in the influent carboy. Also, till day 70 the feed for the influent was prepared about once every 4 days. After day 70 the feed was prepared once every two days. This was to reduce precipitation in the carboy. It should be noted that after the nutrients were added to the carboy, the carboy was shaken thoroughly to get a good mix of the nutrients.

During the initial stage of the research the flow rate of the influent was measured using a 10 ml graduated cylinder. But it was realized that due to possible voltage fluctuations this may not be an accurate measure of the flow rate. Hence the measurement of the influent flow rate was done with the help of a calibrated carboy. The difference in volume was noted each day, and this difference was maintained at almost 4 L per day.

### 3.3.2 Influent feed preparation for the experimental unit

The influent feed preparation for the experimental unit consisted of pretreatment, metal addition and nutrient addition. Here also the feed from the equalization basin was used as the raw influent feed. A typical pretreatment process for the influent feed is described as follows :

A 21 L rectangular reactor (hence forth called the mixing reactor) with a special stirrer was set up. A T line laboratory stirrer model number 134-2 was used. The stirrer had two flat blades of length 7.6 cm and width 2.5 cm. The blades were oriented at 90 degrees to each other. This staggered orientation of the blades helped cause more effective collision among the particles. A pH meter was calibrated and set near the mixing reactor. The wastewater

was poured into the reactor until it reached the 19 L mark. Then the pH probe was dipped into the reactor. After this lime was slowly added and mixed in to the wastewater causing the pH to rise. Lime was added until the pH was above 10.8. After this the pH probe was removed from the reactor. Then the stirrer was set at 100 RPM for one minute, signifying the flash mix. The RPM was then reduced to 20 RPM, for the slow mix and maintained for 30 minutes. Then the stirrer was stopped. For 2 hours the flocs were allowed to settle. After settling there was a clear interface between the liquid and solid phase. The supernatant was then carefully drained into another reactor. This supernatant was checked for pH. It was generally around 10. To reduce the pH to its original condition, concentrated Hydrochloric acid (HCl) was added until the pH was about 4.5. (During the first phase of the research the pH was brought down to around 6.0). After this the required nutrients were added.

The nutrients added included phosphorous, nitrogen and potassium. The effluent samples were randomly tested for phosphorous and it was found that the average phosphorous concentration after precipitation was about 0.15 mg/L. Therefore it was necessary to add phosphorous to keep it from being limiting. Nitrogen was added according to equation (5).

Phosphorous additions were calculated based on elemental cell composition.

From Gaudy and Gaudy<sup>72</sup>, the elemental cell has phosphorous content equal to 3/14 of the required nitrogen. Hence

$$P = (3/14) \times \text{required nitrogen}$$

Phosphorous was added as Potassium Phosphate Monobasic ( $\text{KH}_2\text{PO}_4$ ).

Potassium :

To be consistent with the Celco unit, 25 mg/L of potassium was added. Since Potassium Phosphate Monobasic has 28.73% of potassium, this potassium was accounted for when Potassium Hydroxide was used as a potassium source.

Iron as Ferric Chloride was not added in order to avoid any precipitation of metals in the carboy. Not adding the ferric chloride did not seem to affect the system, compared to the Celco system which received a small amount of ferric chloride (0.5 mg/L).

In addition to the above, other changes in nutrient addition and concentrations are as follows :



Phosphorous was added only from day 15. Until then no phosphorous was added. Ferric chloride was added till day 7 and then stopped. Potassium concentration of 25 mg/L was added to the influent feed from day 34. The concentration added was based on equation (6) until day 25. From day 25 to day 34, the potassium concentration was double the amount calculated by equation (6).

After the addition of nutrients, the metals were added as follows:

Copper was added as  $\text{Cu}^{2+}$ . The addition of copper was done using copper chloride. Purified crystals of  $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$  (2.6825 gm) were taken and dissolved in a liter of distilled water. This gave a stock solution of 1000 mg/L solution.

Nickel was added as  $\text{Ni}^{2+}$  in the form of nickel chloride. A stock solution was prepared by dissolving 4.049 gm of  $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$  in a liter of distilled water. Acid washed pipettes were used for pipetting the required amount of metal solution to the influent feed.

The order in which the metals were added was as follows :

Phase No	Day	Metals addition
1	1 - 25	0 mg/L of Cu and 0 mg/L of Ni
2	26 - 48	1 mg/L of Cu and 0 mg/L of Ni

3	49 - 72	2 mg/L of Cu and 0 mg/L of Ni
4	73 - 94	1 mg/L of Cu and 1 mg/L of Ni
5	95 - 105	1 mg/L of Cu and 0 mg/L of Ni
6	106 - 126	0 mg/L of Cu and 2 mg/L of Ni

Hence forth "phase" in this thesis refers to the above phases. The time line change in operating conditions is shown in Table 3.3.

### 3.4 Sample collection and analysis

The following methodology was adopted to obtain the samples. For influent samples, the influent carboy was shaken thoroughly and then the required samples were taken. In the case of mixed liquor, first the sides of the reactor were scraped and the required samples of the mixed liquor were obtained. For effluent samples, the effluent was directly collected at the point where it comes out of the clarifier. In all the above cases, acid washed glassware was used when metals analysis were to be done. For the purposes of acid washing, a 10 % nitric acid bath was used. The glassware was generally kept in the bath for a day before it was rinsed with distilled water. For other analyses, clean dry glassware was used for collecting the samples. The tests were performed every other day with a couple of exceptions as indicated in the data tables.

Table 3.3: Time line of change in operating conditions for the experimental unit

Day 7	Ferric chloride addition stopped
Day 15	Phosphorous added to influent feed
Day 25	Potassium concentration doubled
Day 26	1 mg/l of copper added to influent feed
Day 34	25 mg/l of potassium added to influent feed
Day 40	pH of influent lowered to 4.5
Day 49	2 mg/l of copper added to influent feed
Day 73	1 mg/l of copper & 1 mg/l of nickel added to influent feed
Day 95	1 mg/l of copper added to influent feed
Day 106	2 mg/l of nickel added to influent feed

The Chemical Oxygen Demand (COD) tests, for both the influent and effluent were performed according to section 5220C (Closed Reflux Titrimetric method), *Standard methods for the examination of water and wastewater*<sup>70</sup>. The influent samples were not filtered for COD analysis so that total COD would be measured, but the effluent samples were filtered through a 0.45 u Whatman filter to remove biomass solids and accurately measure the soluble effluent COD.

The influent, effluent and mixed liquor samples were analyzed for total suspended solids. The total suspended solids were performed according to section 2540D (Total suspended solids dried at 103-105 deg C., *Standard methods for the examination of water and wastewater*<sup>70</sup>). The Volatile solids were done on the basis of section 2540E (fixed and Volatile solids ignited at 550 deg C).

The dissolved oxygen (D.O) measurements were made using models 54A and 57 oxygen meters manufactured by Yellow Springs Inst. Company, Incorporated (Yellow Springs, Ohio). The D.O. probe was calibrated by placing it in a bottle containing water equal to a fourth of its volume. The air present in the bottle ensured that the water was saturated. The D.O. readings were taken every minute.

The Sludge Volume Index (SVI) was determined by placing the mixed liquor in a 1 Liter graduated cylinder and permitting the suspended solids to settle. Interface height readings were taken at 1, 2, 5, 10, 15, 25, and 30 minutes. (The initial 1 and 2 minute readings were skipped if settling was slow.) Then the SVI was calculated using the following equation.

$$\text{SVI} = 30 \text{ min. interface height, (ml/L)} \times 1000 / \text{MLSS (mg/L)}$$

The Zone Settling Velocity (ZSV) was determined by noting the height of the liquid sludge interface at different time intervals. Then the interface height vs. time was plotted. A straight line was drawn through the data points which showed linearity. When the interface between the sludge and the liquid was not clear, then it was not possible to make the initial readings. So the ZSV was determined by drawing a straight line from time = 0 to time at which an interface was visible.

Metals were measured as *total metals* for the influent, effluent and mixed liquor. In the case of mixed liquor the *dissolved metal* analysis was performed. The sample preparation was done as follows:

### Dissolved Metals

The dissolved metals were those that would pass through a 0.45u membrane filter. For the sample preparation, about 50 ml of the mixed liquor was collected in an acid washed beaker. The solids in the mixed liquor was allowed to settle. After about an hour, the supernatant was collected and filtered through a 0.45u membrane filter. Sometimes it was not possible to filter directly through a 0.45u membrane filter due to the non-settleable solids. In this case the supernatant was filtered first through an ordinary filter and through a 0.45u filter. This sample was then preserved in an acid washed test tube with the addition of a drop of nitric acid.

### Total Metals

The total metals represent the concentration of metals determined on an unfiltered sample following vigorous digestion. For the sample preparation, exactly 100 ml of mixed liquor or influent or effluent was collected in an acid washed beaker. Five ml of concentrated nitric acid ( $\text{HNO}_3$ ) was added for digestion purposes. The beaker was then placed on a hot plate. The temperature of the hot plate was kept such that the contents of the beaker did not

boil. When the volume of the contents in the beaker dropped to about 15 ml the hot plate was turned off. Then the beaker was allowed to cool. Next the contents of the beaker were washed down with distilled water. The sample was then filtered (to remove any insoluble particles) into a 100 ml flask and thoroughly mixed. Next a sample was collected from the flask and transferred to an acid washed test tube. The sample in the test tube was preserved with a drop of concentrated nitric acid. The metals were determined by atomic absorption spectrophotometry using a Perkin-Elmer atomic-absorption spectrophotometer.

## CHAPTER 4

# RESULTS

### 4.1 GENERAL

In this chapter, experimental data obtained for both the Celco and experimental units are presented. A brief description of what happened during the experimental work is described.

The experimental data for both the Celco and experimental units were collected beginning May 31 (Day 1). The data were collected every other day, with a few exceptions which are reported in this section. This was a closely monitored system. It should be noted that the influent COD values for the same influent varied from one day to the other. The probable reason was as follows:

-- The measurement of the influent as described in the "Materials and Methods" section, was a 0.5 ml influent sample which was diluted with 4.5 ml of distilled water. Since 0.5 ml of influent is a small quantity, even a small measurement error resulted in an inaccurate influent COD



value. Also, in this section whenever data is said to be incorrect, the reason was due to experimental error unless otherwise stated.

## 4.2 WASTEWATER VARIATION

### EXPERIMENTAL FEED vs. CELCO FEED

The influent wastewater to the Celco unit was not pretreated for metals removal whereas the influent wastewater to the experimental unit was pretreated with lime, and then copper and nickel were added separately or together to evaluate their effects on the performance of the system.

#### 4.2.1 METALS VARIATION

The total copper in the influent feed for the Celco unit varied from 0.20 mg/L to 0.50 mg/L (Figure 4.1). The total nickel in the influent varied from 0.35 mg/L to 0.75 mg/L (Figure 4.2).

For the experimental unit, after the raw influent from the Celco plant was pretreated with lime, the removal of copper was excellent (> 95%). The removal of copper achieved during phases 1 and 6 can be observed in Figure 4.1. During

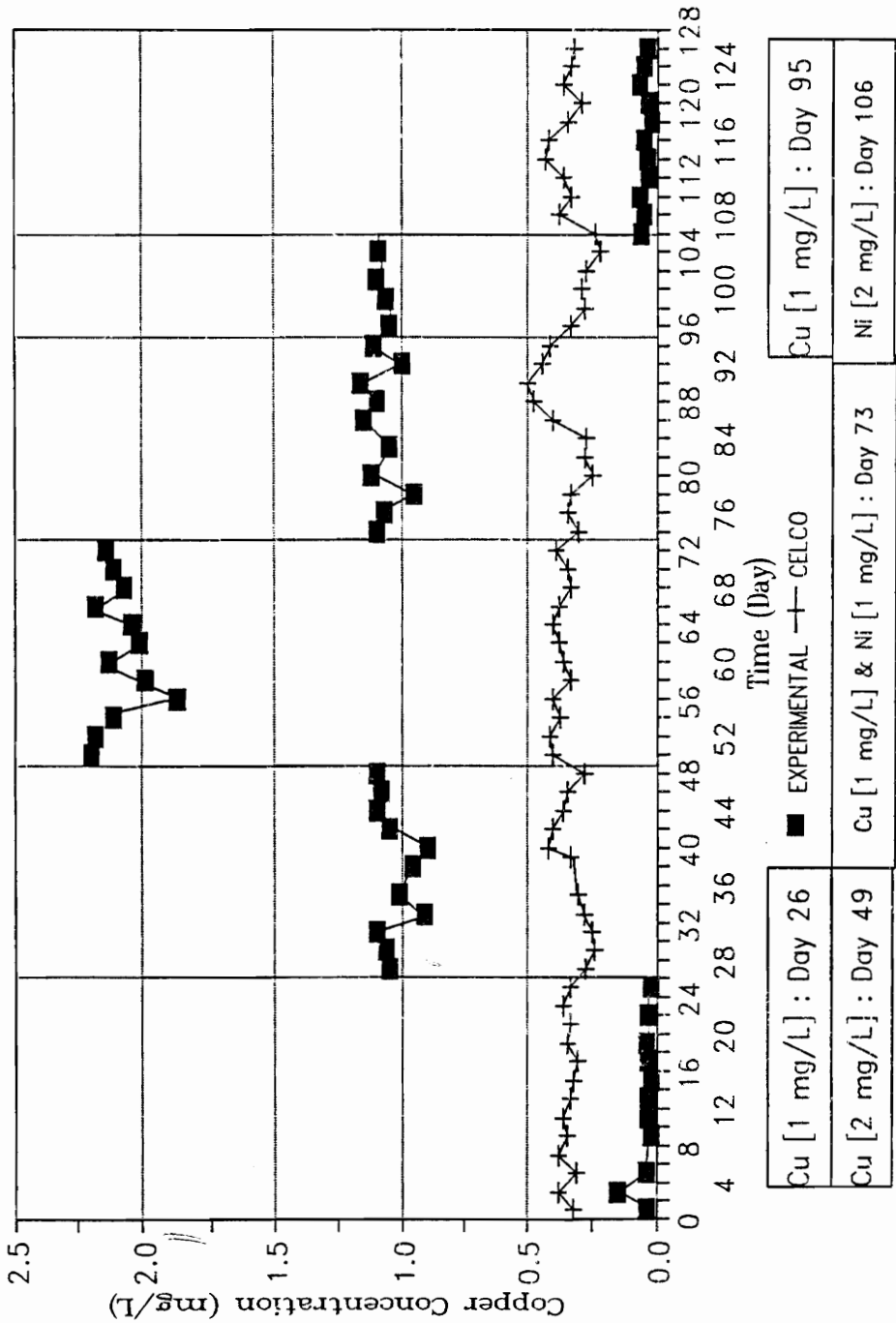


Figure 4.1 Comparison of Total Copper in the Influent Feed for the Celco and Experimental Units

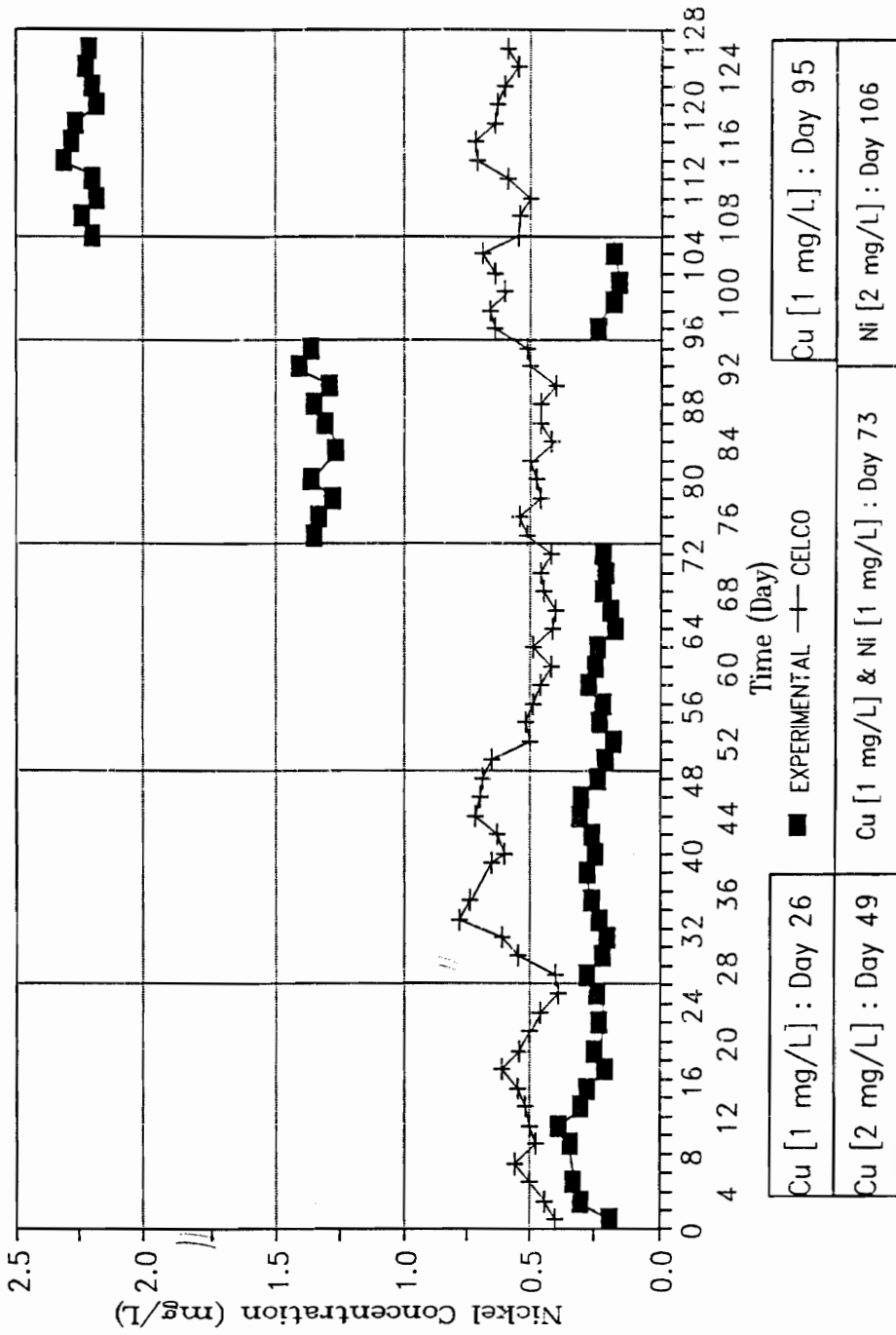


Figure 4.2 Comparison of Total Nickel in the Influent Feed for the Celco and Experimental Units

phases 2 to 5, copper was added separately or in combination with nickel to the influent feed of the experimental unit.

The removal of nickel by lime treatment was around 60% during phases 1,2,3 and 5, when no nickel was added to the experimental unit.

#### 4.2.2 COD VARIATION

Pretreatment of the influent feed with lime did not accomplish any appreciable removal of influent COD. A look at Figures 4.3 and 4.4, shows that the influent COD of the experimental unit had a small increase or decrease in COD values with respect to that of the Celco unit. There were a couple of exceptions to the above statement; the probable reasons are discussed below:

On day 7, a new batch of feed was used for the influent feed. The influent COD of the feed to the Celco unit was 3174 mg/L whereas that of the experimental unit was 2243 mg/L on day 7. The reason for this big difference in values between the Celco unit's influent COD and that of the experimental unit was probably due to one of the following reasons : There was a measurement error when the samples for the Celco unit was pipetted, or the feed for the

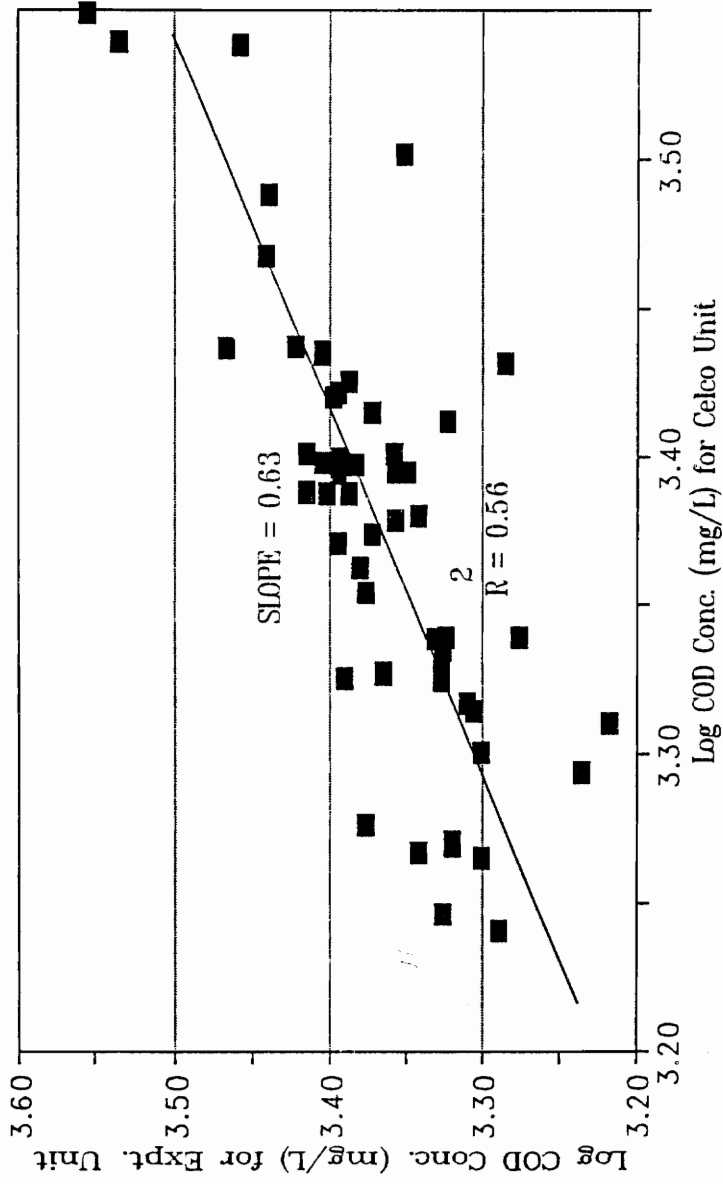
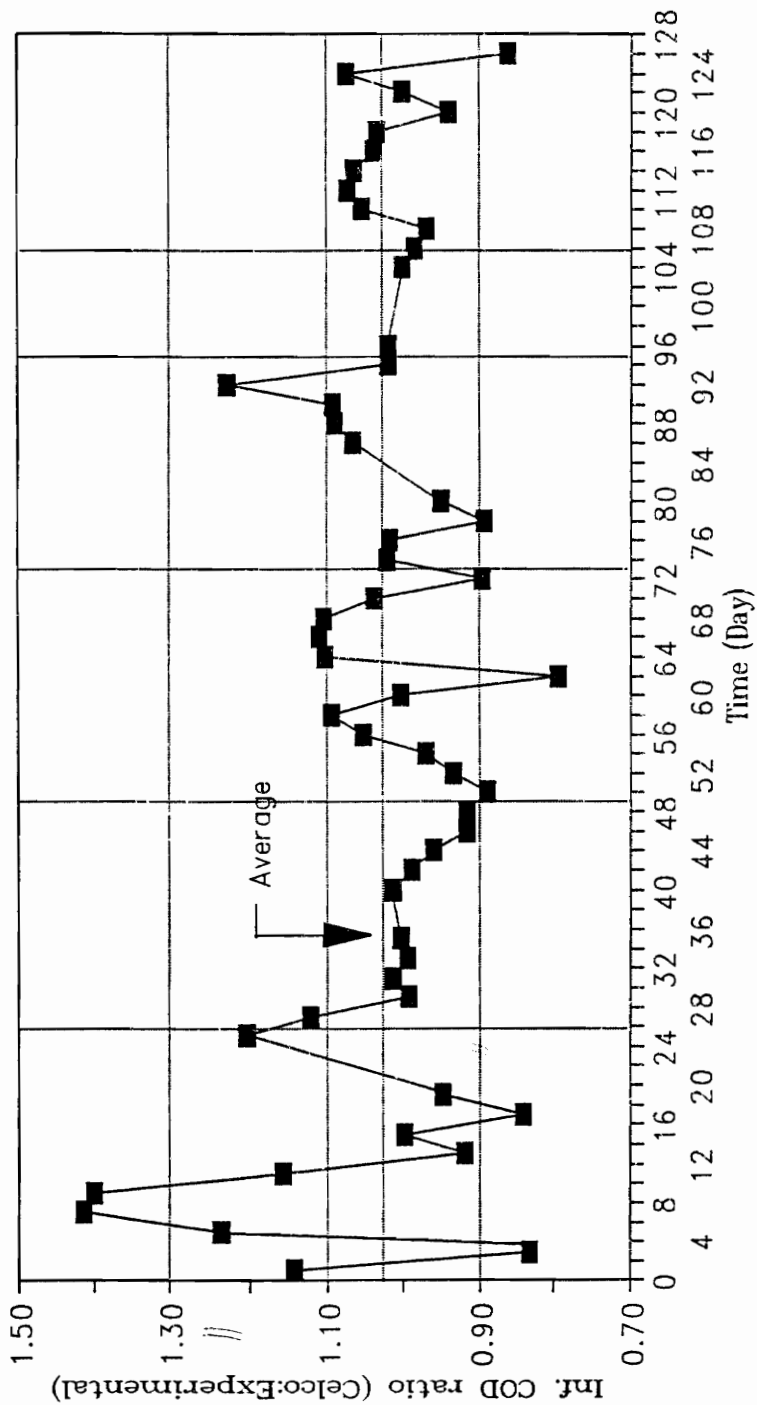


Figure 4.3 Comparison of Influent COD for the Celco and Experimental Units



Cu [1 mg/L] : Day 26	Cu [1 mg/L] : Day 95
Cu [2 mg/L] : Day 49	Ni [2 mg/L] : Day 106
Cu [1 mg/L] & Ni [1 mg/L] : Day 73	

Figure 4.4 Variation of Influent COD Ratio (Celco:Experimental)

experimental unit must have been mistakenly prepared from the old batch. On day 25, again there was a difference in influent COD values between that of the Celco and experimental units. The influent COD of the Celco unit was 3456 mg/L while that of the experimental unit was 2872 mg/L. The reason for this difference was probably due to a measurement error in the influent COD value of the Celco unit, because on day 27, the influent COD of the Celco unit was 3078 mg/L which was closer to that of the experimental unit.

For the remaining part of the research, the ratio of the influent COD for the Celco to that of the experimental unit was between 0.9 and 1.1 with an average value of 1.03 (Figure 4.4). *This implied that lime did not play an important role in the removal of COD.*

#### 4.2.3 SUSPENDED SOLIDS VARIATION

Pretreatment of the influent feed for metals removal had the side effect of suspended solids removal, as indicated by Figure 4.5. The influent suspended solids concentration for the experimental unit was lower than that of the Celco unit. This showed that the coagulation - flocculation process led to a removal of a portion of the suspended

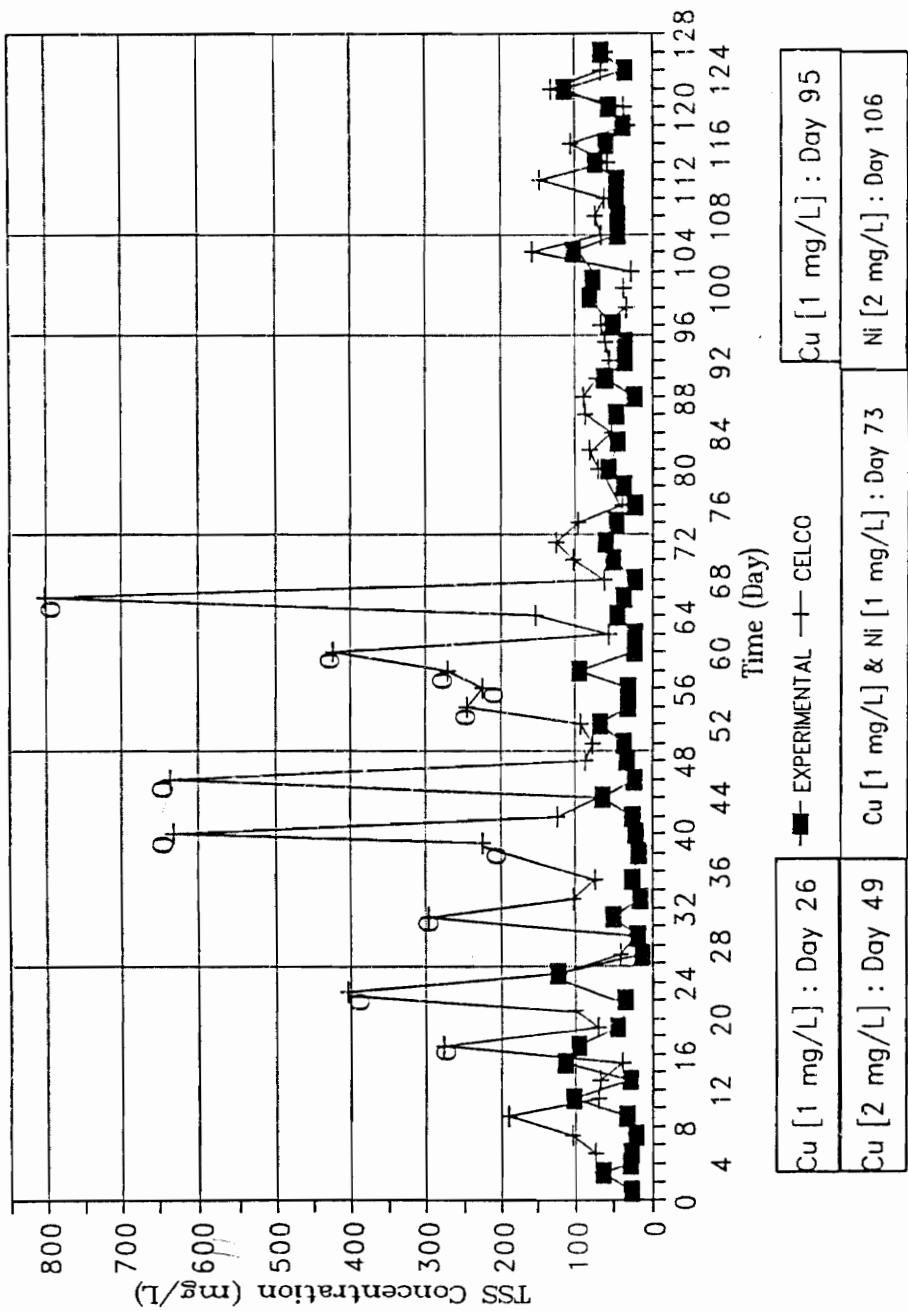


Figure 4.5 Comparison of Influent Suspended Solids for the Celco and Experimental Units

(o = Settlement of solids occurred in carboy)



solids in the influent. The influent suspended solids for the first half of the research were a little higher than those during the second half of the research. This was due to some solids settling in the carboy. During the latter half of the research, higher SS were not observed because the influent feed for the Celco unit was changed more frequently i.e. at the rate of a carboy every 2 days. The probable reason for reduction in influent SS was as follows:

Consider a carboy having 16 Liters of influent feed. If the carboy was changed once in four days, it means that 4 Liters was used each day (HRT = 2 days and reactor volume = 8 Liters), or a total of 16 Liters.

After the introduction of the new feed (day 1), let the SS be denoted by "A" mg in the influent volume of 16 Liters, on day 2 the SS be denoted by "B" mg in the influent volume of 12 Liters, on day 3 the SS be denoted by "C" mg in the influent volume of 8 Liters, and on day 4 the SS be denoted by "D" mg in the influent volume of 4 Liters. Ideally the following equation should be valid:

$$A/16 = B/12 = C/8 = D/4$$

But the above equation did not apply during the research. This was because of the following reasons:

Before taking the sample for SS, the carboy was shaken to ensure a uniform mix of the SS. But during the remaining part of the day when the influent feed was being treated by the activated sludge system, the SS settled in the carboy. On day 2, the carboy was again shaken well to ensure the uniform mix of SS. But this time the concentration of SS was higher than on day 1. This was because while the SS remained almost the same as on day 1, the concentration of the SS increased because of the lesser volume of feed in the carboy on day 2 (Conc. = Quantity/Volume). Similarly the decreased volume on days 3 and 4 caused an increase in concentrations on days 3 and 4 respectively. So the equation obtained was:

$$A/16 < B/12 < C/8 < D/4$$

Now if the carboy was changed once in two days then the concentrations would be A/16 and B/12 in which case the high SS concentration of C/8 and D/4 were not observed. Hence the reduction of SS values when the carboy was changed once in two days. However, all of the values imply that the actual SS concentration fed to the unit were less than those measured.

#### 4.2.4 pH VARIATION

The influent pH for the Celco unit averaged about 4.5. The pH of the experimental unit was maintained at a predetermined value. The influent pH for the Celco and experimental units are compared in Figure 4.6. After the coagulation -flocculation process, the pH of the influent feed for the experimental unit was around 10. This pH was reduced to 6.0 before feeding until day 38. But after day 38, the pH was further reduced to 4.5 to be more similar to the Celco unit and to be sure that precipitation of metals did not take place in the carboy. Hence the influent pH of the experimental unit was more controlled than that of the Celco unit.

#### 4.3 METAL ANALYSIS ELEMENTS

As discussed in the "Materials and Methods" section, the concentration of metal added to the influent feed was measured as "Total metals"; hence in this section the values of the concentration of metals for the influent and effluent will be in terms of "Total Cu" or "Total Ni", as the case may be.

The following terms are defined as follows :

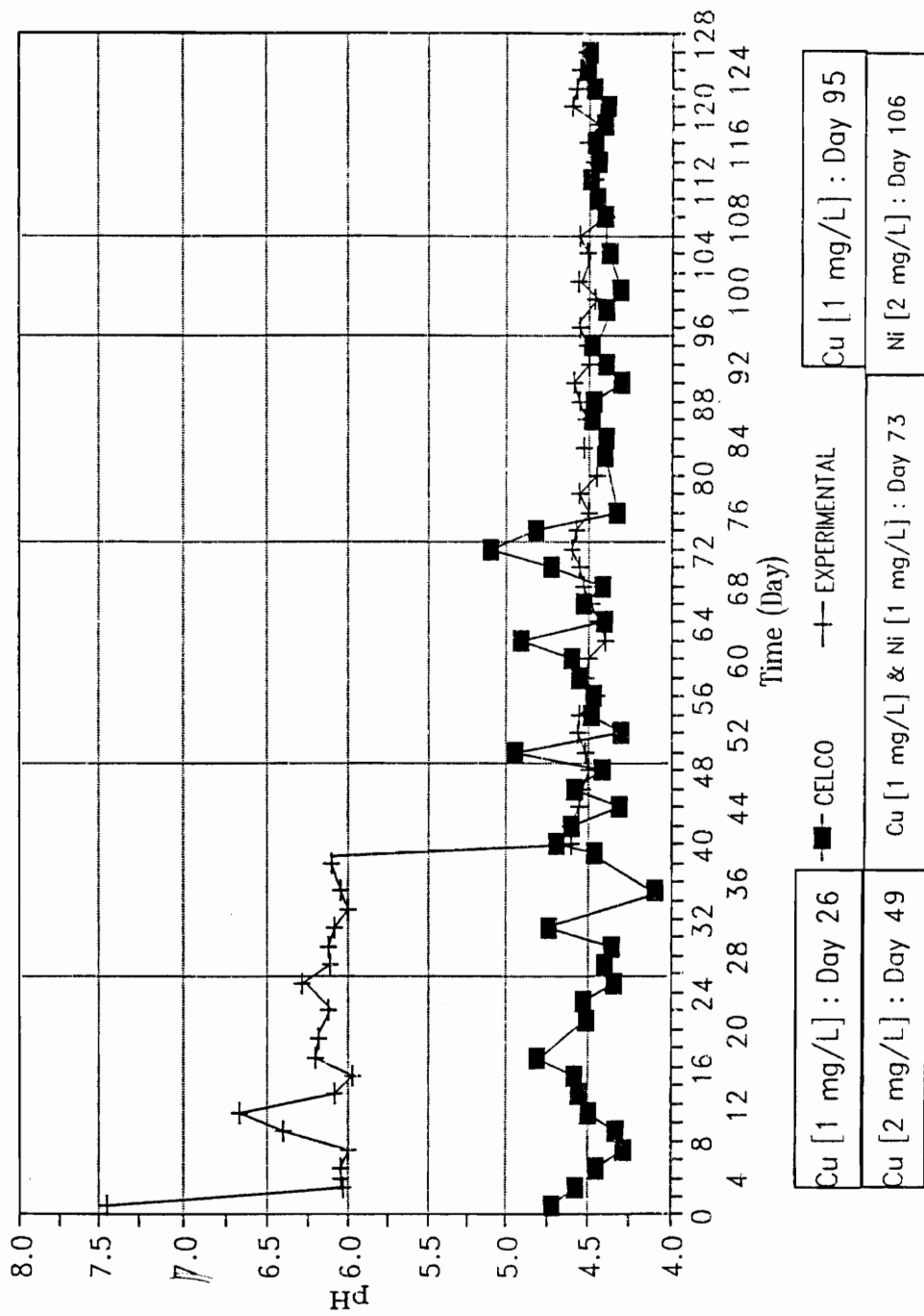


Figure 4.6 Variation of Influent pH for the Celco and Experimental Units

Metal loading rate (mg/Day) = [Flow (L/day) x Conc. (mg/L)]

The above definition of metal loading rate was adopted from the paper entitled, "Metal Loadings and Removal at a Municipal Activated Sludge Plant" by Neilson and Hruday<sup>49</sup>. The word metal in the above definition may be substituted by the word copper or nickel or Total Metal (Cu + Ni) as the case may be. The units of metal loading rate are mg/day. Total Metal Loading Rate is abbreviated as TMLR.

Specific Metal Loading Rate is defined as follows :

Specific Metal Loading Rate (1/day) = Metal Loading Rate/MLVSS

The word metal in the above definition may be substituted by the word copper or nickel or Total Metal (Cu + Ni) as the case may be. The units of Specific metal loading rate is 1/day. Specific Total Metal Loading Rate is abbreviated as STMLR.

The metal accumulated in the MLVSS is denoted by the term Specific Uptake of Metal which is defined as follows:  
Specific Uptake of Metal (SUM) = [Total Metal in the mixed liquor - Dissolved metal in the mixed liquor] (mg/L)/MLVSS (mg/L). Specific uptake of metal is unitless. Specific Uptake of Metal is abbreviated as SUM.

% increases in Total or Soluble metal in the mixed liquor are defined as :

$$\% \text{ Increase in Total metal/day} = [(Y - Z)/Z] \times 100$$

where Y = Total Metal in Mixed Liquor on Day (X+1)

Z = Total Metal in Mixed Liquor on day (X)

and X varies from 1 to 125.

The term Total metal may be substituted by soluble metal in the above case.

The term "average value" when used in this chapter means the average of the values of the parameters like effluent COD, SS etc. for at least a week or more during the end of the particular phase. In this section the variation in soluble and total copper and nickel concentrations in the mixed liquor are discussed. The experimental data of total and soluble copper and nickel are included in the appendix. In Chapter 5, the analysis elements, i.e., Specific Uptake of Metal (SUM), Total Metal Loading Rate (TMLR), and Specific Total Metal Loading Rate (STMLR), are discussed along with the other parameters, i.e., effluent COD, effluent SS, OUR and settling properties. Table 4.1 shows the metal loading rates that were applied to the experimental unit. The values indicated are the average values during a particular phase.

Table 4.1: Experimental Unit Metal Loading by Phase

Phase No.	Copper Loading (mg/day)	Nickel Loading (mg/day)	Total (Cu+Ni) Loading (mg/day)
1	0.12	0.92	1.04
2	4.3	1.2	5.5
3	8.5	0.85	9.35
4	4.4	5.4	9.8
5	4.2	0.8	5
6	0.19	8.9	9.09

#### 4.4 PERFORMANCE OF THE CELCO UNIT

##### 4.4.1 COD REMOVAL

The influent COD of the Celco unit varied from 1800 mg/L to 3500 mg/L during the course of the research. The effluent COD varied from 40 mg/L to 200 mg/L. During the first half of the research the effluent COD averaged about 110 mg/L, while in the second half of the research the effluent COD averaged about 60 mg/L. The probable reason for the higher effluent COD in the first half of the research was that the influent COD was greater than 3000 mg/L during three periods (Figure 4.7). The higher influent COD values resulted in higher effluent COD values but the COD removal efficiency was high throughout the research. The average COD removal efficiency was 95% during the first half of the research and 97% for the latter part of the research.

##### 4.4.2 pH VARIATION

The mixed liquor pH of the Celco unit varied from 7.9 to 8.5. There was no particular trend in the variation of the mixed liquor pH. During phases 1,2,5, and 6, the mixed liquor pH was between 8.0 and 8.3; during phase 3 and 4, the mixed liquor pH was between 8.3 and 8.5 (Figure 4.8). The



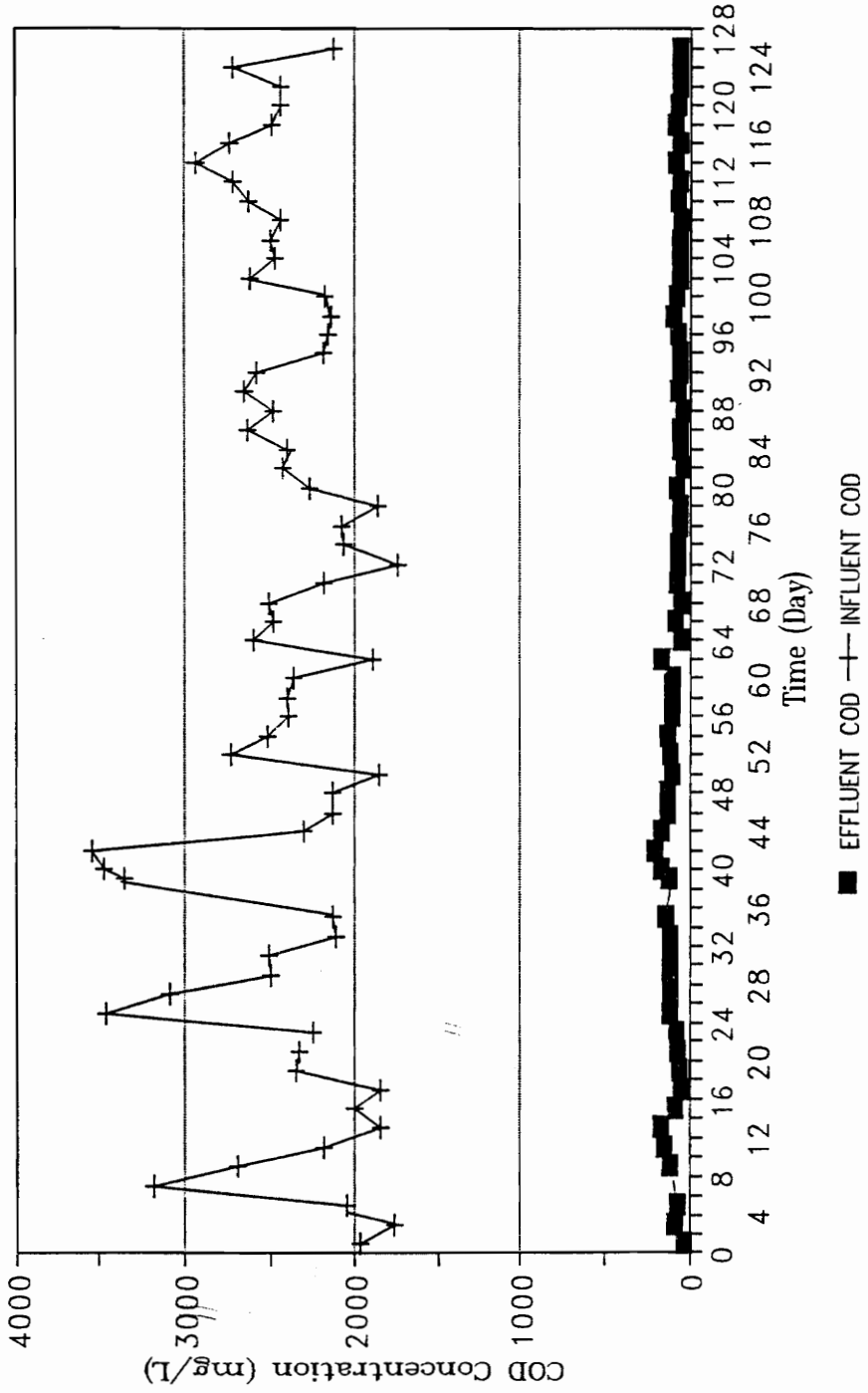


Figure 4.7 COD Removal by the Celco Unit

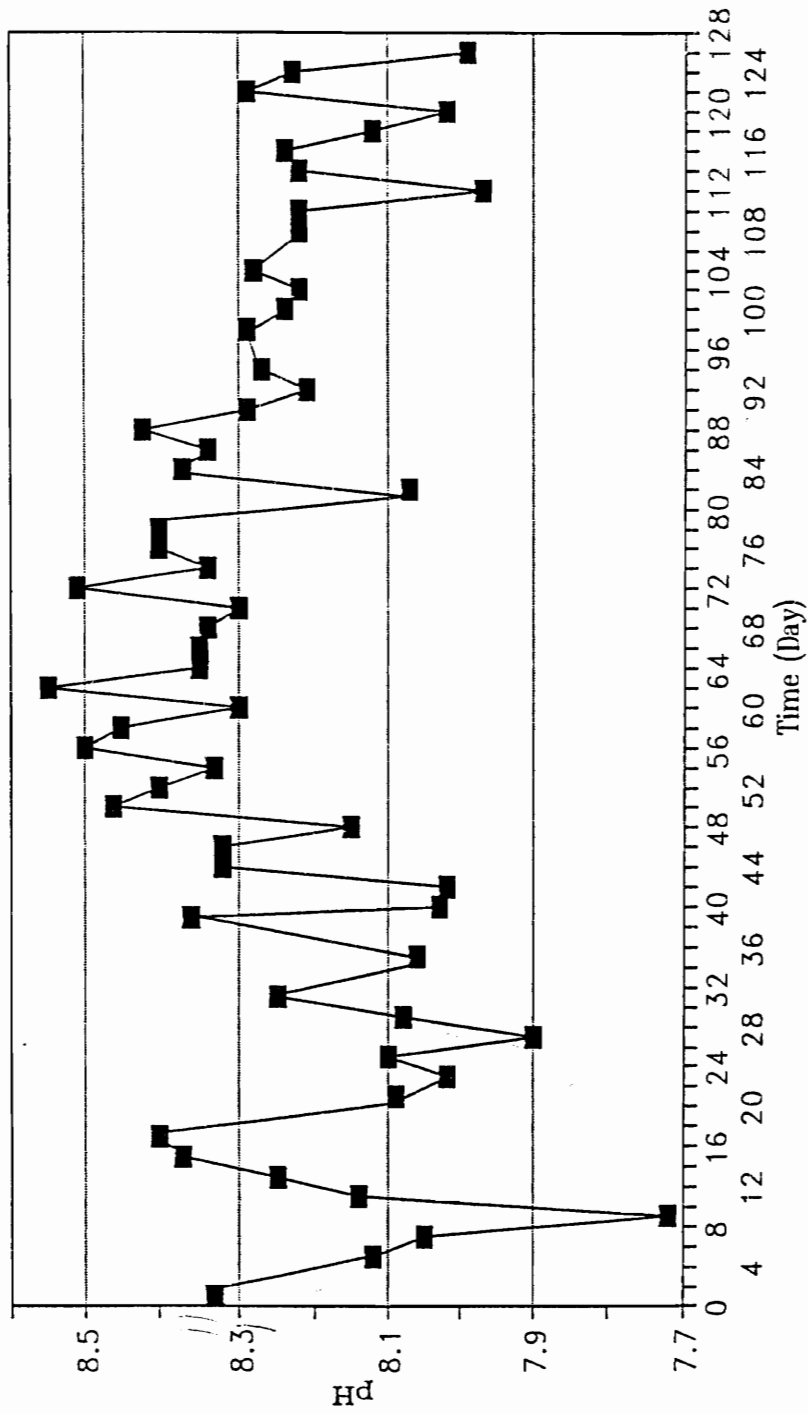


Figure 4.8 Variation in Mixed Liquor pH for the Celco Unit

reason for this variation was not clear. The effluent pH did not show any significant variations (Figure 4.9).

#### 4.4.3 MLVSS/MLSS and F:M VARIATION

The MLVSS/MLSS varied between 0.7 and 0.9 with an average value of 0.81 and standard deviation of 0.04. No significant trends were observed for the Celco unit. The variation in MLSS and MLVSS is shown in Figure 4.10. The food : microorganism (F:M) ratio varied from 0.30 to 0.65 with an average value of 0.41 and standard deviation of 0.07. During the first half of the research, the F:M ratio varied by 0.1 units above and below the F:M ratio of 0.5. The peaks seen in Figure 4.11 were due to high influent COD peaks that occurred during those periods. The F:M was generally stable for the second half of the research.

#### 4.4.4 EFFLUENT SUSPENDED SOLIDS VARIATION

For the first 40 days of the research, the effluent solids were high. It was thought that potassium might be the limiting nutrient and hence changes in potassium dosing were made. Potassium concentration in the influent feed was increased to 25 mg/L from day 34. After a week the performance of the Celco unit in terms of SS removal

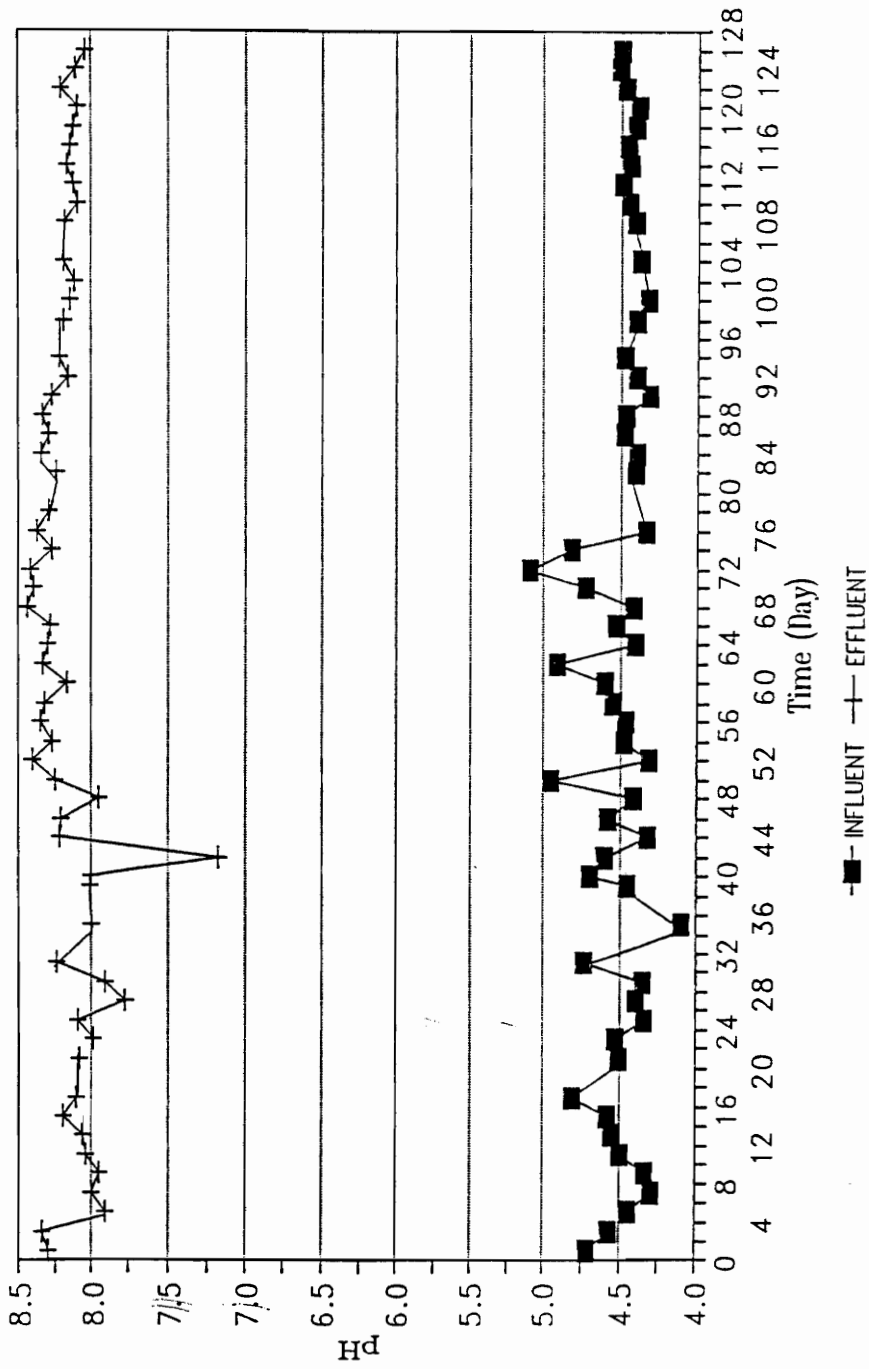


Figure 4.9 Variation of Influent and Effluent pH for the Celco Unit

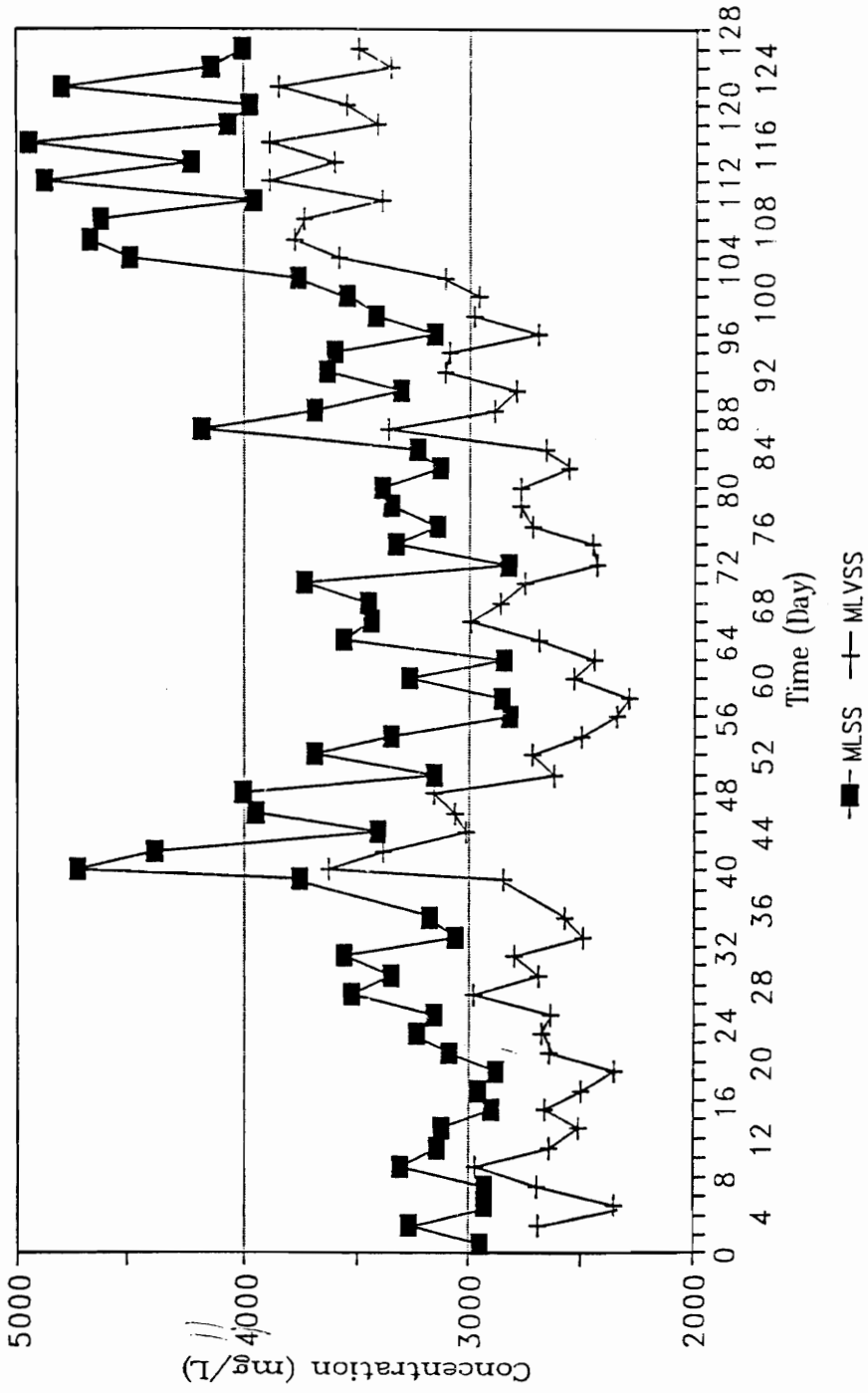


Figure 4.10 Variation in MLSS and MLVSS for the Celco Unit

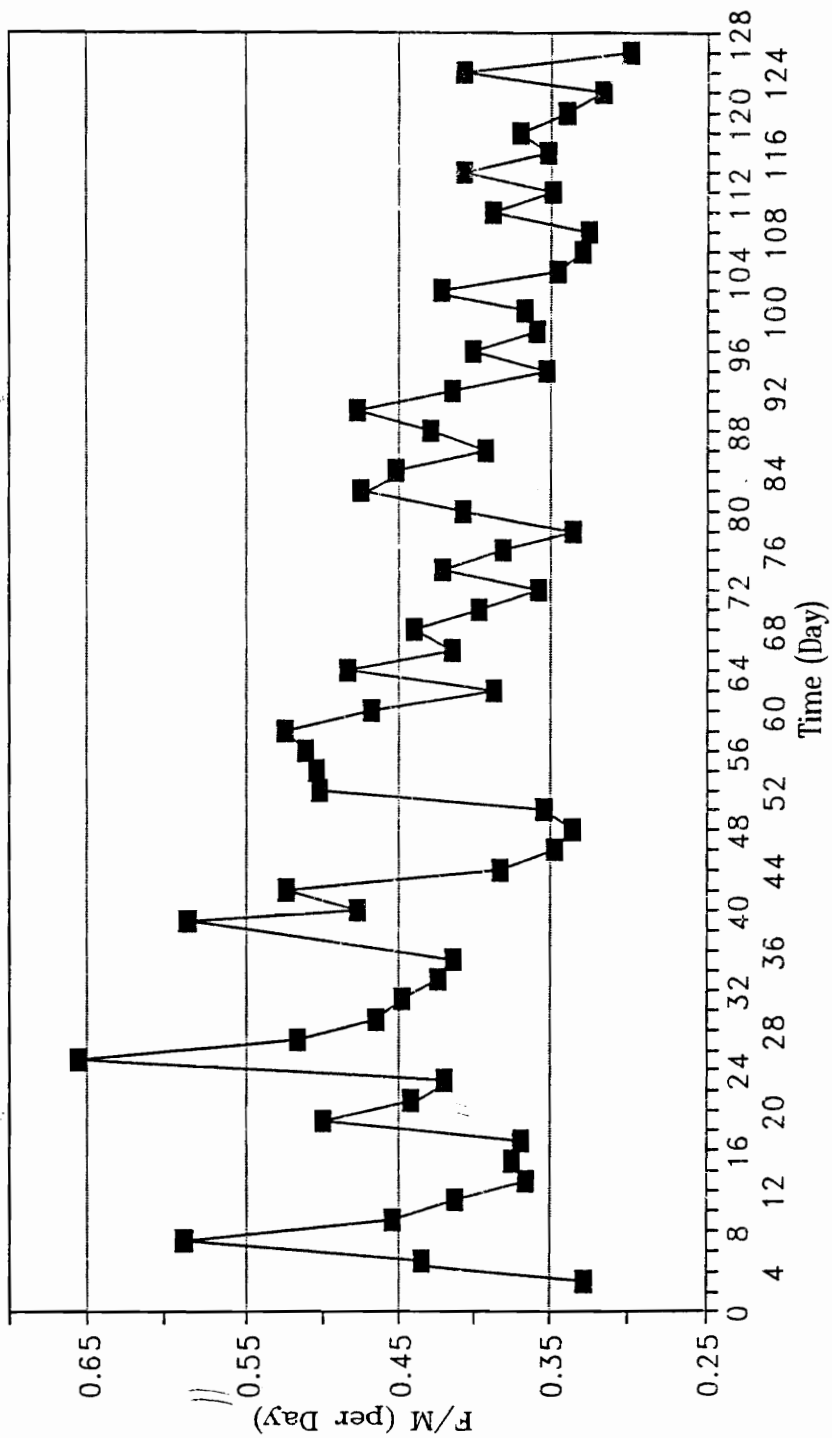


Figure 4.11 Variation in Food : Microorganism ratio for the Celco Unit

increased significantly, with the effluent SS values falling below 50 mg/L (Figure 4.12). The effluent SS deteriorated during the days 58 to 62. After day 62, the effluent SS showed three increases on days 78, 100 and 116. The reason for the increase in effluent SS was not clear, but generally the system improved and the effluent SS was below 50 mg/L from day 64.

#### 4.4.5 OUR and SOUR VARIATION

The variation in OUR with time is shown in Figure 4.13. As can be seen from Figure 4.13, the OUR was above 550 mg/L/day after day 110. This was probably due to higher MLVSS during this time period. To get a correlation between the OUR and MLVSS, the SOUR is plotted in Figure 4.14. As can be observed from Figure 4.14, the SOUR varied from 0.15 per day to 0.25 per day.

#### 4.4.6 SVI and ZSV VARIATION

The SVI and ZSV are plotted in Figures 4.15 and 4.16 respectively. The SVI for the Celco unit was generally high throughout the course of the research. The exact reason for the high values of the SVI could not be determined. Microscopic examination of the mixed liquor did not indicate

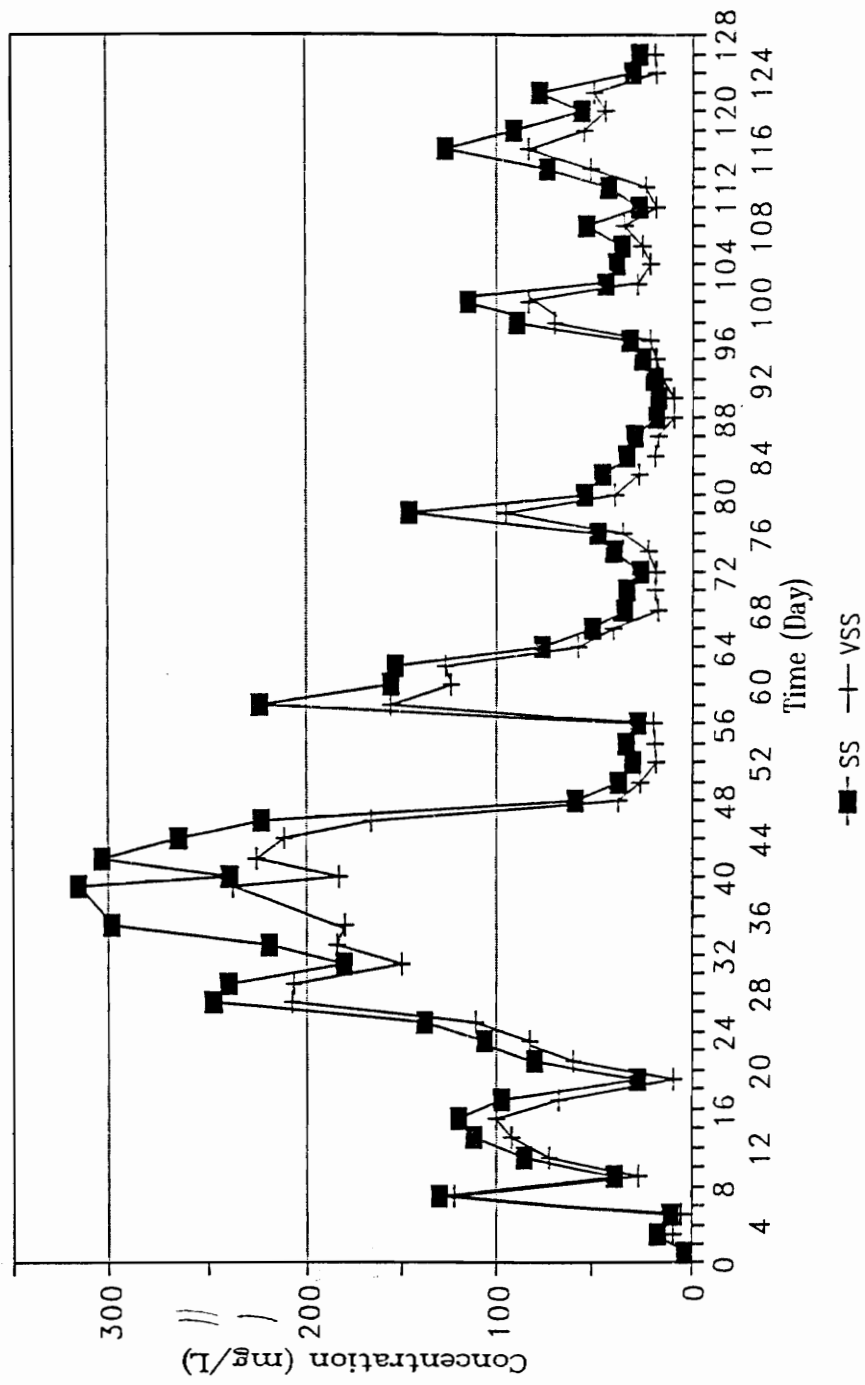


Figure 4.12 Variation of Effluent Suspended Solids and Volatile Suspended Solids for the Celco Unit



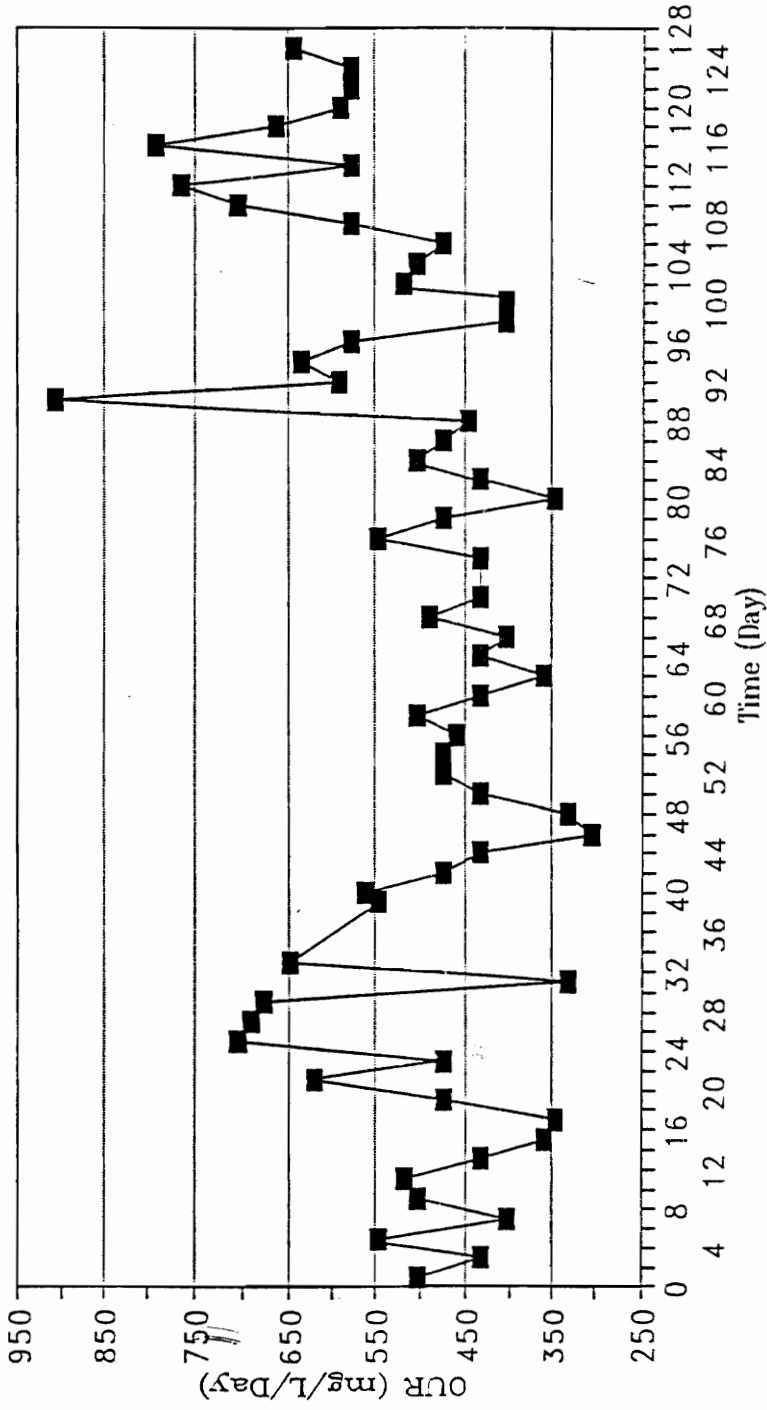


Figure 4.13 Variation in Oxygen Uptake Rate for the Celco Unit

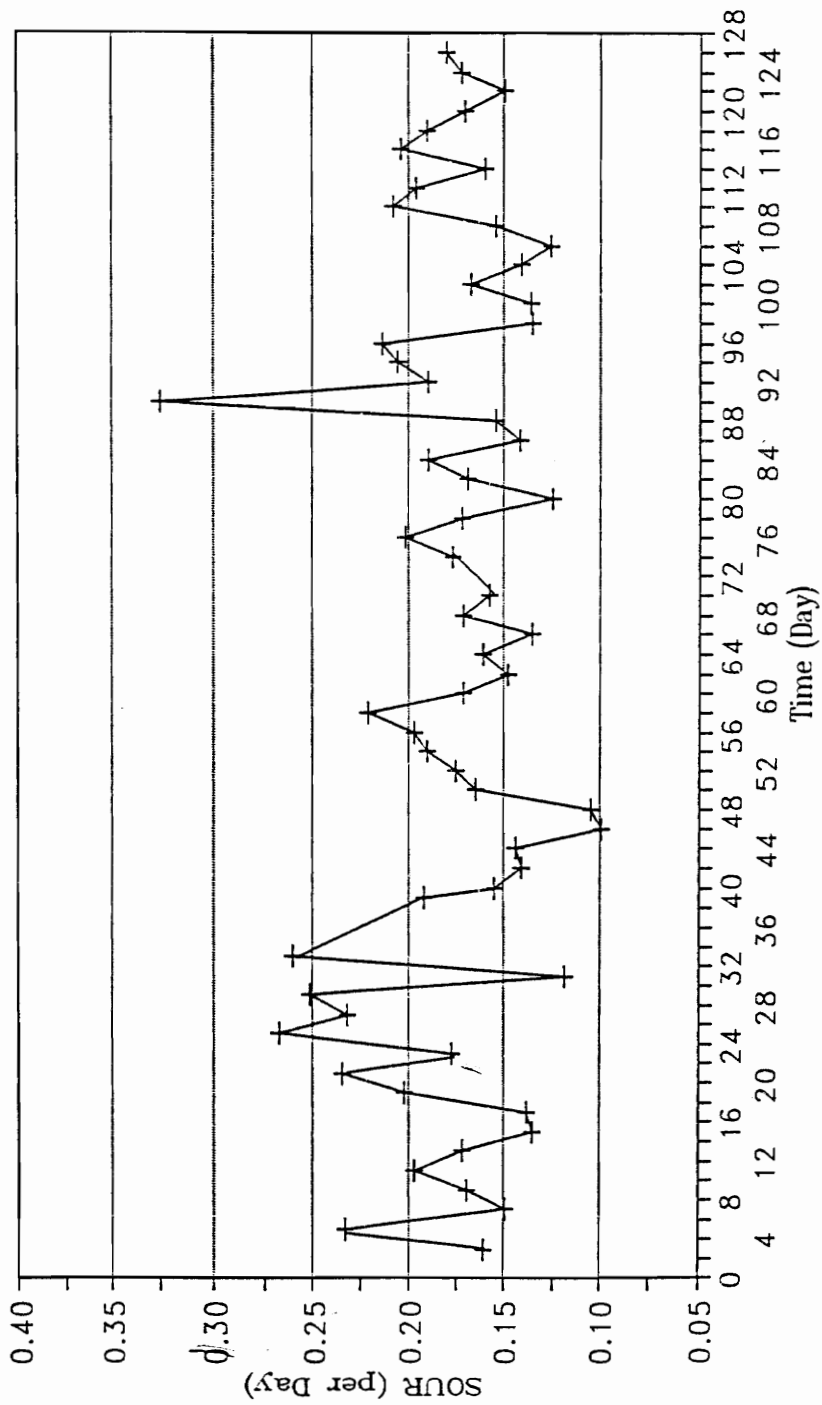


Figure 4.14 Variation in Specific Oxygen Uptake Rate for the Celco Unit

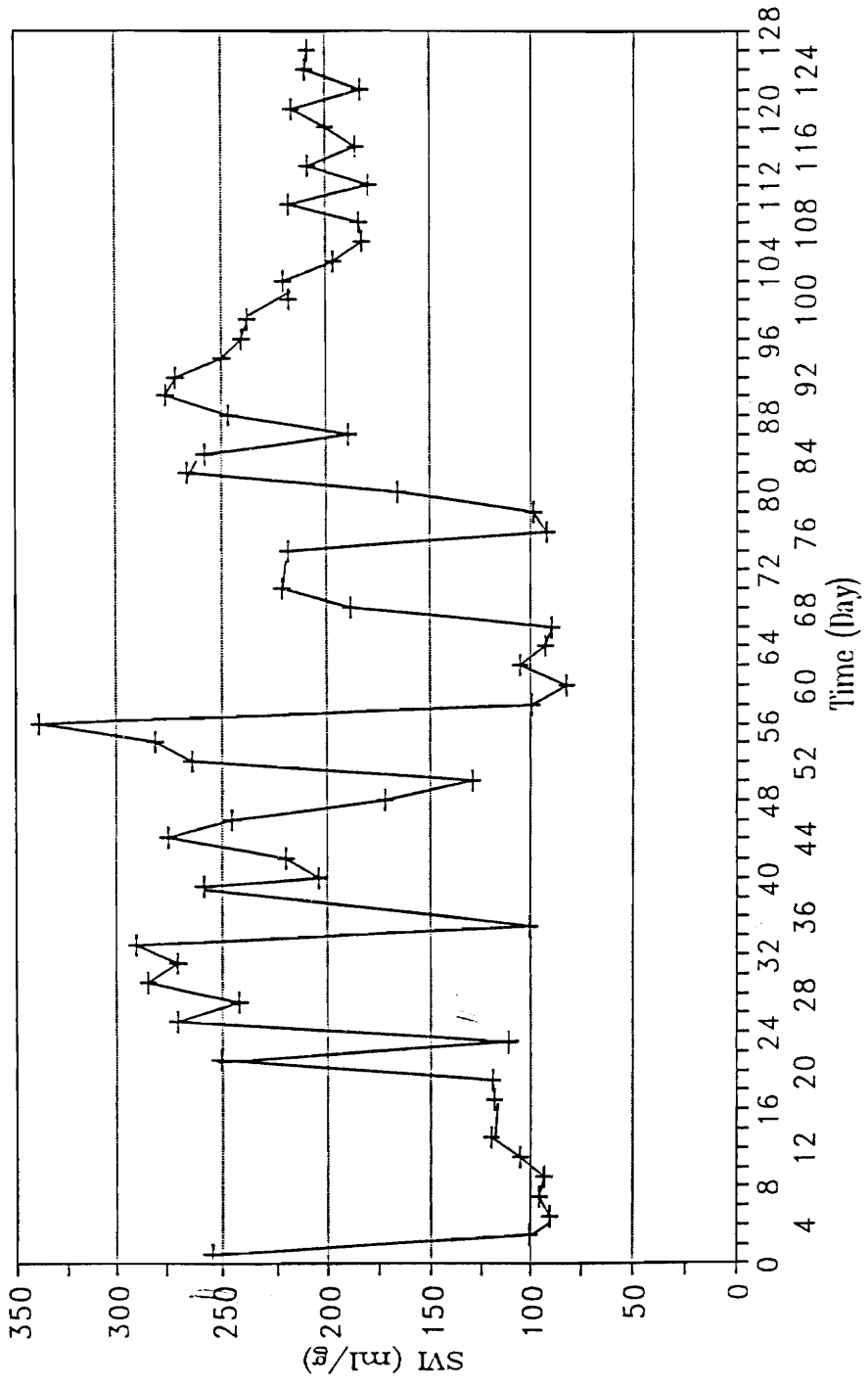


Figure 4.15 Variation of Sludge Volume Index for the Celco Unit

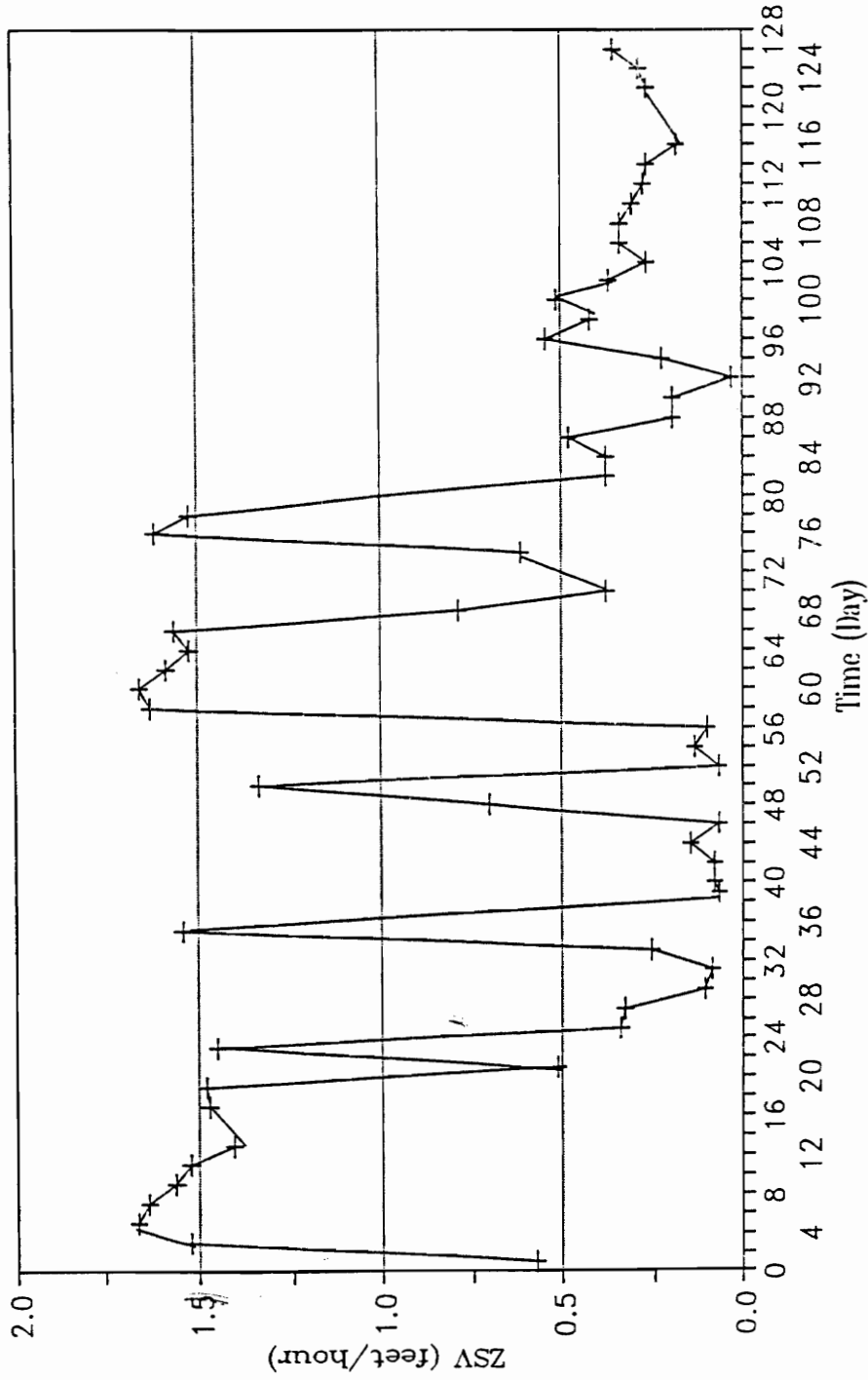


Figure 4.16 Variation of Zone Settling Velocity  
for the Celco Unit

the presence of substantial filamentous organisms. The addition of metals, as shown for the experimental unit, reduced the SVI values.

The low ZSV values, however, left a clear supernatant after the activated sludge had settled in the graduated cylinder. It was interesting to note that the SVI values for the Celco unit was never less than 75 ml/g whereas that of the experimental unit was for the most part of the research less than 75 ml/g (See Figure 4.26).

#### 4.4.7 ACCUMULATION OF METALS IN THE MIXED LIQUOR

The Celco unit was not pretreated with lime, i.e., no change in the concentration of metals to the influent feed took place. Hence, the variation in copper and nickel concentrations were as measured in the influent feed. The copper in the influent feed reached a low value of about 0.25 mg/L during three time periods in the course of the research. During these three periods, the copper in the effluent also reached its lowest values. This indicated that the copper in the effluent depended on the concentration of copper in the influent feed. The variation of the copper in the mixed liquor also depended on the variation of copper in the influent feed. For example, the

copper in the influent feed increased from 0.25 mg/L to 0.5 mg/L from day 80 to day 90. During this time period, the copper in both the mixed liquor and the effluent showed increases, as can be seen from Figures 4.17 and 4.18. The accumulation of copper in the mixed liquor varied from 0.7 mg/L to 1.1 mg/L. The nickel concentration in the influent varied from 0.39 mg/L (day 25) to 0.78 mg/L (day 33). During this time period the nickel in the effluent and the mixed liquor also showed increases as can be seen from Figures 4.19 and 4.20. The accumulation of nickel in the mixed liquor varied from 1.2 mg/L to 2.2 mg/L. This indicated that the accumulation of metals in the mixed liquor was a function of the metal loading rate. The validity of the above statement was brought out more explicitly in the case of the experimental unit.

#### **4.5 PERFORMANCE OF THE EXPERIMENTAL UNIT**

##### **4.5.2 EFFECT OF METALS ON COD REMOVAL**

The influent and effluent COD concentrations for the experimental unit are shown in Figure 4.21. A look at Figure 4.21 indicates that there were no significant changes in effluent COD removal due to the addition of the metals. It appears that when the first dose of copper was introduced

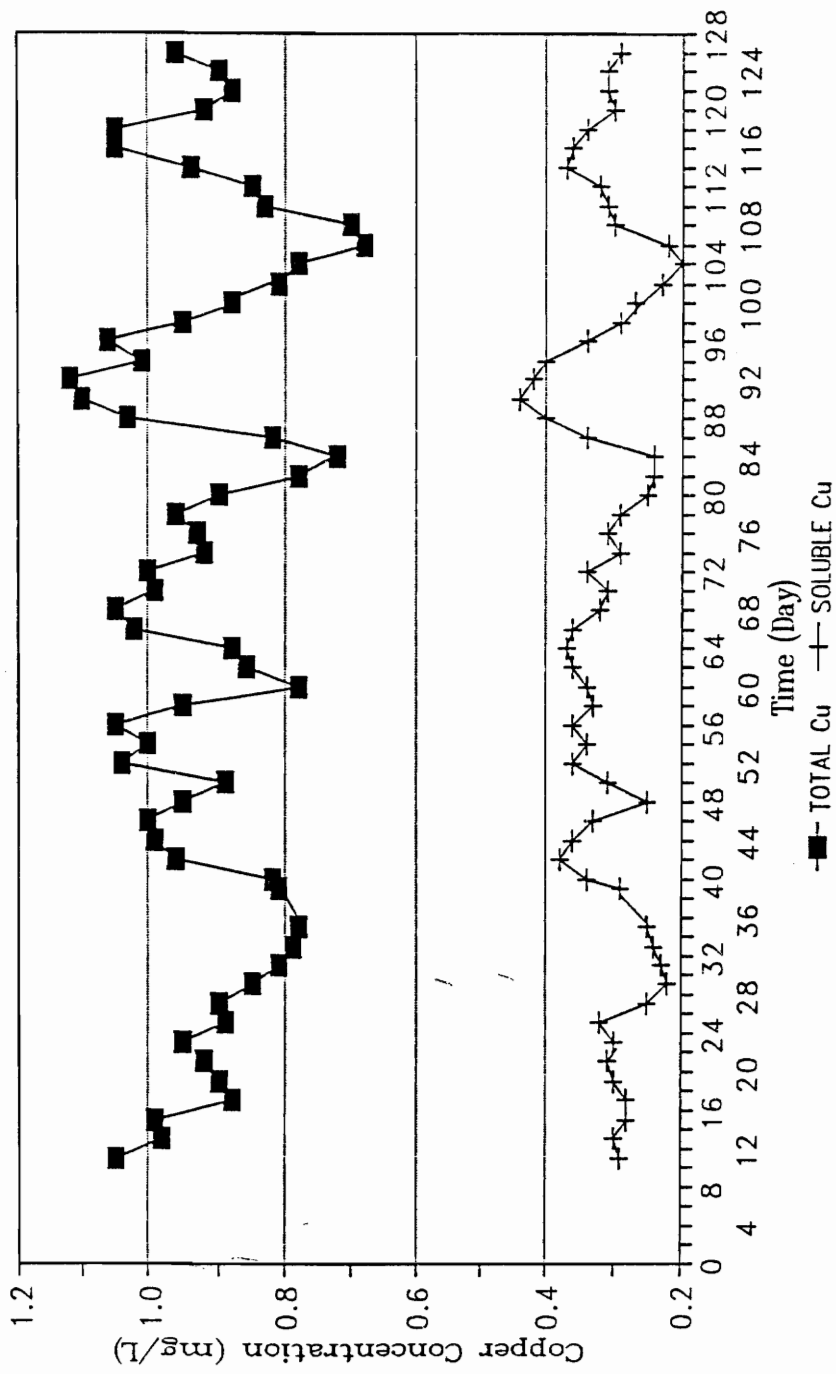


Figure 4.17 Variation of Total and Soluble Copper in Mixed Liquor for the Celco Unit

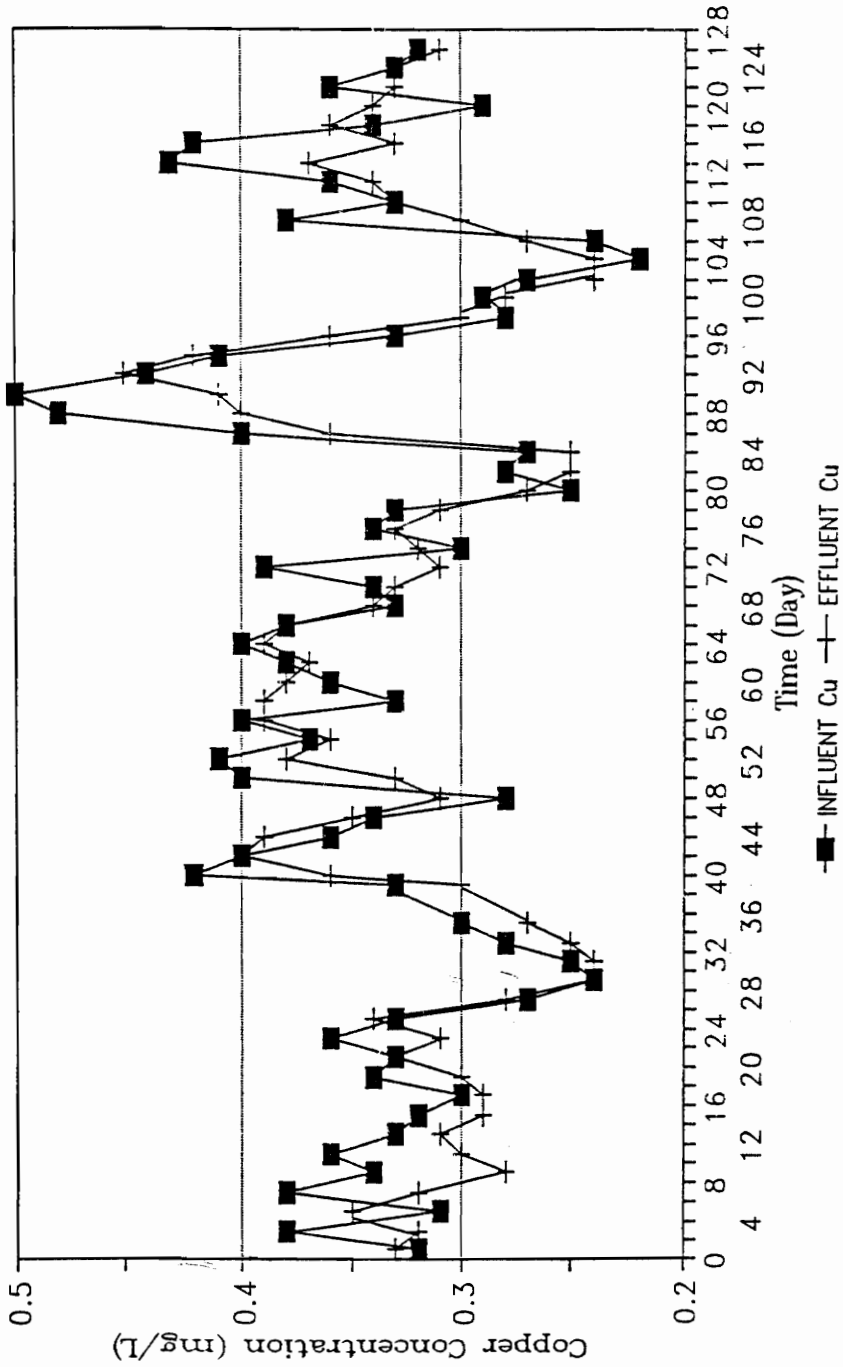


Figure 4.18 Variation of Total Influent and Effluent Copper in the Celco Unit



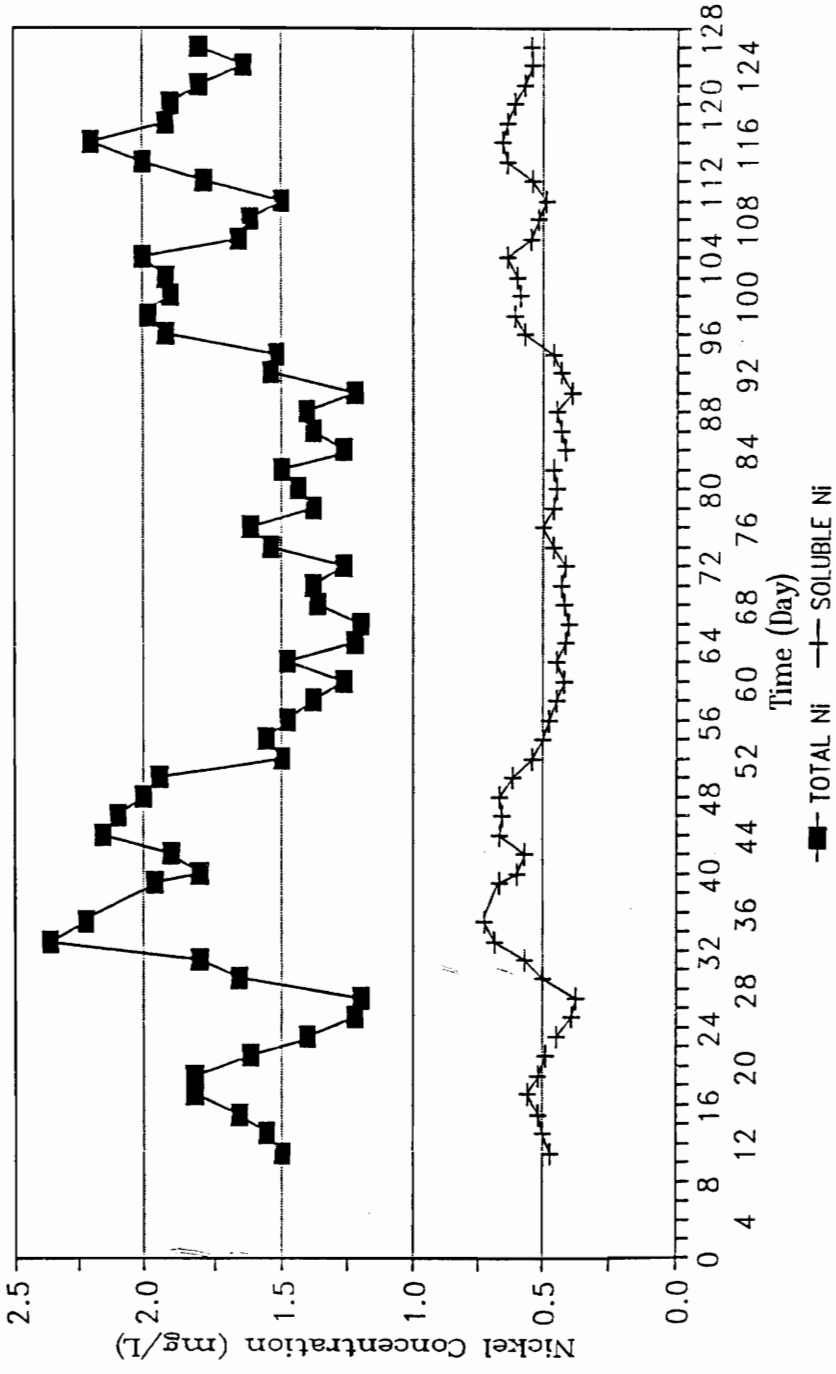


Figure 4.19 Variation of Total and Soluble Nickel in the Mixed Liquor of the Celco Unit

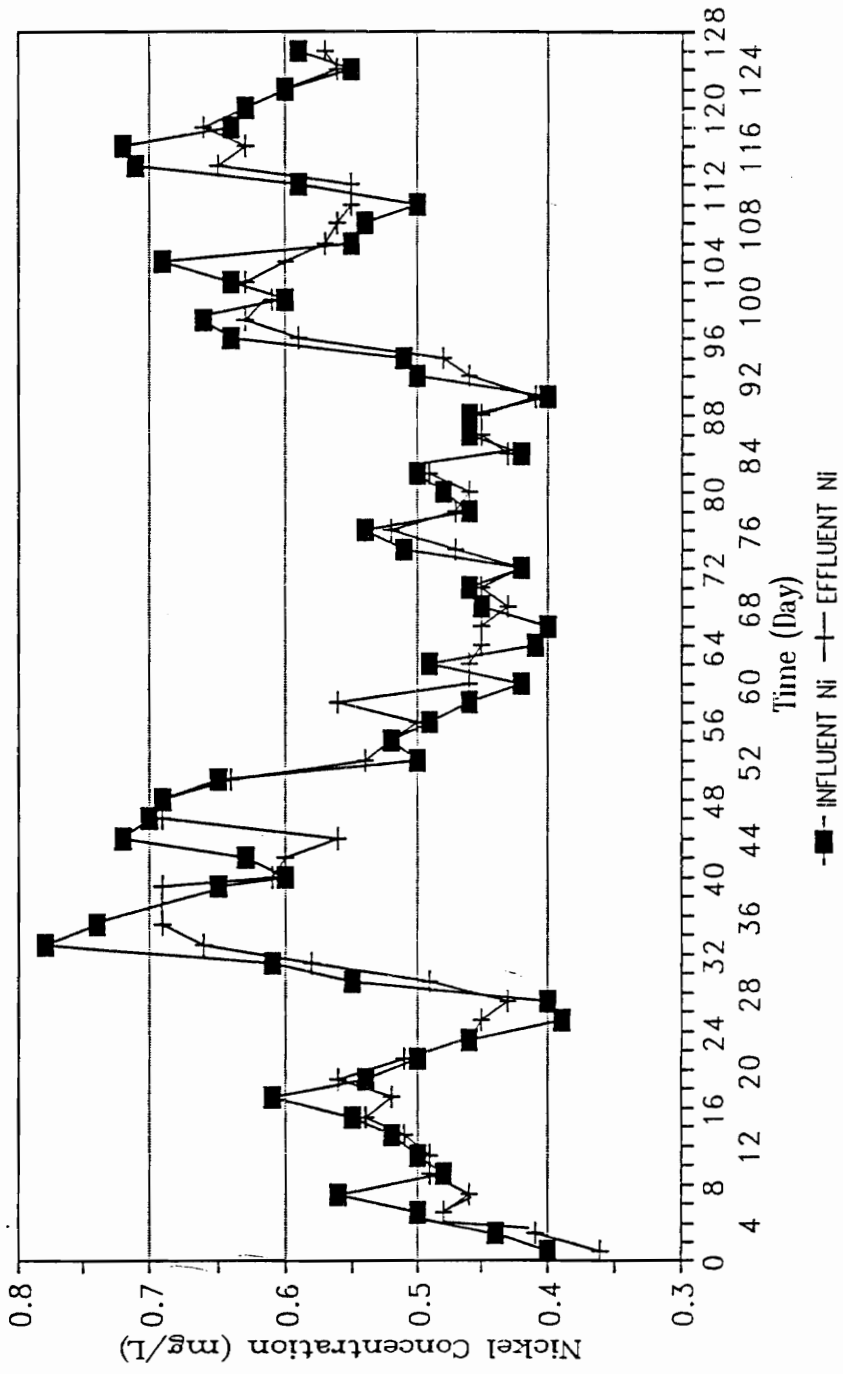


Figure 4.20 Variation of Total influent and effluent Nickel for the Celco Unit

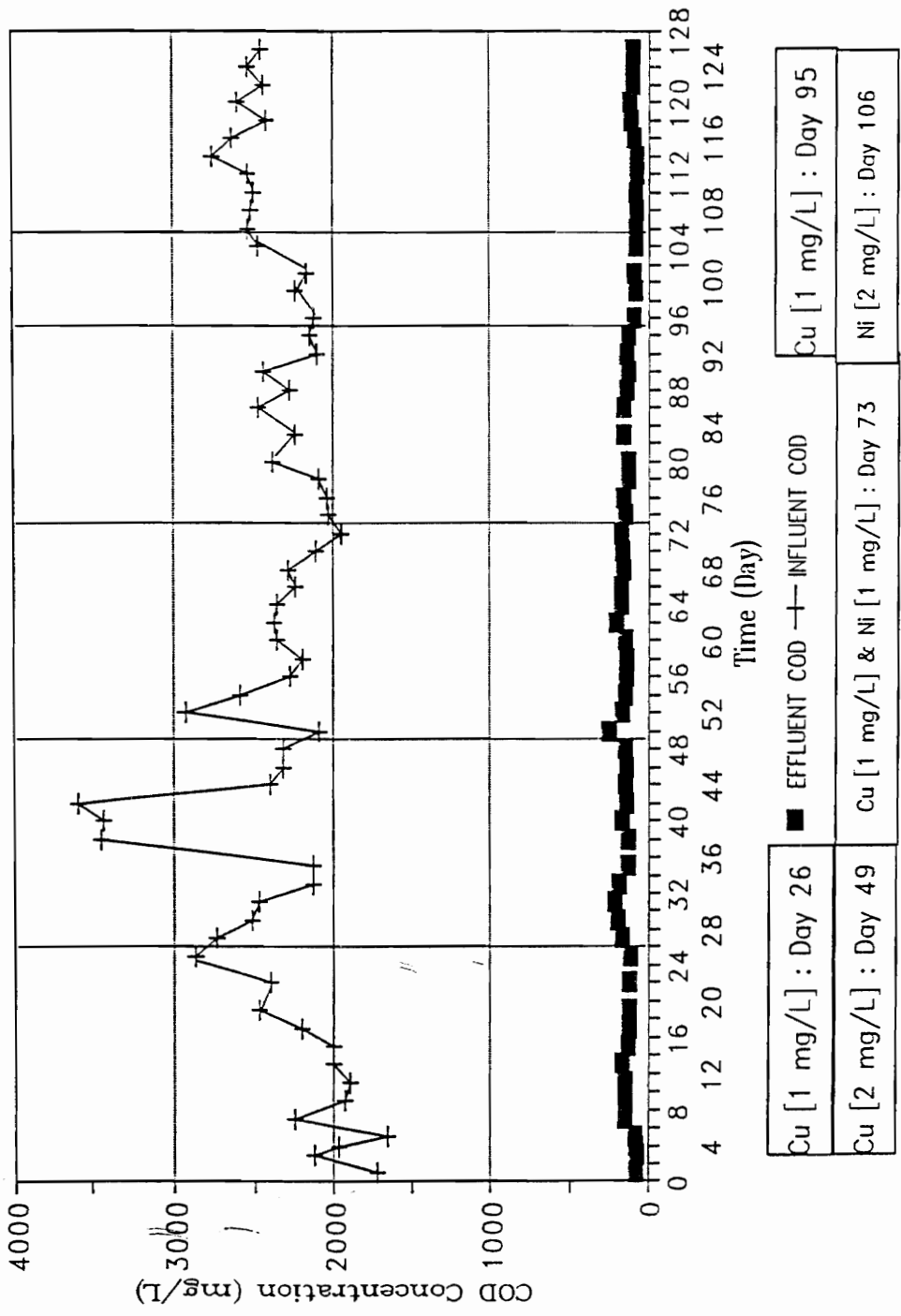


Figure 4.21 COD Removal by the Experimental unit

to the system (phase 2) there was an increase in effluent COD (Figure 4.22). This increase in effluent COD cannot however be attributed to copper addition alone. This was because at this time there was an increase in influent COD by 400 mg/L above the average value. The immediate increase in effluent COD after the introduction of 2 mg/L of copper on day 49 was probably caused by copper. When nickel was introduced in the system from day 73, there were no significant changes in effluent COD. No major changes were observed during other phases.

#### 4.5.3 EFFECT OF METALS ON OUR and SOUR

Before discussing the effects of metals on oxygen utilization, it can be noted here that the loading of metals to the system affected the biomass concentration, which in turn determined the OUR. Hence the discussion of SOUR is important.

The OUR varied from 350 mg/L/day to 850 mg/L/day during the entire course of the research (Figure 4.23). Copper loading of 4.20 mg/day was applied from day 26. The OUR dropped from 700 mg/L/day to 300 mg/L/day. It was difficult to conclude that this drop in OUR was due to copper alone since there were similar variations during the course of the

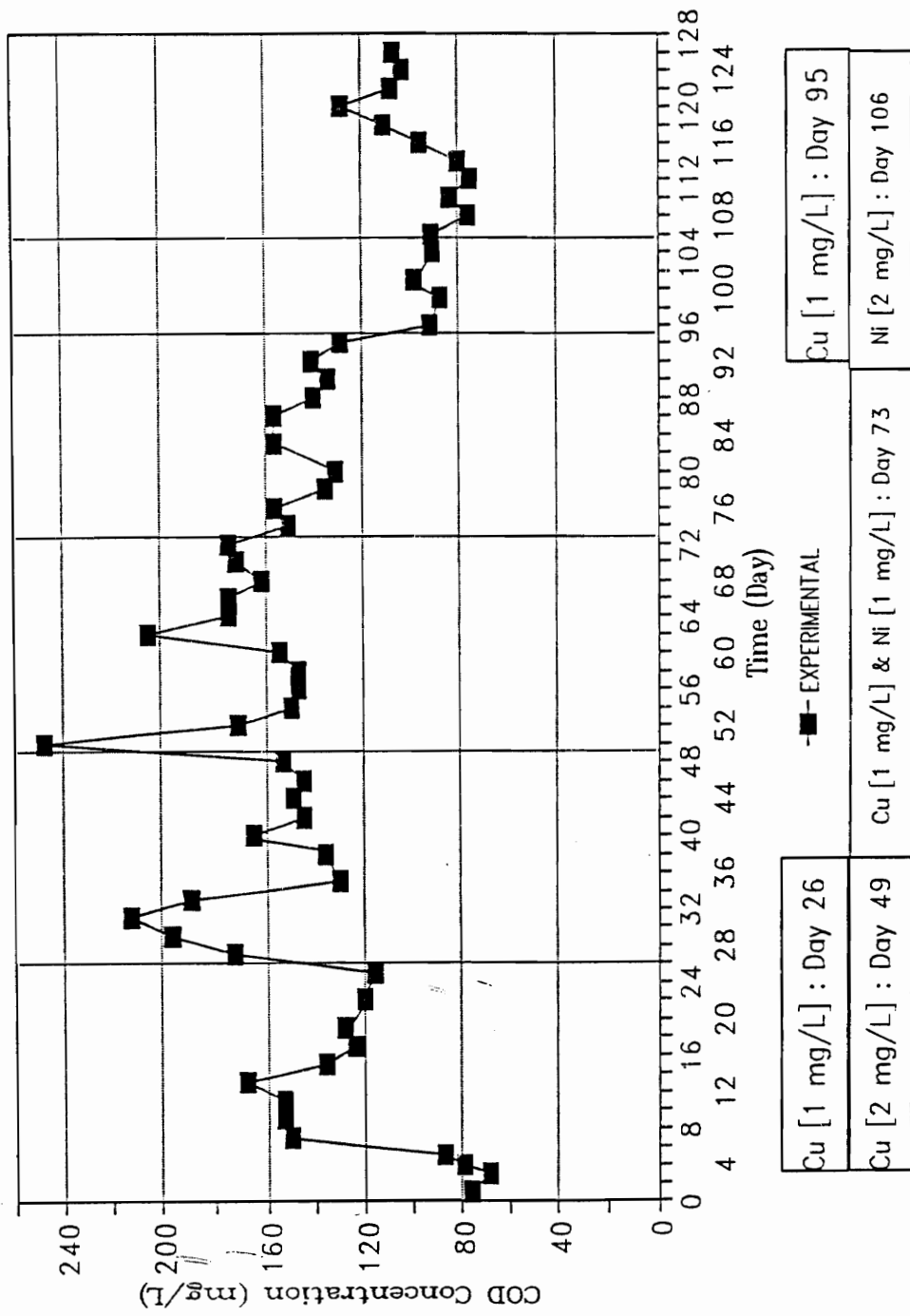
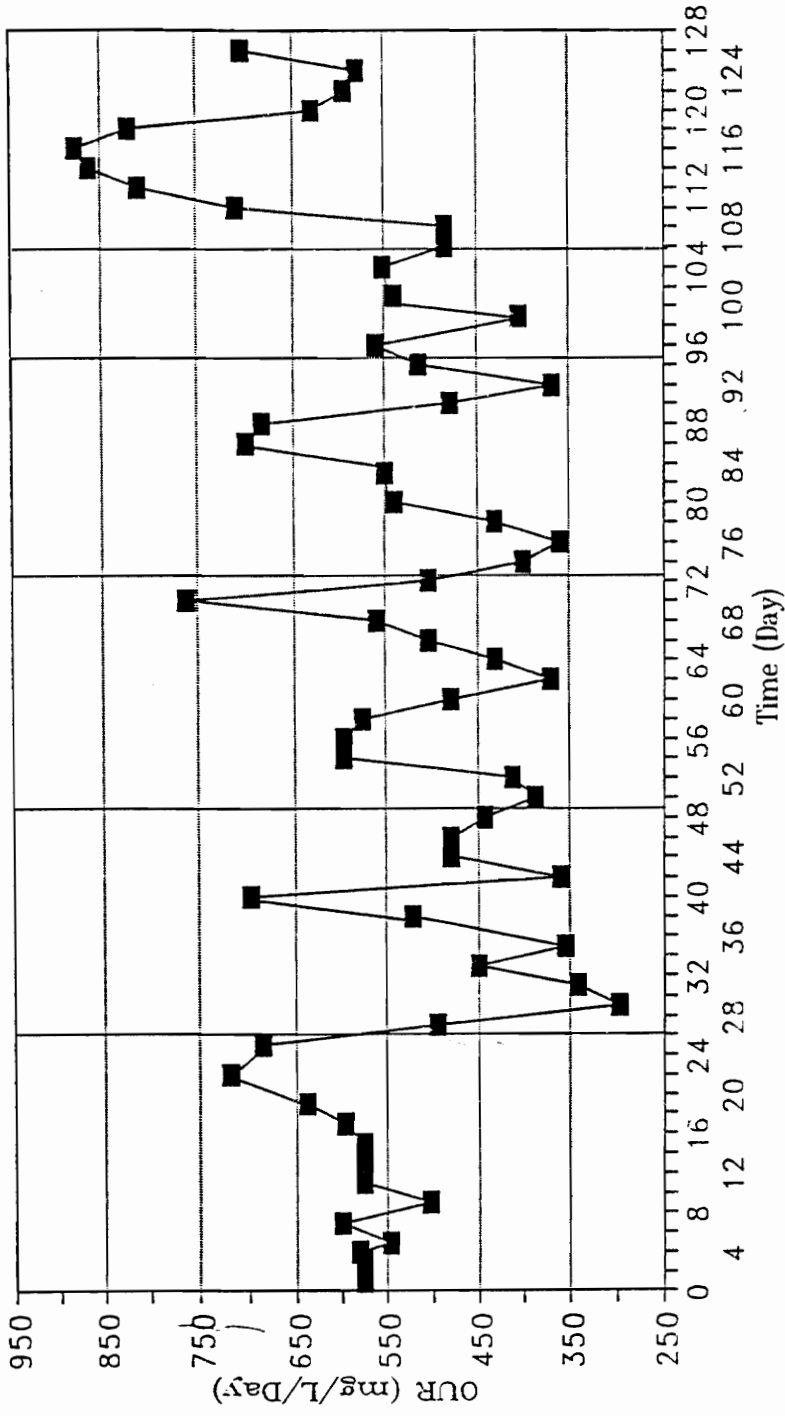


Figure 4.22 Variation of Effluent COD Concentration for the Experimental Unit



Cu [1 mg/L] : Day 26	Cu [1 mg/L] : Day 95
Cu [2 mg/L] : Day 49	Ni [2 mg/L] : Day 106
Cu [1 mg/L] & Ni [1 mg/L] : Day 73	

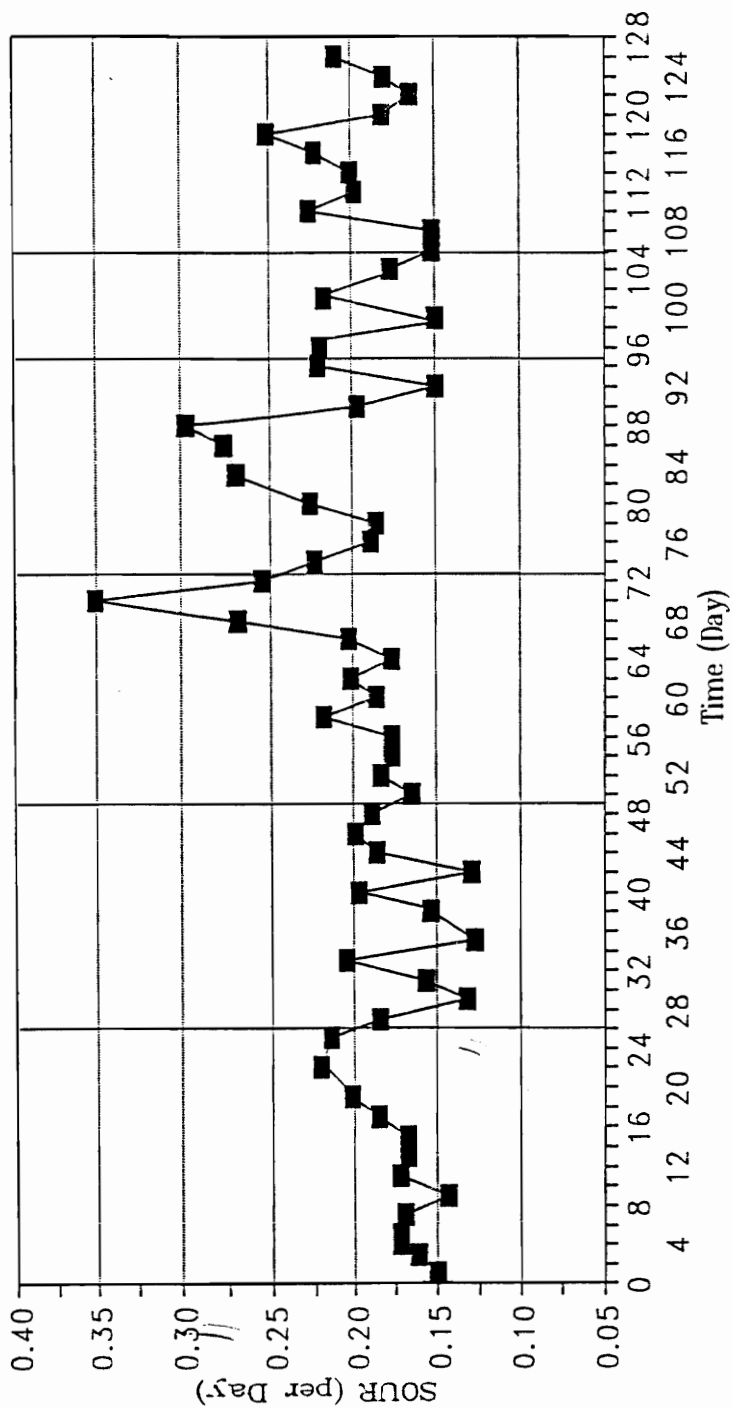
Figure 4.23 Variation in Oxygen Uptake Rate for the Experimental Unit

research. In order to get a better picture of the oxygen uptake by the biomass, the SOUR is plotted in Figure 4.24. As can be observed from Figure 4.24 there were no significant changes in SOUR during the course of the research.

#### 4.5.4 EFFECT OF METALS ON EFFLUENT SUSPENDED SOLIDS

##### PHASE 1 and PHASE 2

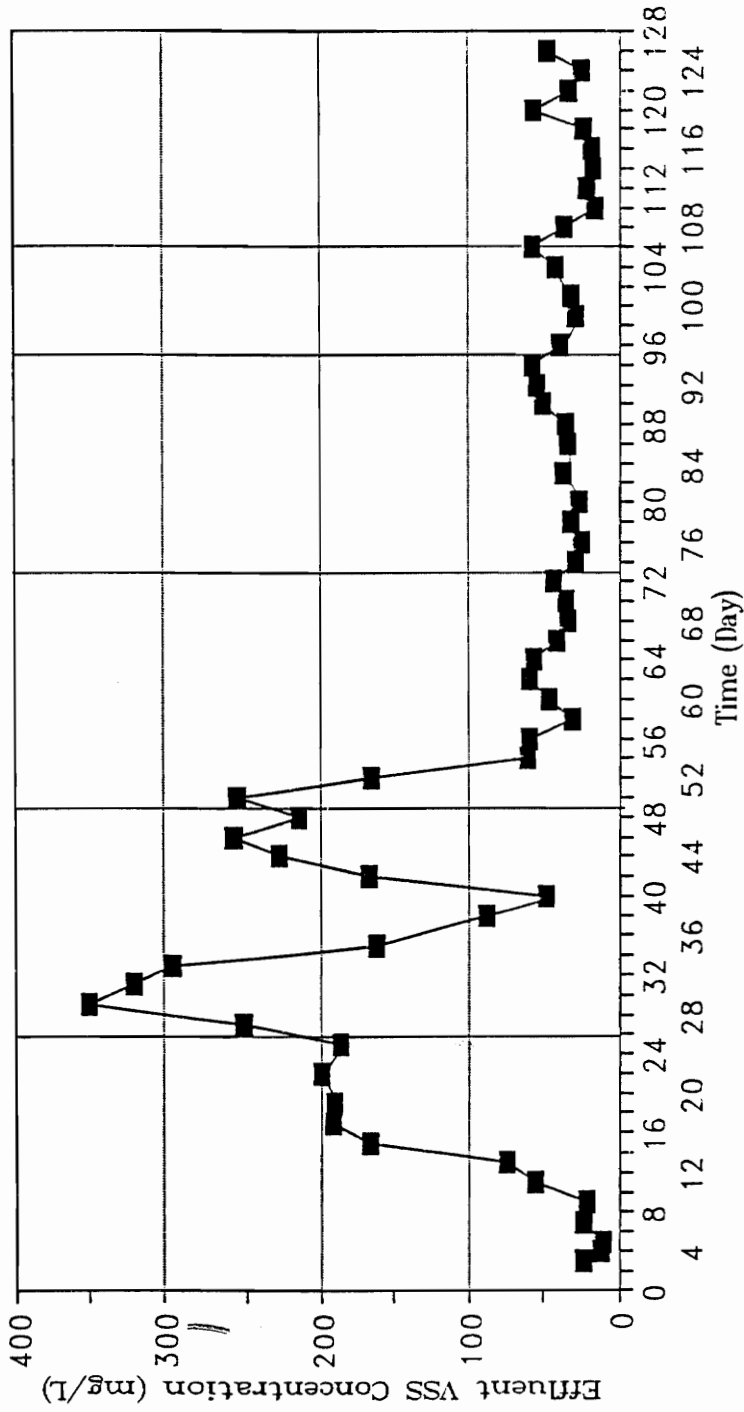
The effluent VSS values for the experimental unit are plotted in Figure 4.25. During Phase 1, the effluent SS concentration was high. The average VSS during Phase 1 was 192 mg/L and standard deviation of 5 units. The probable reason was that pretreatment of the influent to remove metals also removed or reduced other metals/nutrients which might have been limiting metals/nutrients. During Phase 1, the average Total Metal Loading Rate (TMLR) was 1.1 mg/day. From day 26 (beginning of Phase 2), the average TMLR increased to 5 mg/day. The effluent SS and VSS got worse and showed an increasing trend till day 29. After day 29, the effluent SS started decreasing and reached the low value of 70 mg/L on day 40. It was thought during this time that accumulation of metals in the mixed liquor probably helped in lowering the effluent SS. But, the effluent SS started



Cu [1 mg/L] : Day 26	Cu [1 mg/L] : Day 95
Cu [2 mg/L] : Day 49	Ni [2 mg/L] : Day 106
Cu [1 mg/L] & Ni [1 mg/L] : Day 73	

Figure 4.24 Variation in Specific Oxygen Uptake Rate for the Experimental Unit





Cu [1 mg/L] : Day 26	Cu [1 mg/L] : Day 95
Cu [2 mg/L] : Day 49	Ni [2 mg/L] : Day 106
Cu [1 mg/L] & Ni [1 mg/L] : Day 73	

Figure 4.25 Variation of Effluent Volatile Suspended Solids for the Experimental Unit

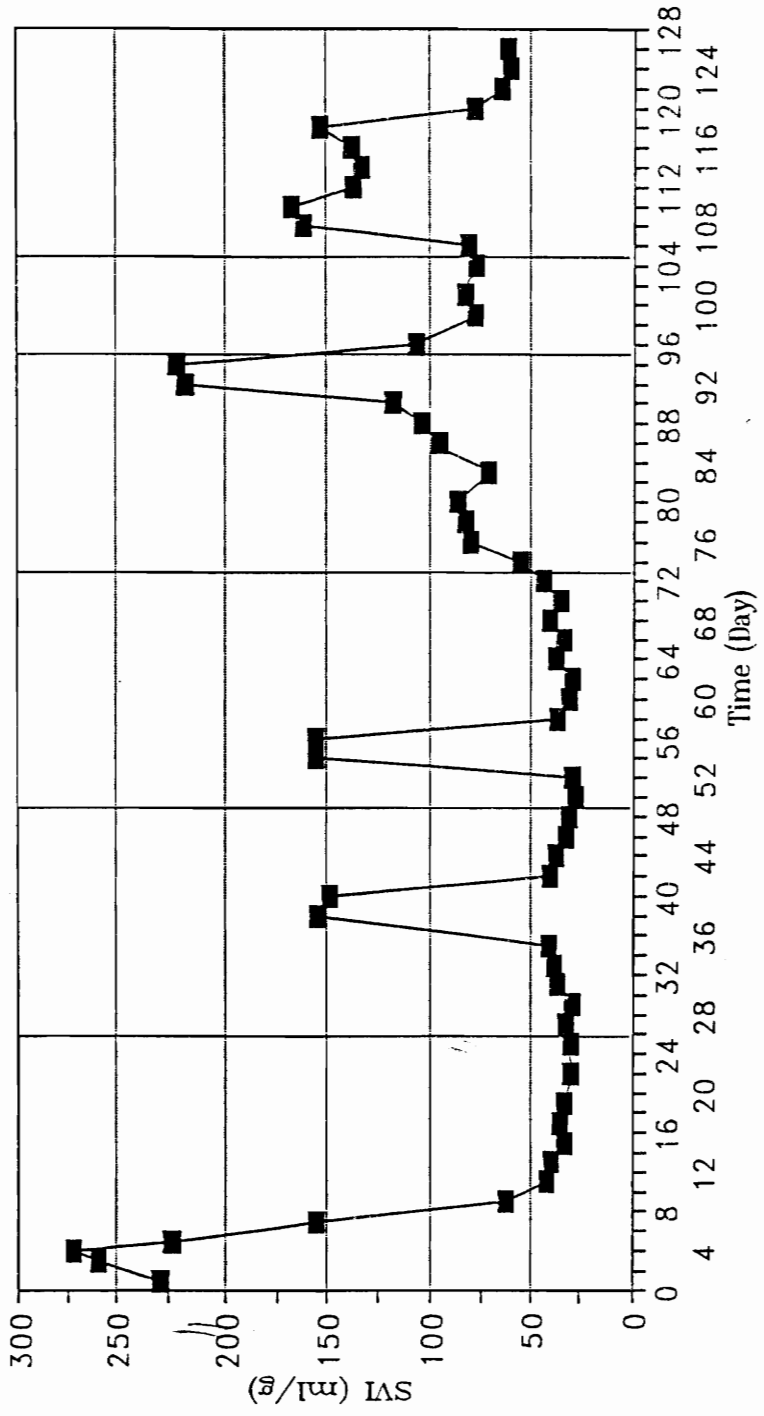
increasing from day 42. This increase in effluent SS was probably because the influent pH was decreased to 4.5 beginning on day 40. The pH of the influent was reduced from 6 to 4.5. From phase 3 the effluent VSS was less than 75 mg/L for the rest of the research. This indicated that changes in metal concentration after the activated sludge was acclimated did not have significant effects on effluent SS.

#### 4.5.5 EFFECT OF METALS ON SETTLING PROPERTIES

##### PHASE 1 and PHASE 2

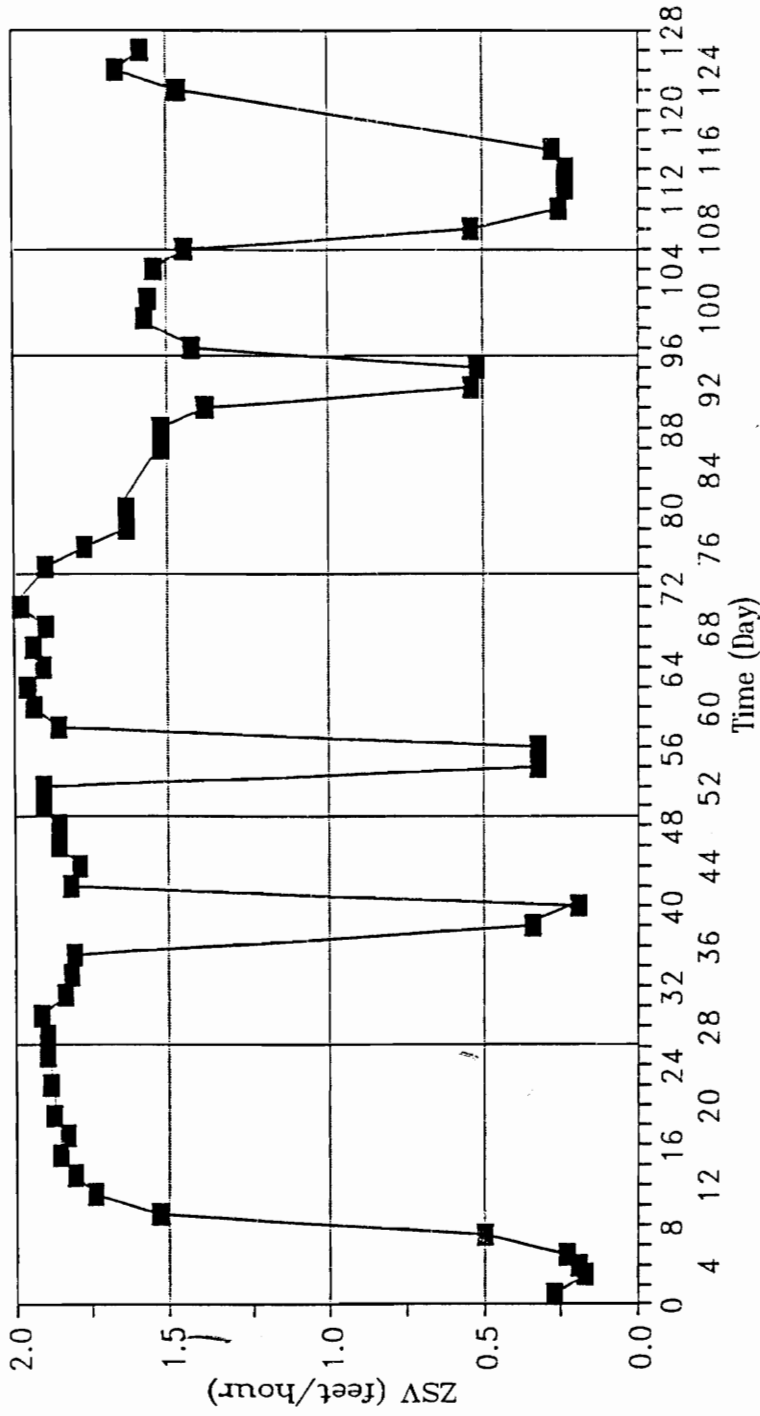
During Phase 1, no metals were added. The SVI for the experimental unit was very good with an average value of 33 ml/g. The SVI started with a high value of 229 ml/g on day 1, but within a week the SVI dropped to 63 ml/g (Day 8). The ZSV also improved during the above period from a slow 0.27 feet/hr to a faster 1.53 feet/hr. The SVI was low (< 42 ml/g) and the ZSV high (> 1.74 feet/hr) for the remainder of Phase 1. This showed that removal of metals did help in good settling of the mixed liquor. The Figures for SVI and ZSV are 4.26 and 4.27 respectively.

Copper of 1 mg/L was introduced to the influent feed on day



Cu [1 mg/L] : Day 26	Cu [1 mg/L] : Day 95
Cu [2 mg/L] : Day 49	Ni [2 mg/L] : Day 106
Cu [1 mg/L] & Ni [1 mg/L] : Day 73	

Figure 4.26 Variation of Sludge Volume Index for the Experimental Unit



Cu [ 1 mg/L ] : Day 26	Cu [ 1 mg/L ] : Day 95
Cu [ 2 mg/L ] : Day 49	Ni [ 2 mg/L ] : Day 106
Cu [ 1 mg/L ] & Ni [ 1 mg/L ] : Day 73	

Figure 4.27 Variation of Zone Settling Velocity for the Experimental Unit

26. On day 36, the SVI deteriorated for two days. It is possible that an increase of potassium dose from around 12 mg/L to 25 mg/L on day 34 was responsible for the SVI increase, but there is no indication in the literature that potassium at this concentration has any detrimental effect on the activated sludge. Overall no significant change in settling properties was observed during Phase 2 although another two day deterioration period occurred. This showed that accumulation of copper in the mixed liquor did not lead to deterioration of the settling of the mixed liquor. The copper loading was doubled from phase 2 to phase 3. Still the settling of the mixed liquor was good. This showed that addition of copper up to 2 mg/L in the influent feed did not affect the settling properties of the mixed liquor. It is possible that the addition of copper improved the settling of the mixed liquor.

For phase 4, copper loading was reduced from 8.5 mg/day to 4.4 mg/day, while that of nickel was increased from 0.85 mg/day to 5.3 mg/day. Hence, the TMLR was almost constant (9.4 mg/day to 9.7 mg/day) during these two Phases. But as can be observed from Figure 4.26, the SVI values showed a gradual increase during Phase 4. This indicated that the combined loading of copper and nickel of about 5 mg/day each, led to a deterioration of the settling properties.

The reason for this was not clear. One possibility was the presence of filamentous bacteria, but an observation of the mixed liquor under the microscope did not confirm this. Another reason could be that the combined loading of copper and nickel might have been toxic, which would have caused cell lysis and this would have interfered with settling. Or there may have been some other reason for the poor settling of the mixed liquor.

In order to verify that the combination of copper and nickel was the cause of the poor settling of the mixed liquor, the addition of nickel was stopped from day 95. Only copper at a loading of 4.2 mg/day was applied. The SVI showed improvement as indicated in Figure 4.26. This resulted in two observations. The combination of copper and nickel loadings of around 5 mg/day each was detrimental to the settling of the sludge. The addition of copper alone apparently improved settling of the sludge.

During phase 6, the addition of copper was stopped, but nickel loading was increased to 8.9 mg/day. The SVI deteriorated. The interesting aspect of phase 6 was that after day 118, the settling of the mixed liquor improved. The reason for the poor settling during the first part of phase 6 and subsequent improvement may be explained as

follows :

During phase 5, copper loading of 4.2 mg/day was applied. This loading resulted in the uptake of copper by the biomass. Even though the loading of copper was stopped on day 106, copper present in the mixed liquor acted in combination with the nickel that was loaded to the reactor from day 106. This combination acted as if copper and nickel loadings were simultaneously applied to the reactor. Hence the poor settling of the mixed liquor took place from day 106 to 118. By day 118, the presence of copper in the mixed liquor was low, while the presence of nickel was substantial. Hence the observation from this period was that copper or nickel loadings alone did not lead to poor settling of the activated sludge but a combination of copper and nickel led to poor settling of the activated sludge.

# CHAPTER 5

## DISCUSSION

### 5.1 Accumulation of metals in mixed liquor

The influent wastewater to the experimental unit was pretreated with lime to reduce the metals concentration, and then copper and nickel were added separately or together to evaluate their effects on the performance of the system. The consistent concentrations resulting from lime pretreatment enabled a more accurate evaluation of the metals. After the raw influent from the Celco plant was pretreated with lime, the removal of copper was excellent (> 95%); while the removal of nickel was around 60%. The Figures corresponding to the experimental unit are 5.1, 5.2, 5.3, and 5.4.

During phase 1, no metal was added. After pretreatment, the influent concentration of copper was around 0.04 mg/L and that of nickel varied from 0.2 mg/L to 0.3 mg/L. A look at the total copper in the mixed liquor indicated an average value of 0.23 mg/L (Figure 5.1), but the nickel concentration had a comparatively much higher value of 0.65



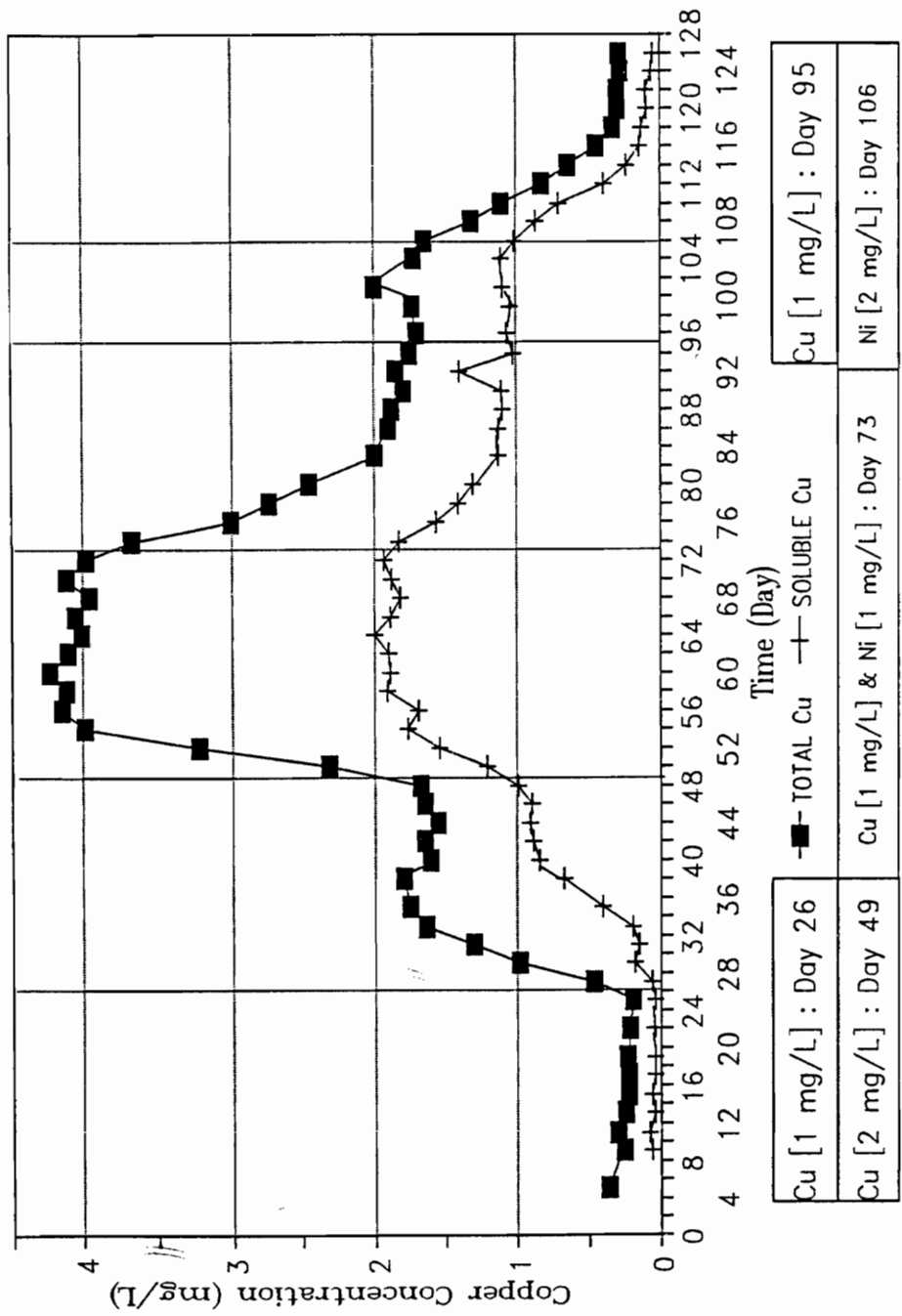


Figure 5.1 Variation of Total and Soluble Copper in Mixed Liquor for the Experimental Unit

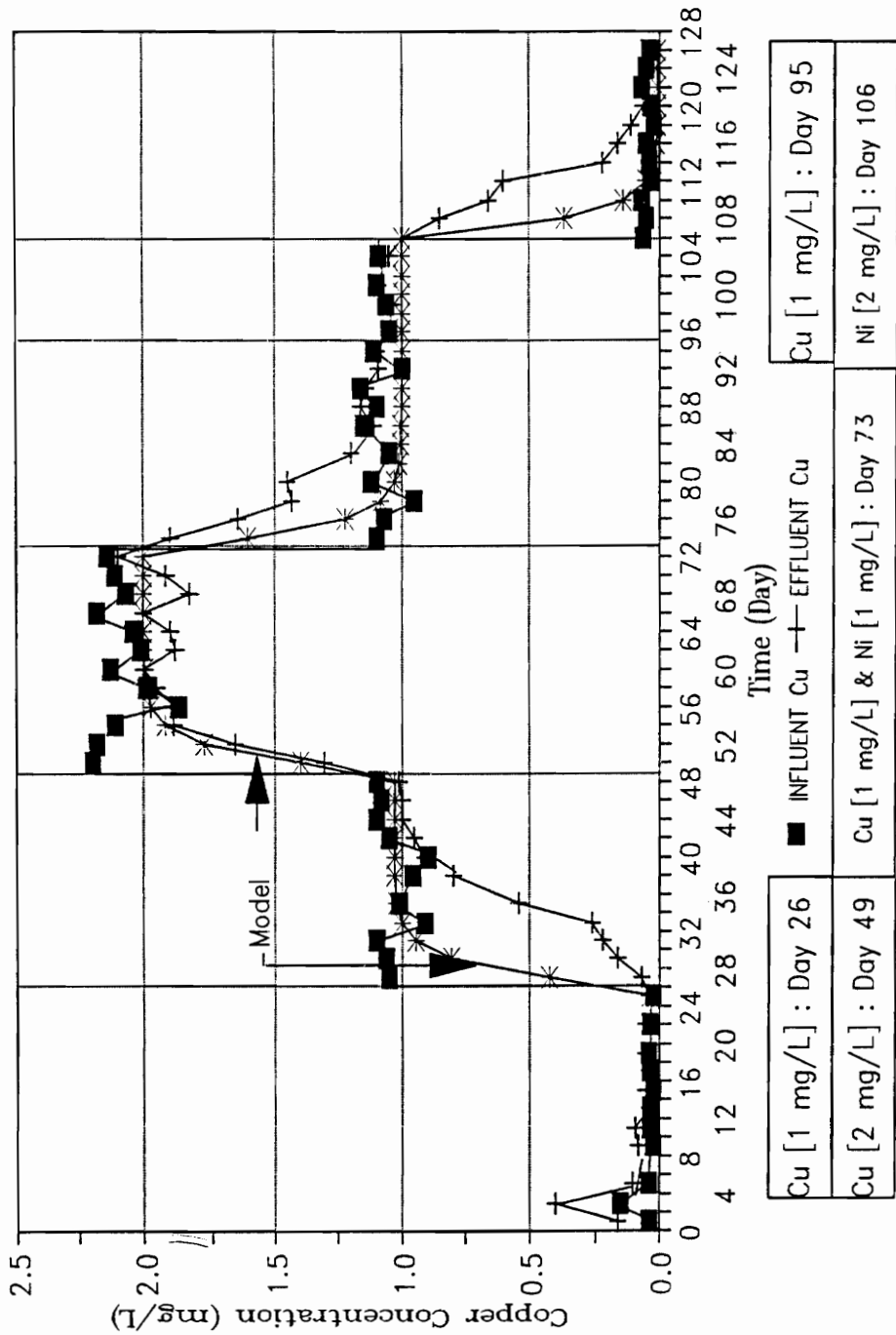


Figure 5.2 Variation of Total Influent and Effluent Copper for the Experimental Unit

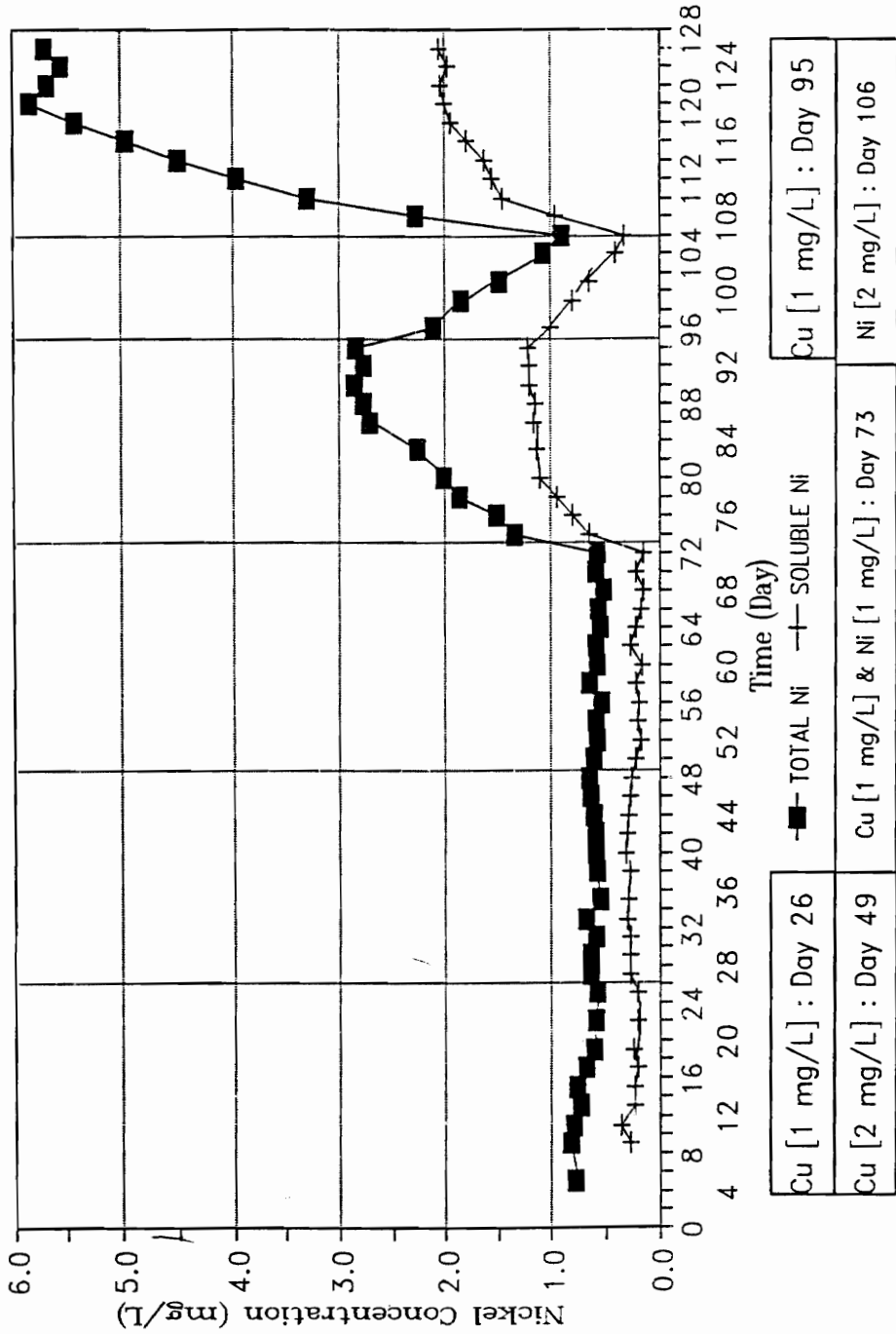


Figure 5.3 Variation of Total and Soluble Nickel in Mixed Liquor for the Experimental Unit

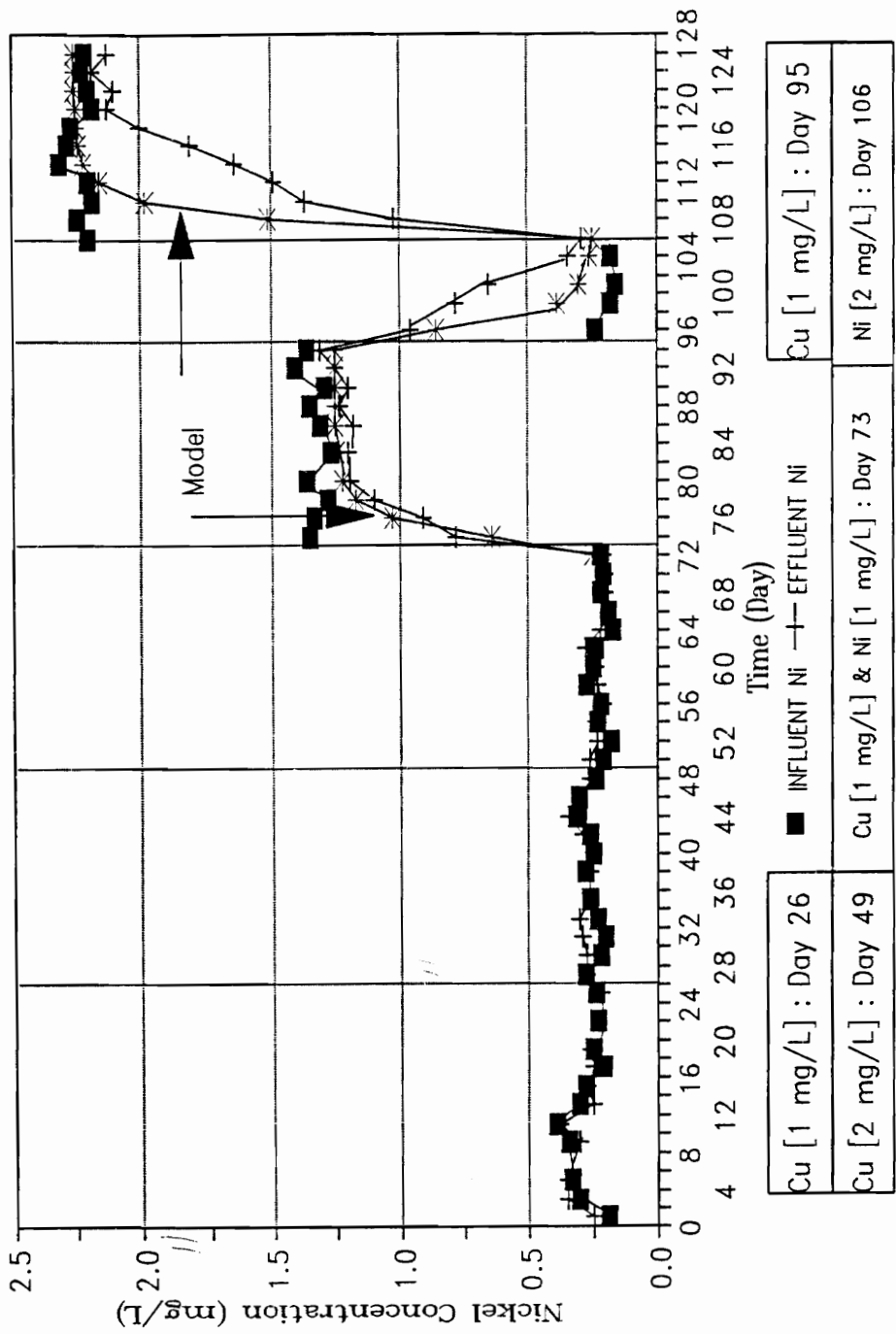


Figure 5.4 Variation of Total Influent and Effluent Nickel for the Experimental Unit

mg/L (Figure 5.3). The reason for the comparatively higher value of nickel in the mixed liquor was due to the higher loading rate of nickel during this phase.

From day 26, 1 mg/L of copper was added to the influent feed. The accumulation of copper in the mixed liquor showed an interesting phenomena. From day 26 to day 34, the accumulation of copper occurred primarily in the biomass. This is shown by Figure 5.1, because the dissolved metal in the mixed liquor showed very small increases as compared with the total metal in the mixed liquor. This indicated that the biomass had a substantial sorption capacity for copper when the loading was first increased. Biomass sorption came into equilibrium with the loading after a few days because from day 36 the dissolved metal in the mixed liquor began to show significant increases.

Another important observation that can be made from Figure 5.1 is that the increase in dissolved metal was slow only when the first dose of copper was introduced to the reactor. The increase in dissolved metal in the mixed liquor was faster when the additional 1 mg/L of copper was introduced from day 49. This showed that non-acclimated sludge tends to retain more metal in the biomass than an acclimated sludge when increases in metal dosage are made.

### Modeling of effluent characteristics :

The effluent metal flow characteristics appeared to follow characteristics similar to the introduction of a dye to a completely stirred tank reactor. It was decided to plot the following equation to see how closely it fits the effluent metal flow characteristics. The equation used was the hydraulic model for dye tracing.

$$M_{\text{eff}} = + M_{\text{inf}} \times (1 - e^{-T/t}) + M_{\text{back}}$$

where

$M_{\text{inf}}$  = Total metal in the influent (mg/L)

$M_{\text{eff}}$  = Total metal in the effluent (mg/L)

T = Time after the introduction of the metal (days)

t = HRT

$M_{\text{back}}$  = Background concentration of metal

The above equation is plotted in Figures 5.2 and 5.4. While it can be seen that there is a good correlation between the model and the observed data, it appears that the model is more "steep" when compared to the experimental data in certain cases. This is probably because that, while the "t" used in the model was strictly HRT, the appropriate "t" should also be a function of MCRT also. In other words  $t = f(\text{HRT}, \text{MCRT})$ , with the contribution of MCRT being a small

value. Nevertheless, the model is a good approximation for estimating the effluent metal data for low metal loadings. The relationship between metal loading rate, uptake of metals and dissolved metal in the mixed liquor are discussed in the following paragraphs.

## **5.2 Metal Analysis Parameters - DM, TMLR, STMLR, and SUM**

Four metals analysis parameters were used to analyze the data and are proposed for analyzing the effects of metals on the different performance parameters like effluent COD, SS etc. They are the Dissolved Metal (DM) in the mixed liquor, the Total Metal Loading Rate (TMLR) (Figure 5.5), the Specific Total Metal Loading Rate (STMLR) (Figure 5.6) and the Specific Uptake of Metal (SUM) (Figure 5.7). The advantages and disadvantages of using each of the above analysis methods are discussed below :

The TMLR parameter expresses the magnitude of the metal loading that was applied to the system. The TMLR was approximately constant for any particular phase during the experiment (Figure 5.5). But TMLR analysis by itself does not take into account the biomass present in the mixed liquor. Hence this analysis is not sufficient within a phase, if used for correlating with the changes in effluent

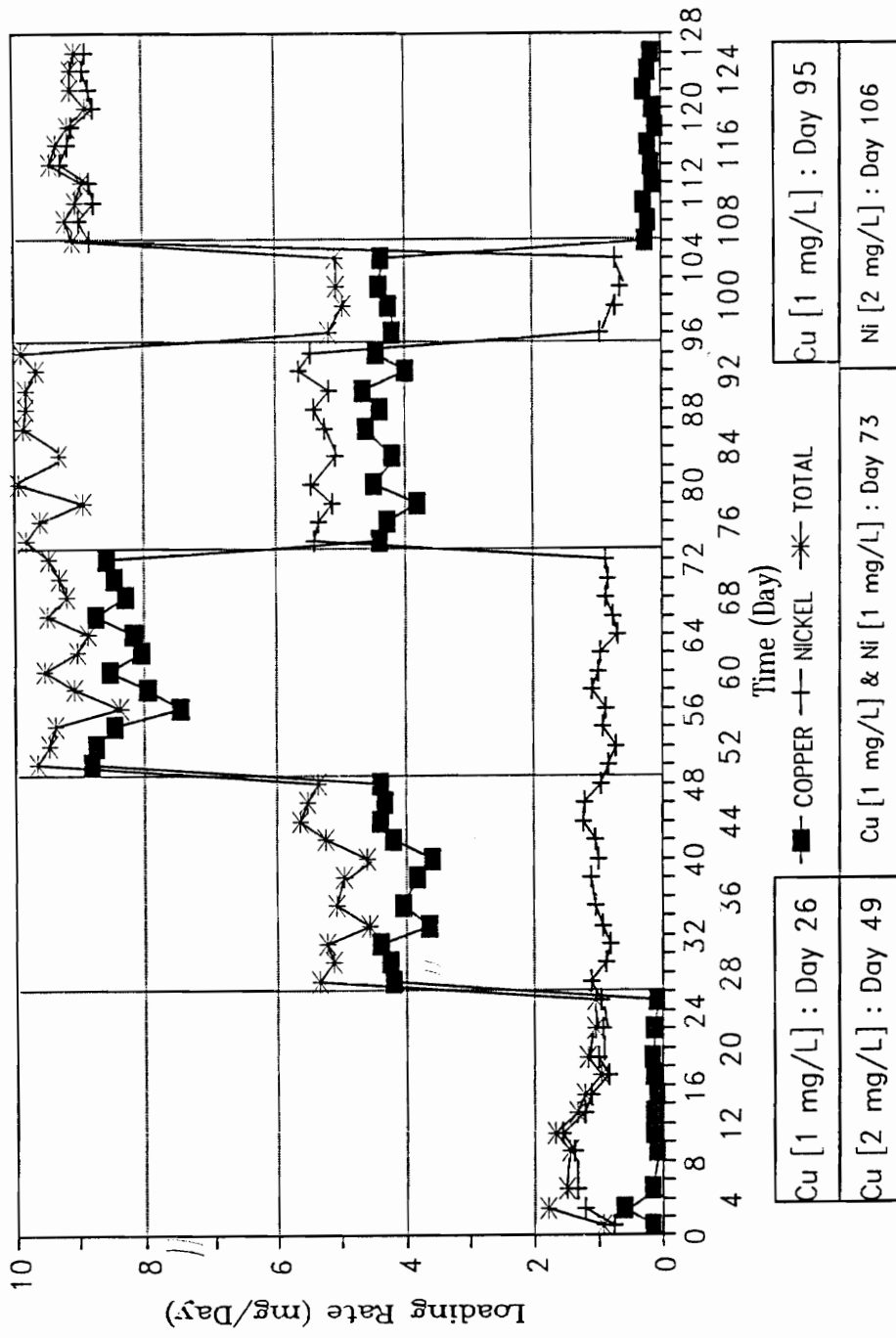


Figure 5.5 Variation of Loading Rate (Copper, Nickel and Total) for the Experimental Unit



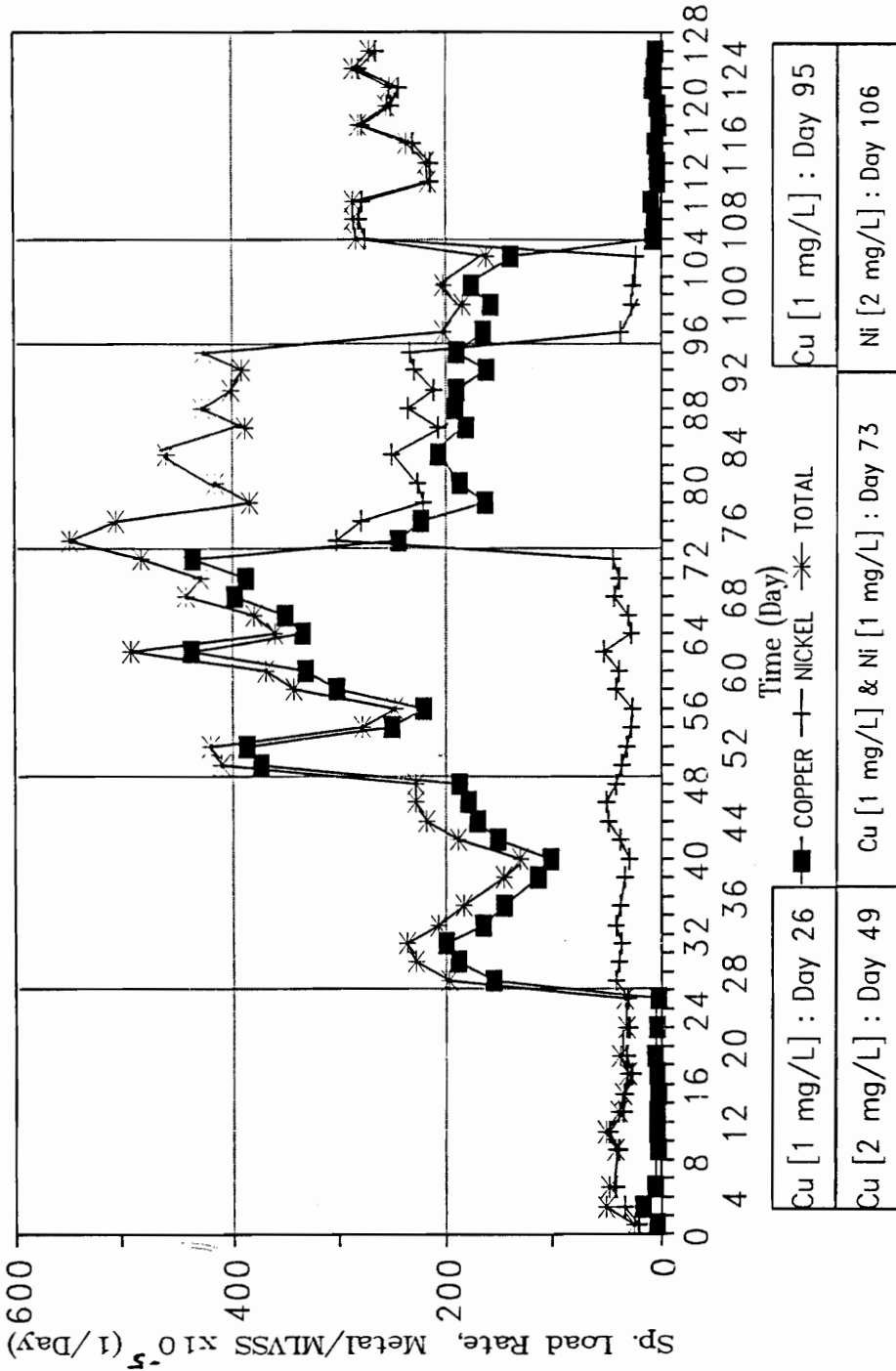


Figure 5.6 Variation of Specific Loading Rate (Copper, Nickel, Total) for the Experimental Unit

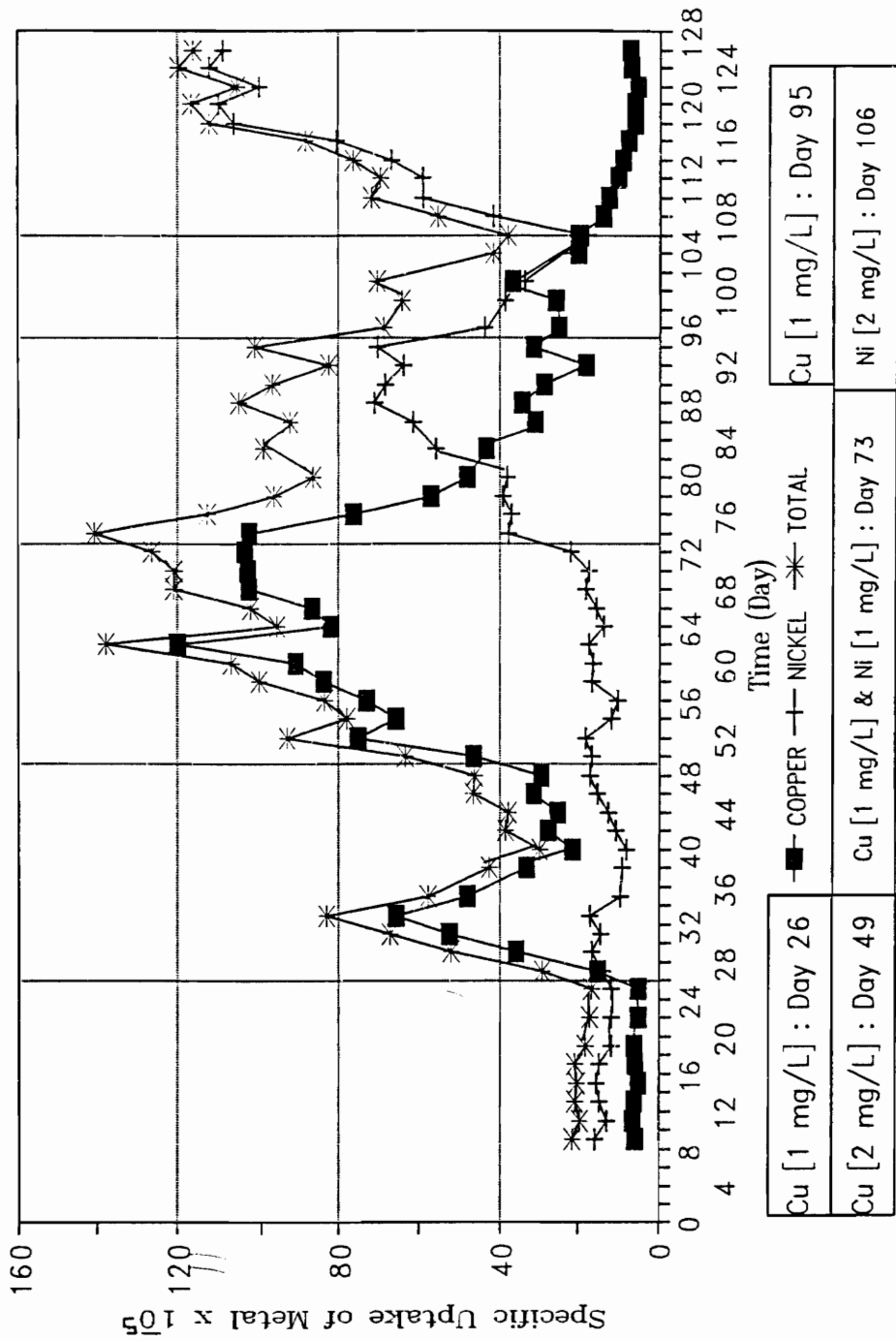


Figure 5.7 Variation of SUM (Copper, Nickel and Total) for the Experimental Unit

COD, etc. The advantage, however, is its simplicity, since it gave the magnitude of metal loading to the reactor.

The second parameter used was the STMLR. This parameter, unlike the TMLR, takes into account the presence of biomass. The TMLR was approximately constant for a particular Phase because a predetermined amount of metal was added to the influent. Hence, within a phase, the STMLR was inversely proportional to the changes in MLVSS only. When this parameter was used for analysis the other parameters like effluent COD, etc., are compared to the inverse of MLVSS for the particular phase. Thus this parameter was useful for comparing changes in the effluent parameters (effluent COD etc.) between phases.

The third parameter used was the SUM, which accurately described the metal sorbed by the biomass because the dissolved metal concentration is subtracted from the total. The metal present in the mixed liquor was a variable, because retention of the metal by the mixed liquor depended on a number of factors including the dosage of the metal, the mixed liquor pH<sup>36</sup> and the amount of biomass present in the mixed liquor. Because both the biomass (as represented by MLVSS) and the amount of metal present in the mixed liquor were measured, this parameter was a useful tool in

the analysis of metals.

### **5.3 Relationship between the Different Metal Analysis Parameters**

The experimental data indicated that there was adsorption or desorption of metals depending on the metal loading rate that was applied to the experimental unit. It was decided to quantify this adsorption/desorption phenomena. Quantification was difficult initially, because of the different parameters like total metal, dissolved metal, etc., and the focus initially was on these parameters. Later, when trying out various combination of the parameters, it was found that there were correlations between the different parameters.

The terms used in the following Figures 5.8 through 5.28, are defined as follows:

"NM" denotes the average value for the parameters at the end of phase 1, where no metal was added. "C" denotes the average value at the end of either phases 2,3, or 5, where only copper was added. "N" denotes the average value at the end of phase 6, where only nickel was added. "CN" denotes the average value at the end of phase 4, where both copper and nickel were added.

Figure 5.8 shows a plot between TMLR and SUM for each of the different phases. The correlation between SUM and TMLR was of the second order. The following equation was developed.

$$\text{SUM} = 0.000012 \times \text{TMLR}^2 - 0.000014 \times \text{TMLR} + 0.00018$$

The  $R^2$  for the curve was found to be 0.92. From Figure 5.8, it can be seen that the SUM increases at a faster rate at higher metal loading rates rather than at lower metal loading rates to the reactor.

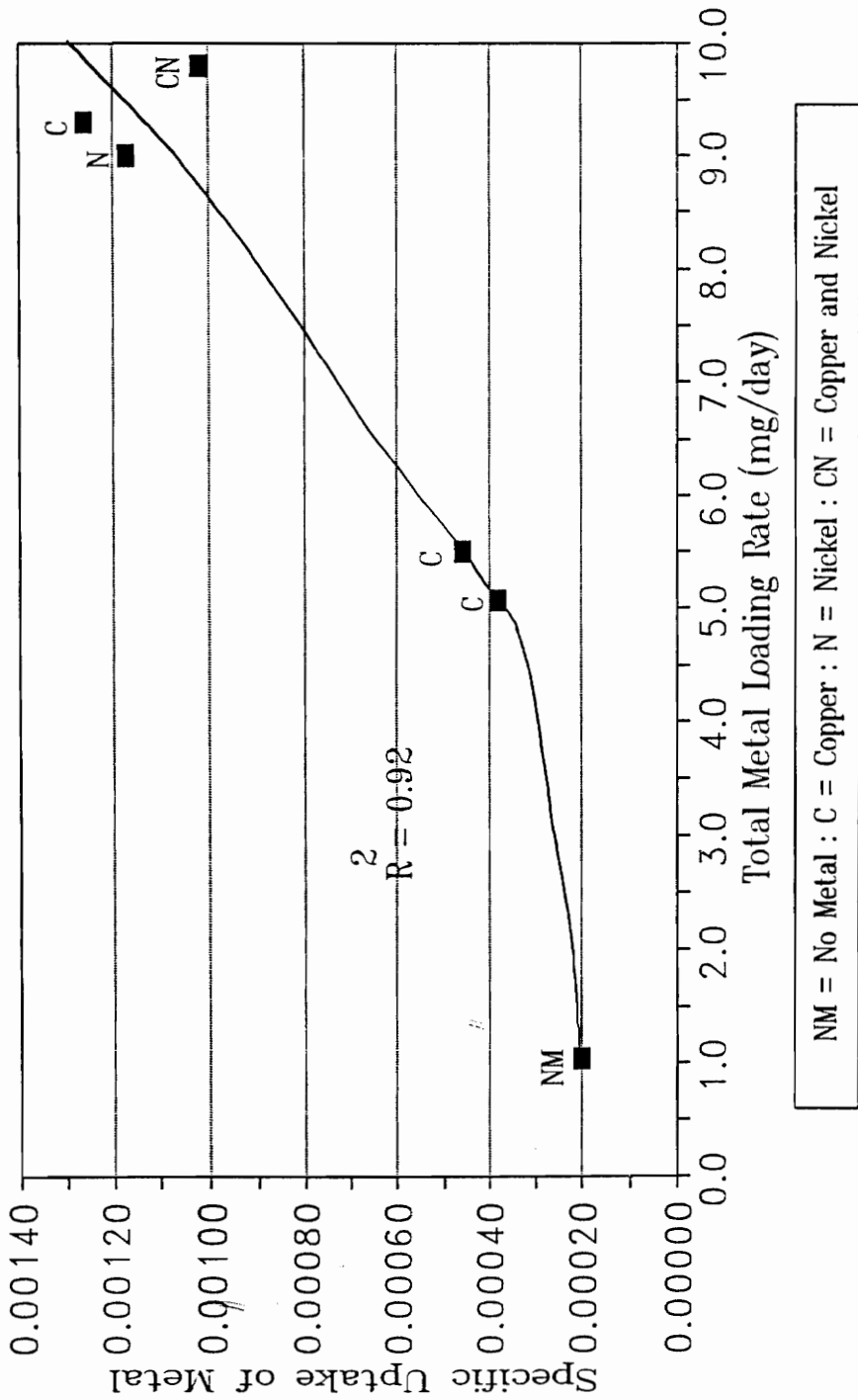
Figure 5.9, shows the plot between SUM and DM. The correlation between SUM and DM was of the second order. The following equation was developed.

$$\text{SUM} = 0.00028 \times (\text{DM})^2 - 0.00017 + 0.0002$$

The  $R^2$  for the curve was 0.9. It can be seen that the SUM increases at a faster rate at higher concentrations of dissolved metal in the mixed liquor. The higher concentrations of dissolved metal in the mixed liquor were linear with loading rates as shown in Figure 5.10. The equation for the relationship is as follows:

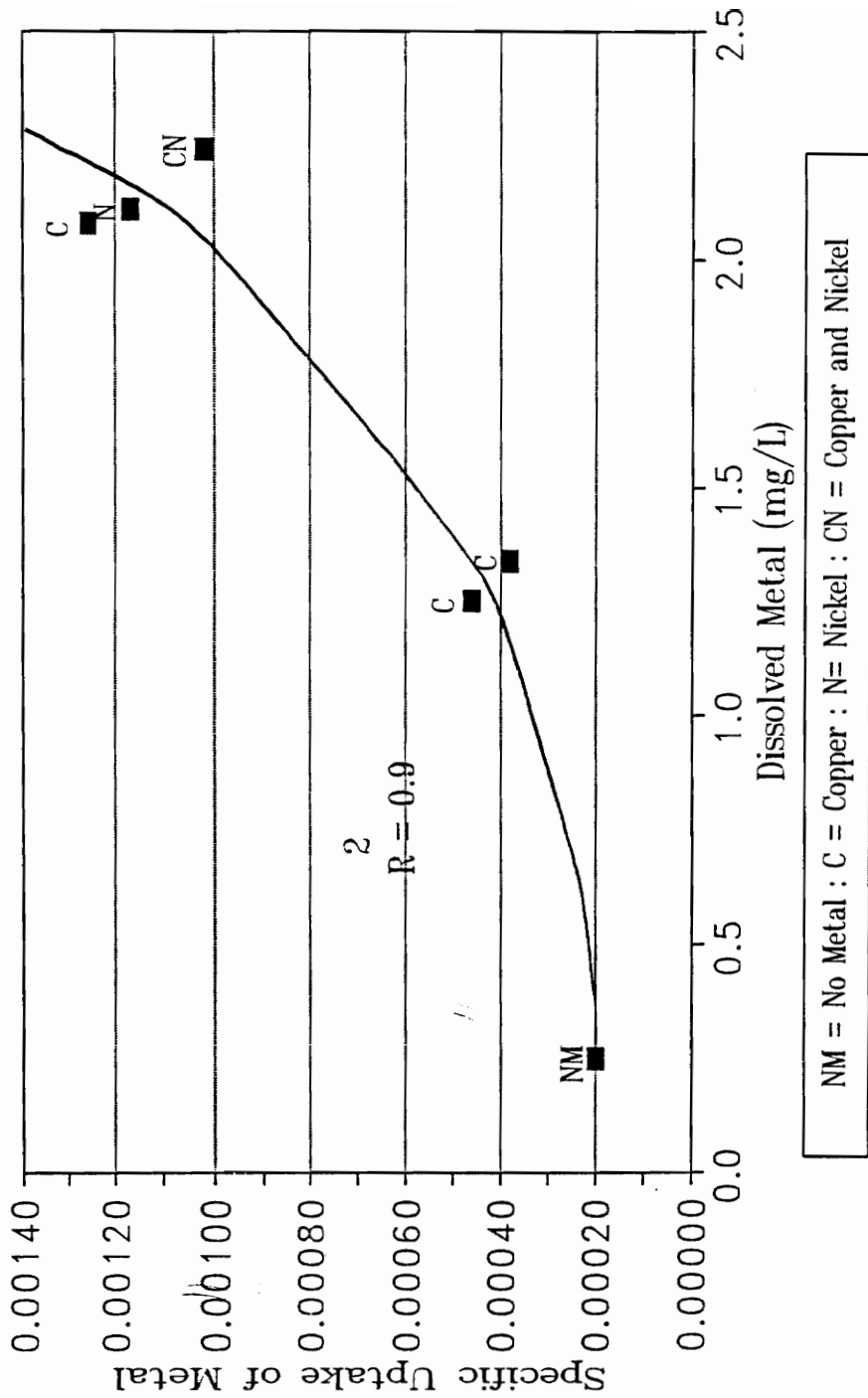
$$\text{DM} = 0.22 \times (\text{TMLR}) + 0.07$$

The relationship between STMLR and DM was of the second order as shown in Figure 5.11. This indicated that at



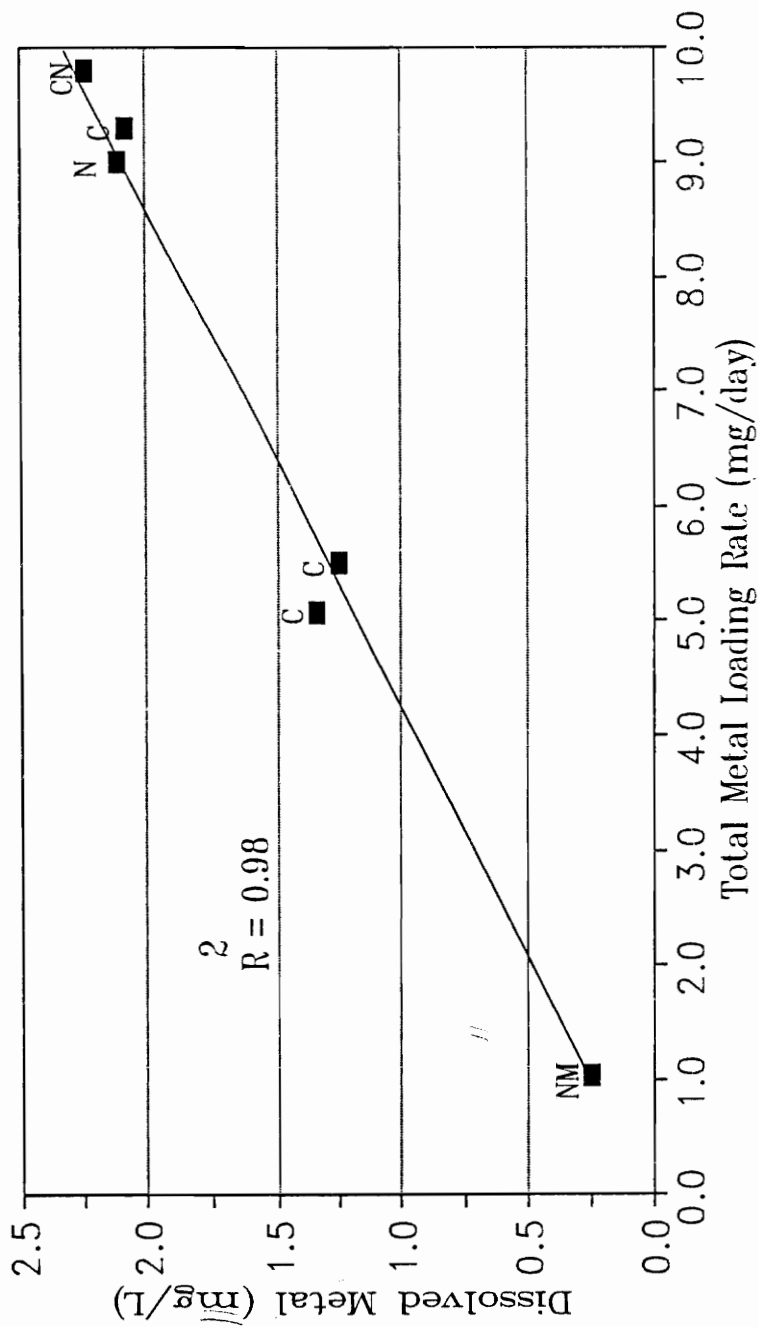
$$\text{SUM} = 0.000012 \times (\text{TMLR})^2 - 0.000014 \times (\text{TMLR}) + 0.00018 \quad \dots \text{Eq 1}$$

Figure 5.8 Correlation between SUM and TMLR



$$\text{SUM} = 0.00028 \times (\text{DM})^2 - 0.00017 (\text{DM}) + 0.0002 \quad \dots \text{Eq 2}$$

Figure 5.9 Correlation between SUM and DM

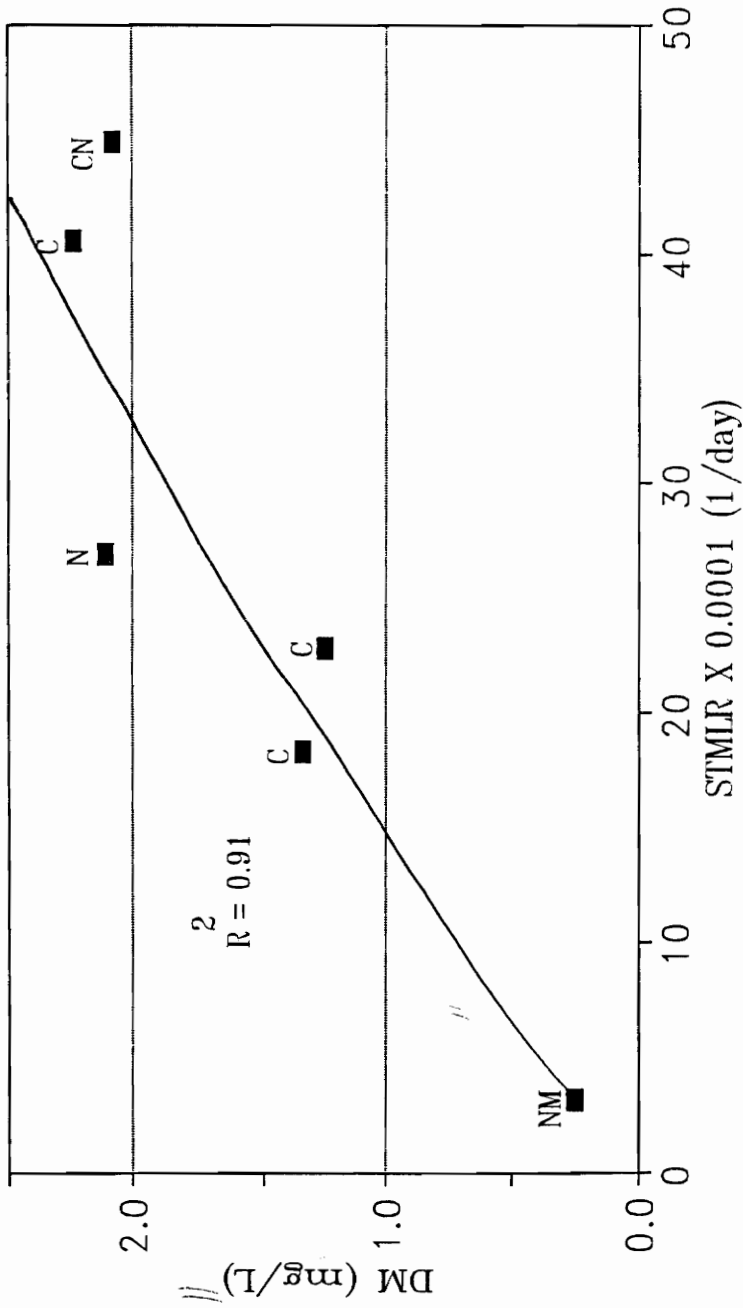


NM = No Metal : C = Copper : N = Nickel : CN = Copper and Nickel

$$\text{DM} = 0.22 \times (\text{TMLR}) + 0.07 \quad \dots \text{Eq 3}$$

Figure 5.10 Correlation between TMLR and DM





NM = No Metal : C = Copper : N = Nickel : CN = Copper and Nickel

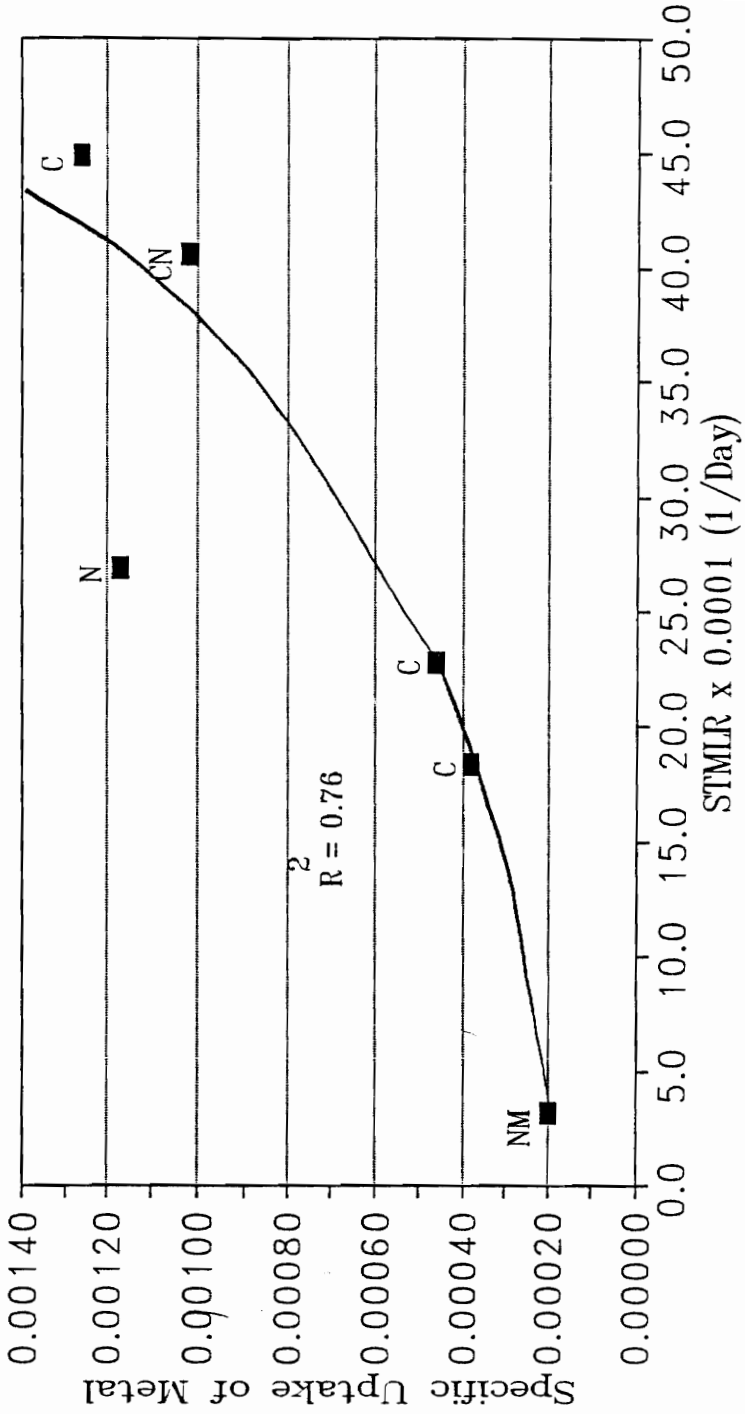
$$DM = -106098 \times (STMLR)^2 + 983 \times STMLR - 0.093 \quad \dots \text{Eq 4}$$

Figure 5.11 Correlation between STMLR and DM

higher specific loading rates, the dissolved metal concentrations in the mixed liquor decreased. Or, in other words, there was more uptake of metals by the biomass at higher specific loading rates. A second order relationship between STMLR and SUM was obtained as shown in Figure 5.12. The  $R^2$  value of 0.76 indicated that it may not be a very good correlation between SUM and STMLR. This was because during phase 6, when only nickel was added, the MLVSS values increased thereby leading to a smaller STMLR value for nickel as indicated by Figure 5.11. The conclusion obtained from Figure 5.11 is similar to the conclusion obtained for Figure 5.8, i.e., at higher STMLR's the uptake of metal by the biomass increased rapidly.

#### **5.4 Metal Analysis Elements and their effects on Effluent COD, Effluent SS, SOUR and Settling properties of the activated sludge.**

The next few figures illustrate the usefulness of the metal analysis elements for analysis of the effects on effluent COD, effluent SS and SOUR. The figures of interest are 5.13, 5.14, 5.15, and 5.16. The average values at the end of each phase are shown in the figures. It can be seen that for low concentrations of metals in the influent feed, the SUM, TMLR, STMLR and dissolved metal are useful metal analysis



NM = No Metal : C = Copper : N = Nickel : CN = Copper and Nickel

$$\text{SUM} = -0.17 \times (\text{STMLR})^2 + 0.26 \times \text{STMLR} + 0.000065 \quad \dots \text{Eq 5}$$

Figure 5.12 Correlation between SUM and STMLR

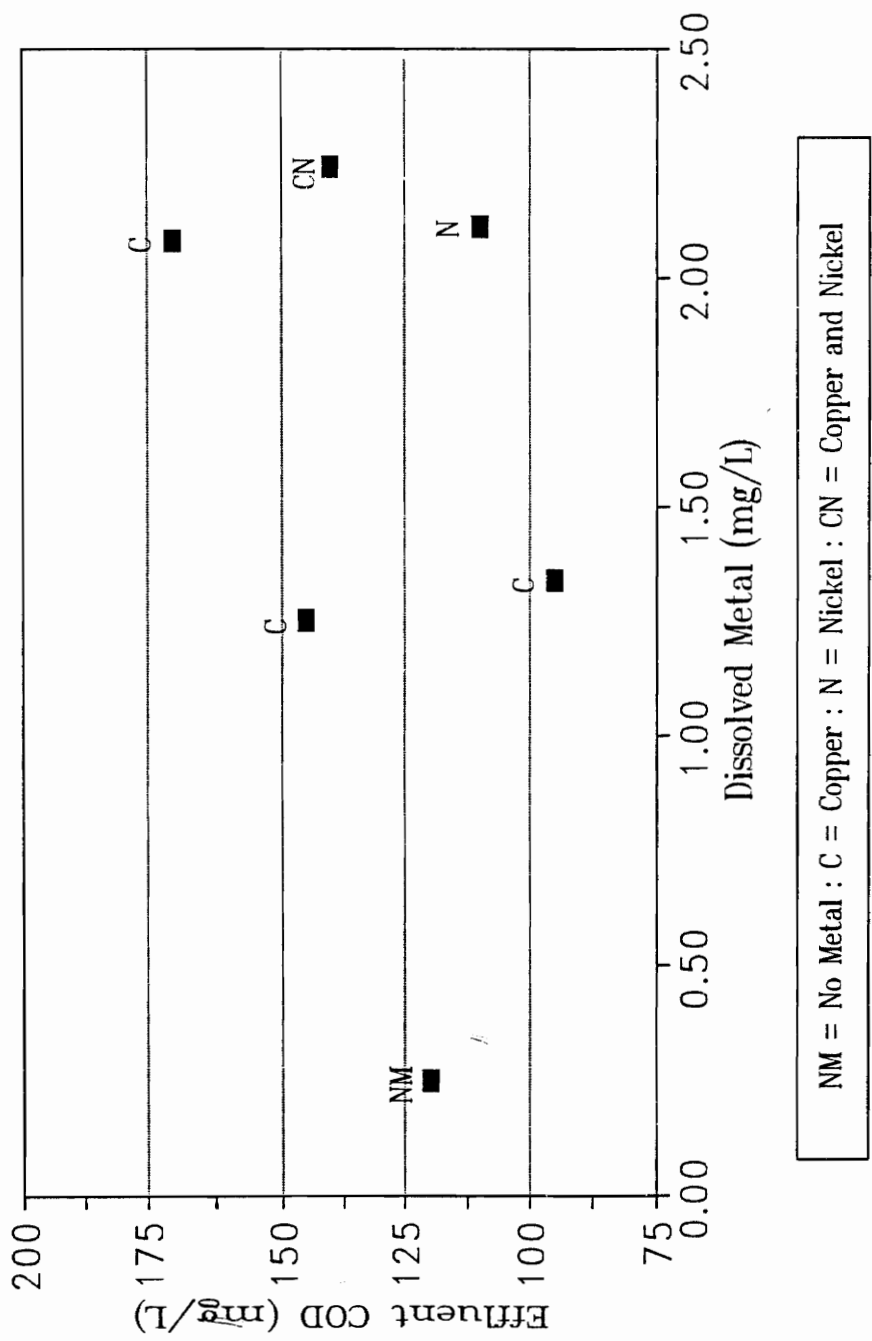
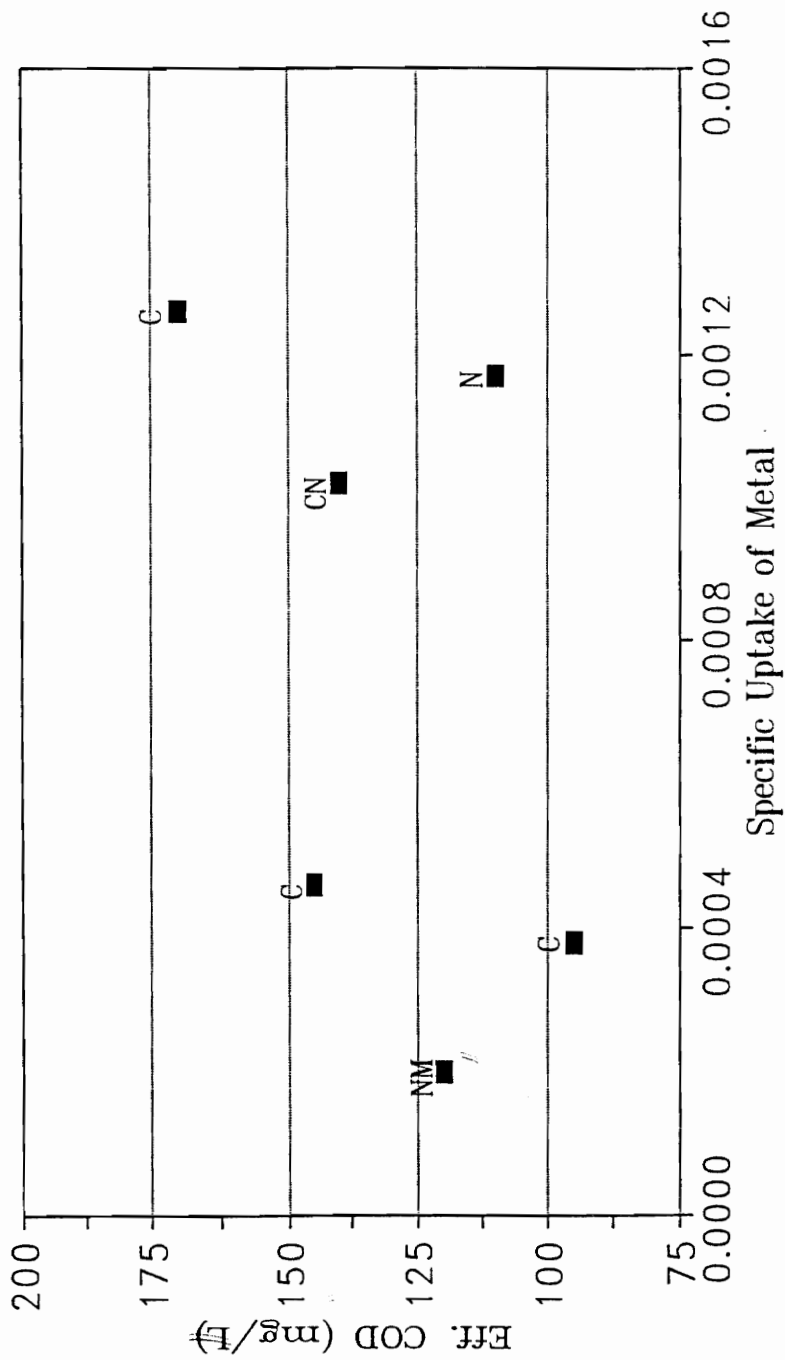


Figure 5.13 Variation of Eff. COD with DM Concentration



NM = No Metal : C = Copper : N = Nickel : CN = Copper and Nickel

Figure 5.14 Variation of Eff. COD with SUM

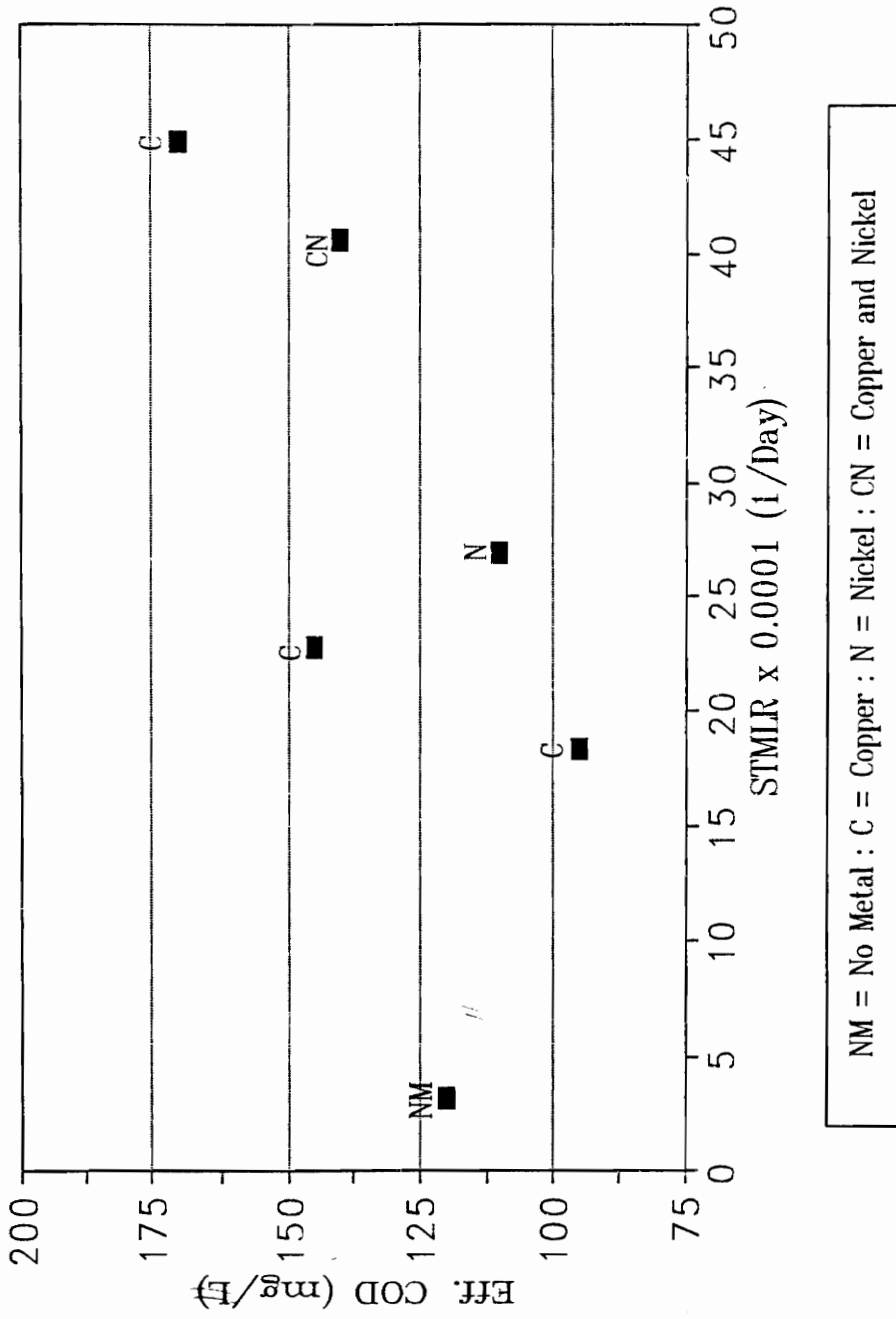


Figure 5.15 Variation of Eff. COD with STMIR

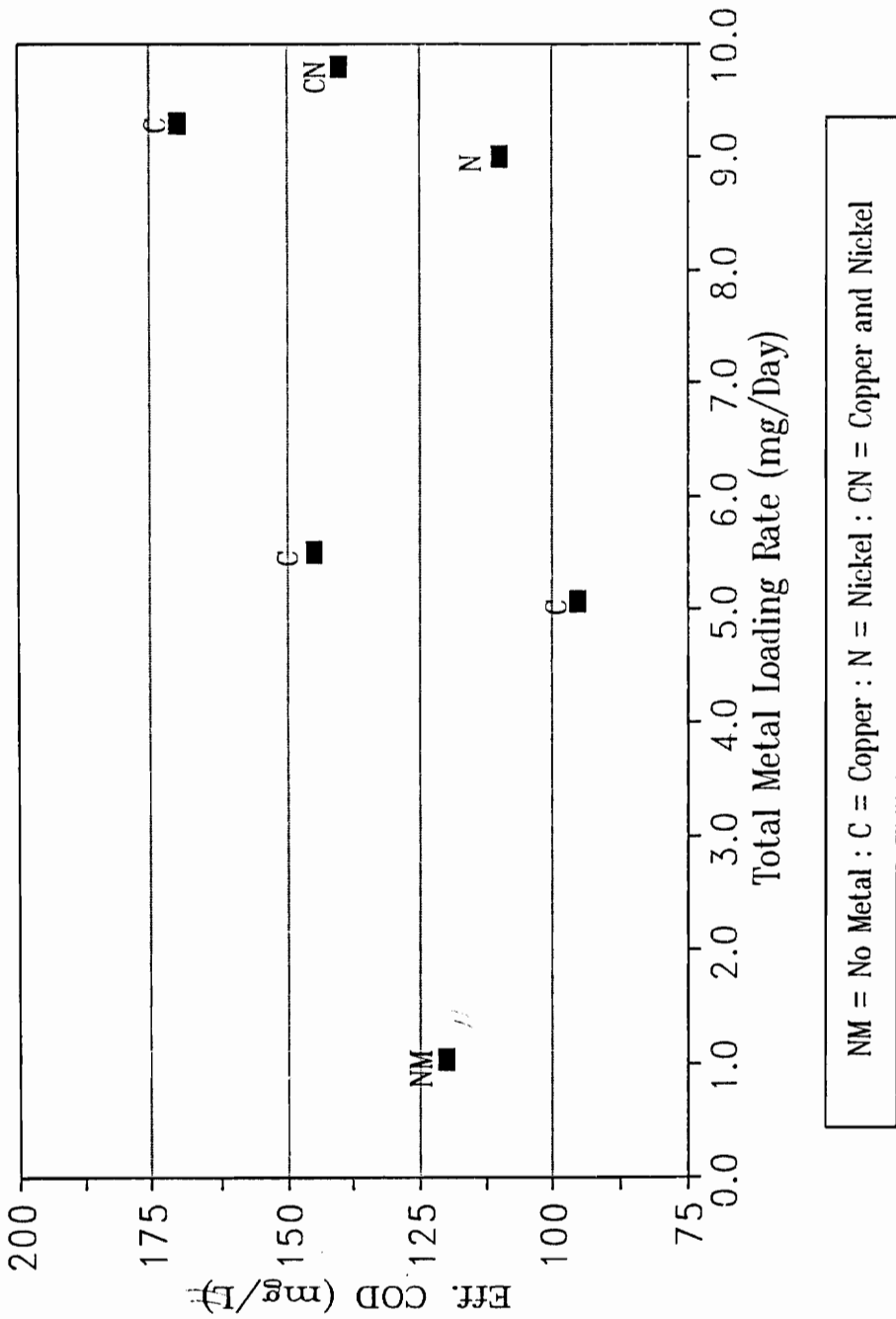


Figure 5.16 Variation of Eff. COD with TMLR

elements for studying the effects of metals on parameters like effluent COD. The variation of effluent COD did not show any significant changes with SUM or DM. From Figures 5.15 and 5.16, the effluent COD appears to show a very small increase at higher loading rates. But it is difficult to draw any definite conclusions from the Figures. Hence, it can be said the effluent COD was not affected by the addition of metals in the amounts described earlier.

The variation of effluent VSS with the different parameters are shown in Figures 5.17, 5.18, 5.19 and 5.20. The Figures show that higher loading rates, SUM, DM or STMLR did not significantly affect effluent VSS concentrations. During the early part of the research the effluent VSS values were high (as discussed in Chapter 4) and are indicated by the "NM" and "C" symbols.

The variation of SOUR with the different parameters are shown in Figures 5.21, 5.22, 5.23 and 5.24. From the Figures, it appears that the SOUR first decreases and then increases at higher values of the metal analysis parameters. There appears to be a correlation between SOUR and STMLR as shown by Figure 5.23. But considering the small range of the SOUR values in the Figures, it can be said that there were no significant changes in SOUR values.



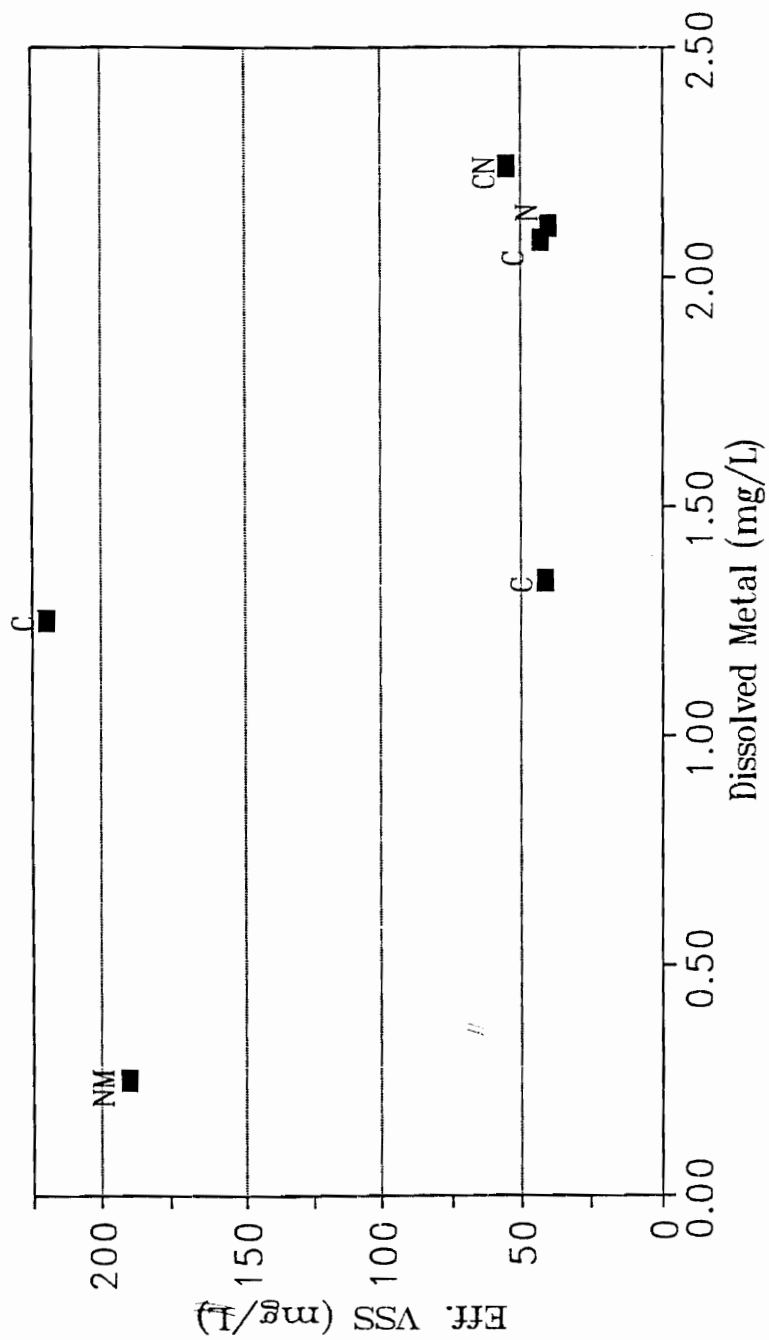
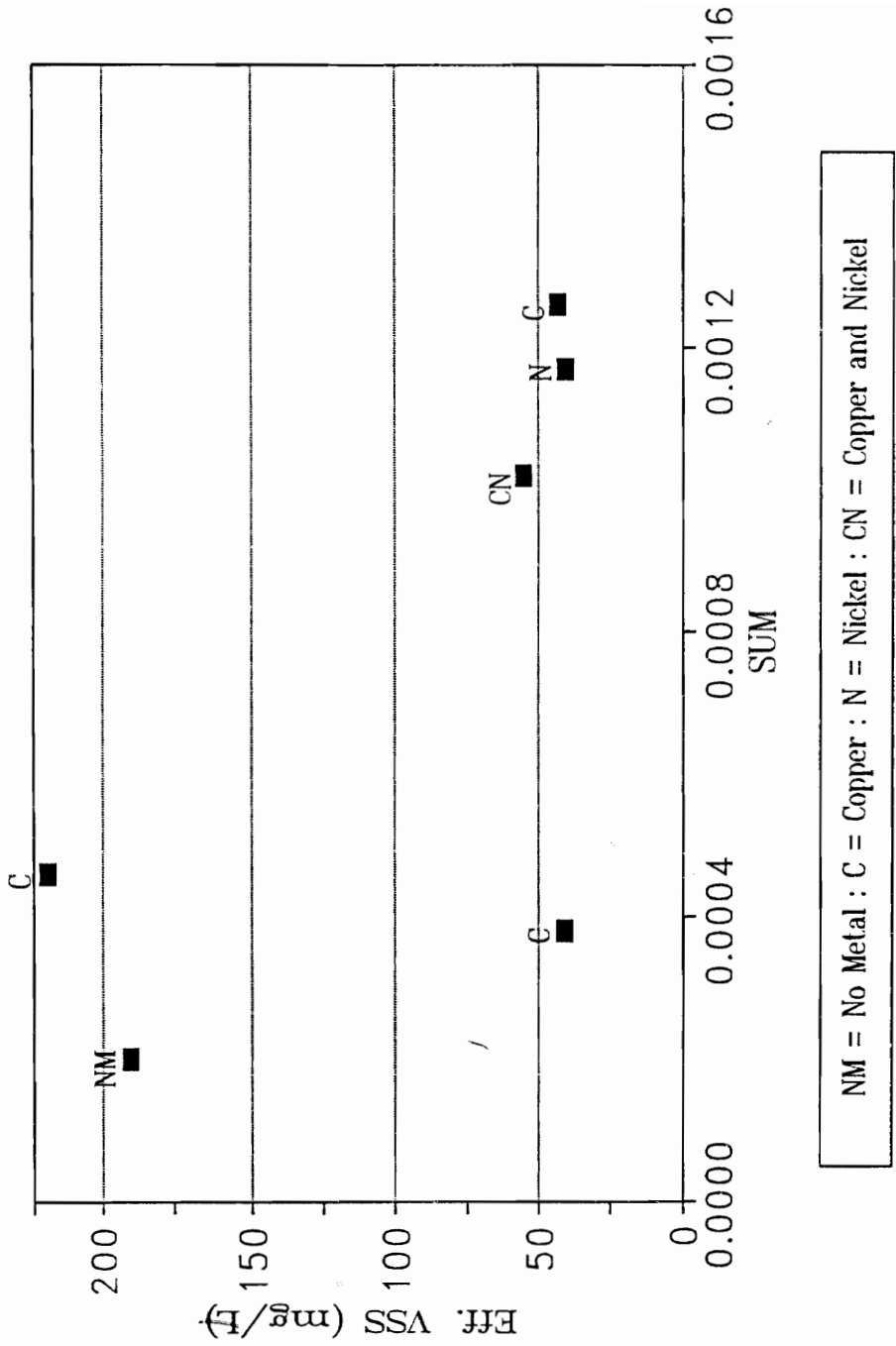
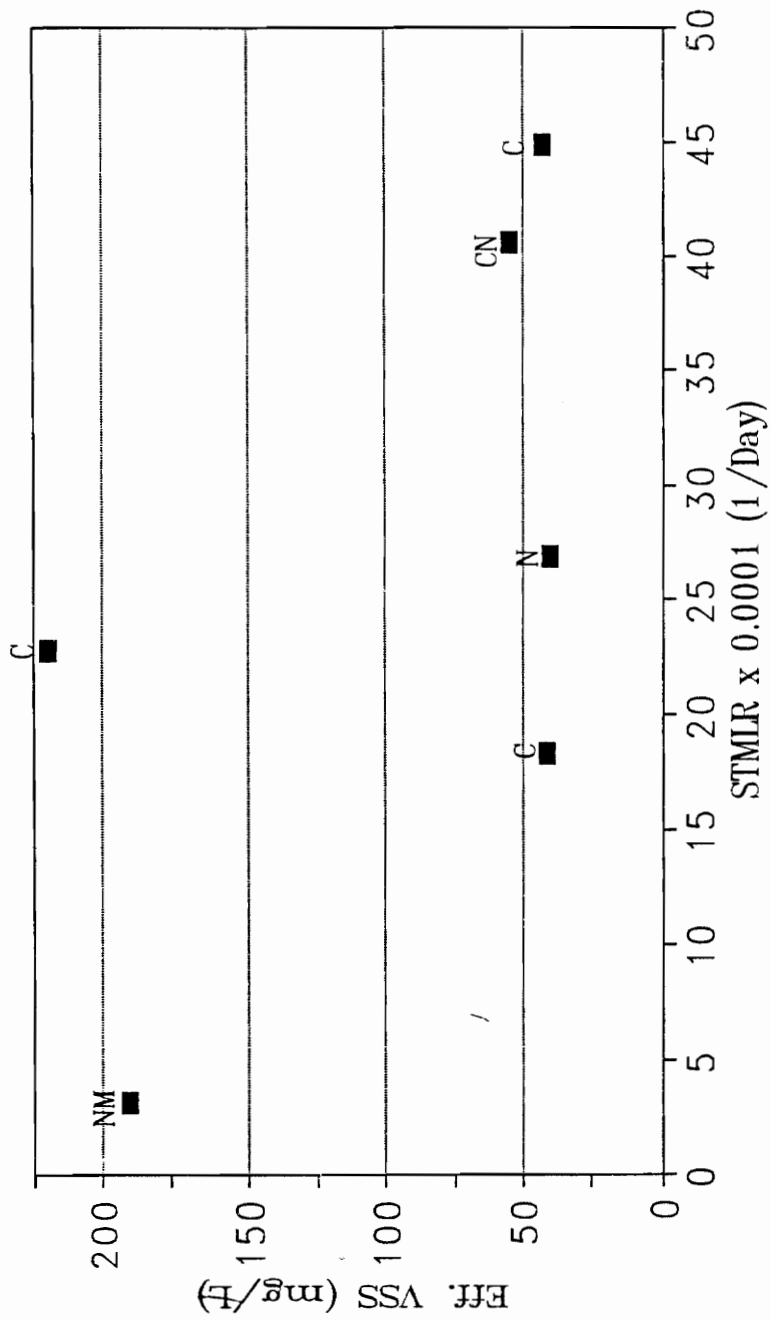


Figure 5.17 Variation of Eff. VSS with DM Concentration



NM = No Metal : C = Copper : N = Nickel : CN = Copper and Nickel

Figure 5.18 Variation of Eff. VSS with SUM



NM = No Metal : C = Copper : N = Nickel : CN = Copper and Nickel

Figure 5.19 Variation of Eff. VSS with STMLR

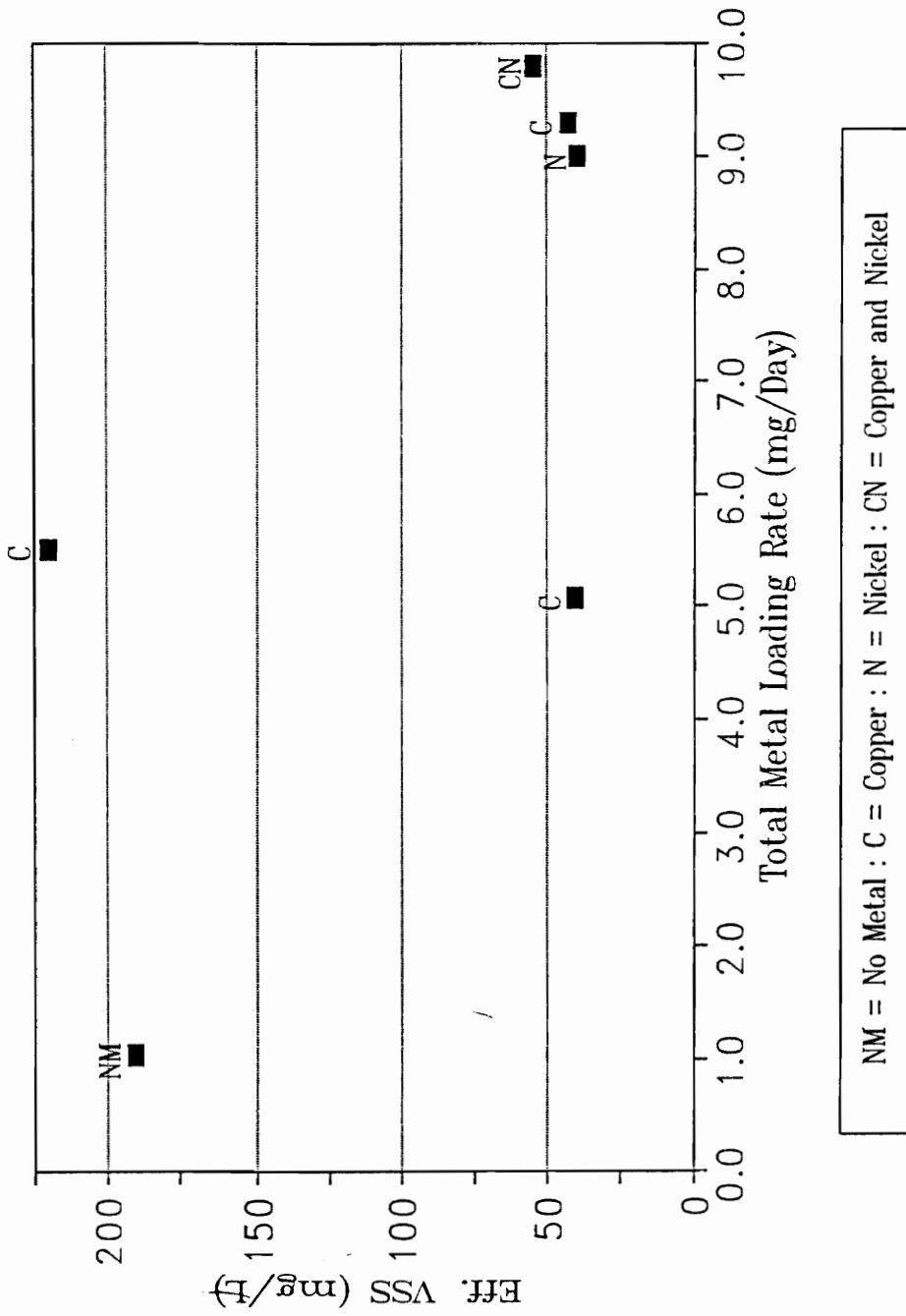
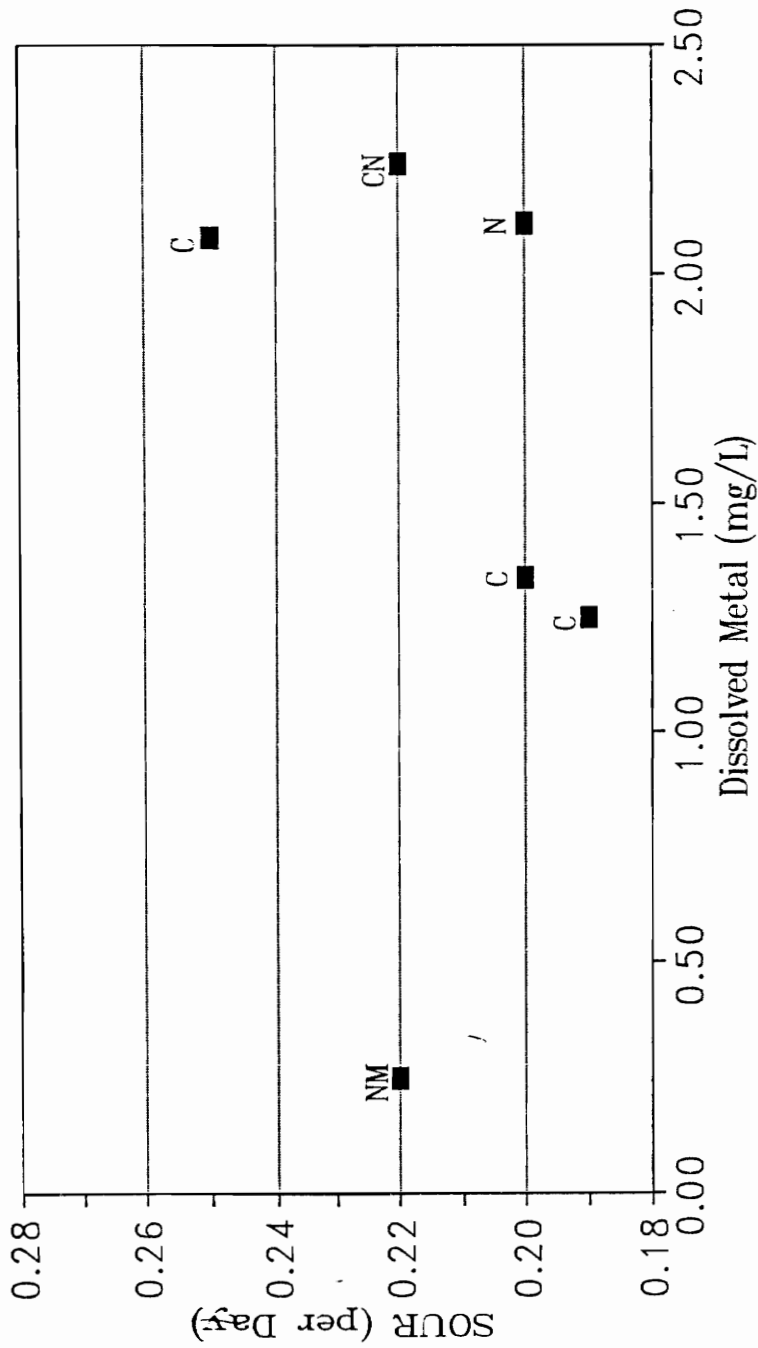
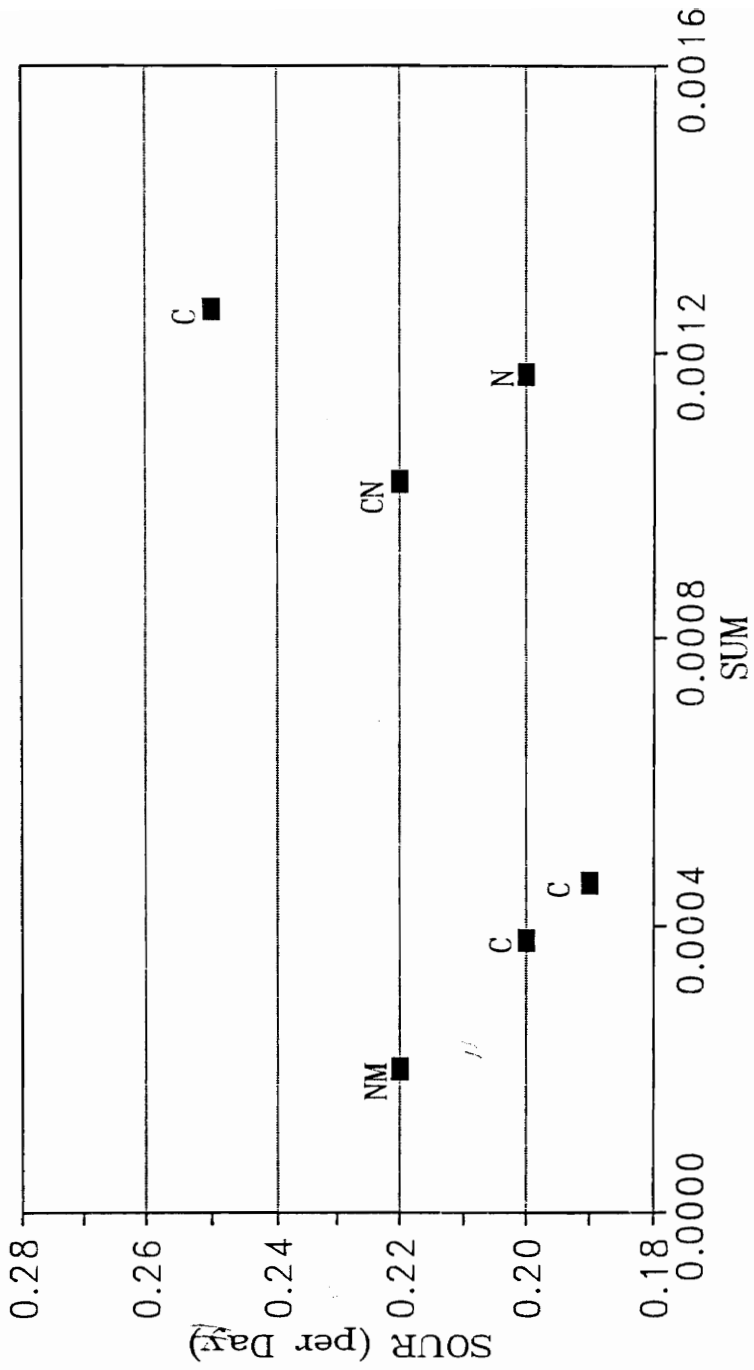


Figure 5.20 Variation of Eff. VSS with TMLR



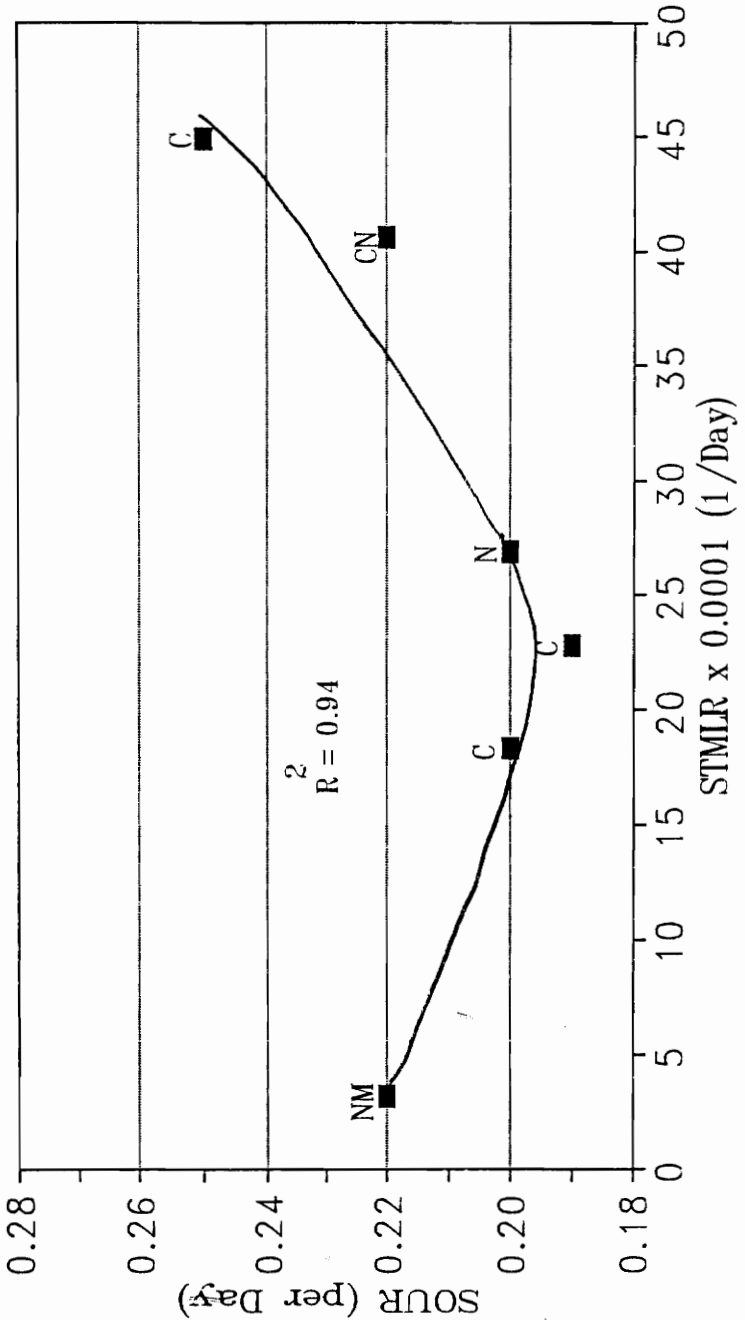
NM = No Metal : C = Copper : N = Nickel : CN = Copper and Nickel

Figure 5.21 Variation of SOUR with DM Concentration



NM = No Metal : C = Copper : N = Nickel : CN = Copper and Nickel

Figure 5.22 Variation of SOUR with SUM



NM = No Metal : C = Copper : N = Nickel : CN = Copper and Nickel

$$\text{SOUR} = 8671 \times (\text{STMLR})^2 - 36.2 \times (\text{STMLR}) + 0.23$$

Figure 5.23 Variation of SOUR with STMLR

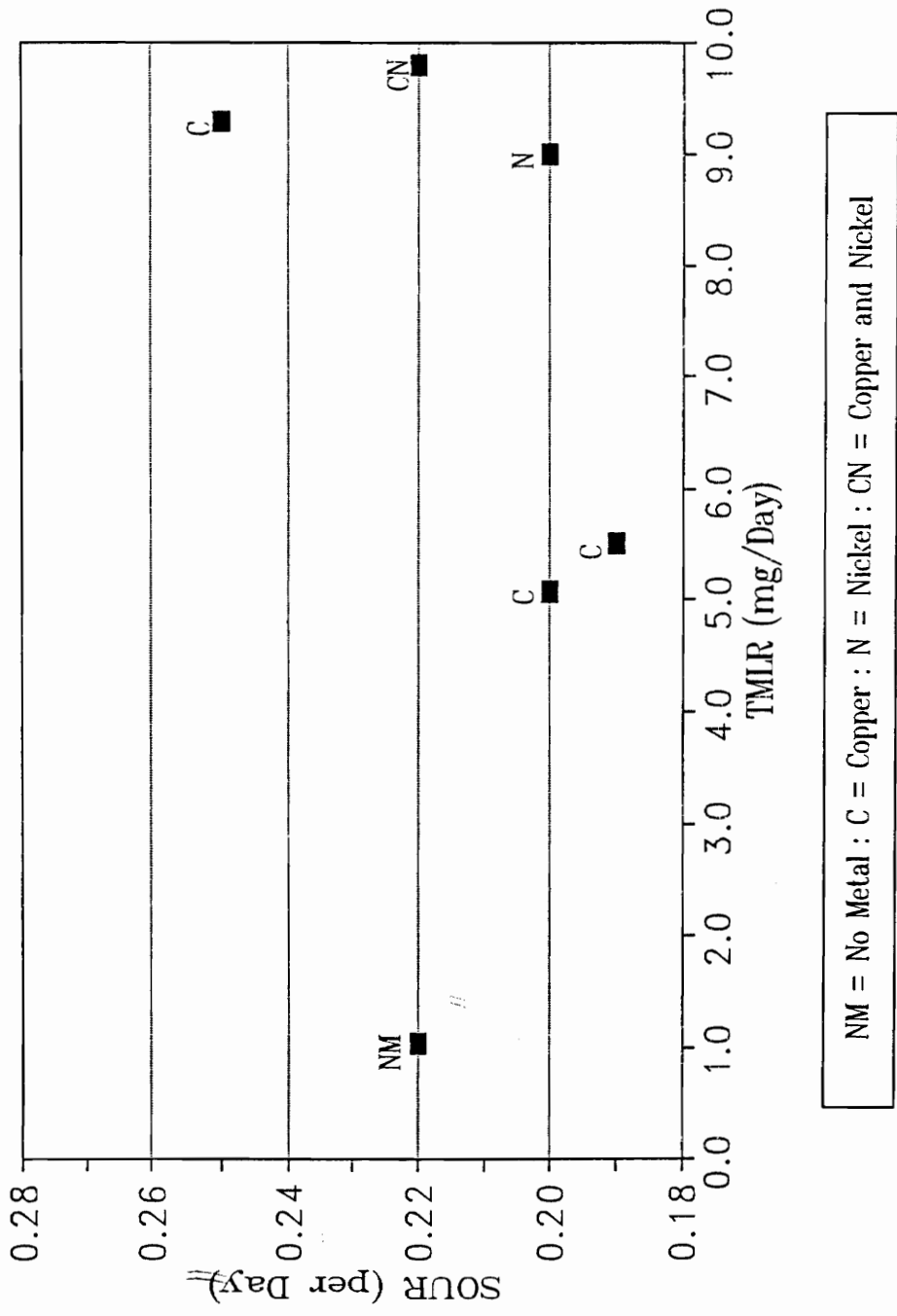


Figure 5.24 Variation of SOUR with TMLR



The variation of SVI with the different parameters are shown in Figures 5.25, 5.26, 5.27 and 5.28. From the Figures it can be seen that the SVI values were not significantly affected when either copper or nickel was added separately. But when a combination of copper and nickel was added, the SVI increased to 220 ml/g. This probably meant the combination of copper and nickel was toxic, which may have caused cell lysis or interfered with substrate metabolism and this would have interfered with settling.

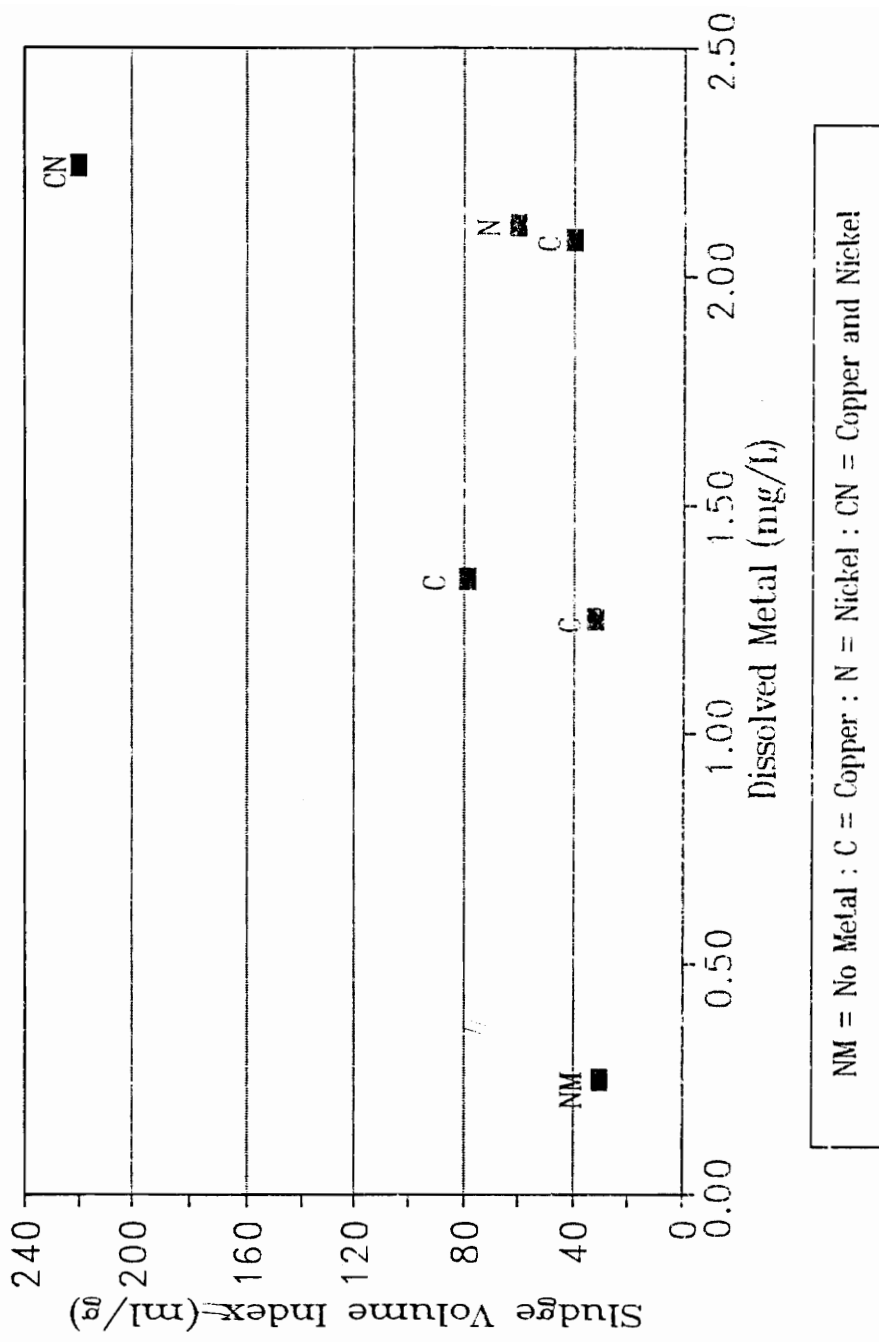


Figure 5.25 Variation of SVI with DM Concentration

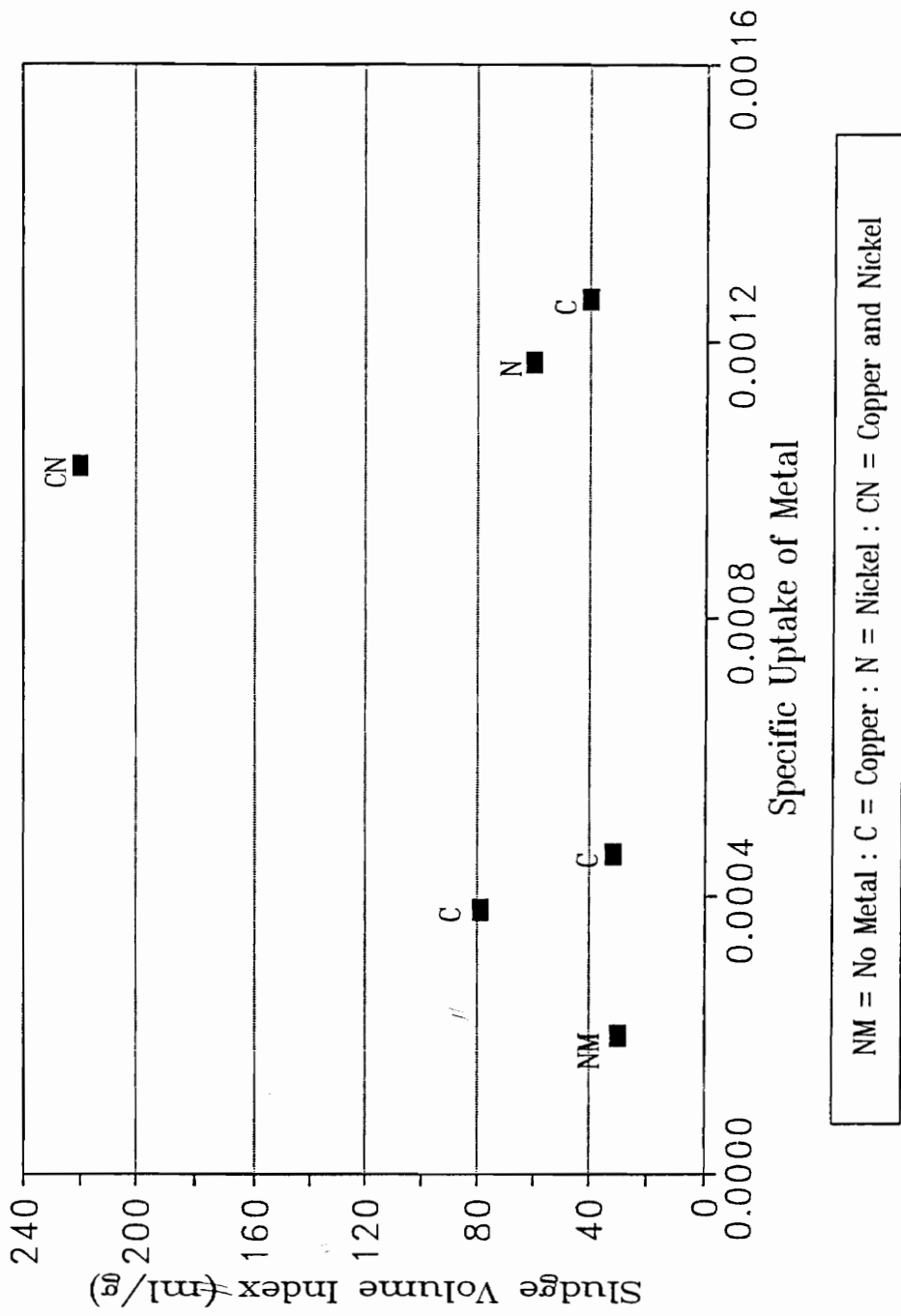
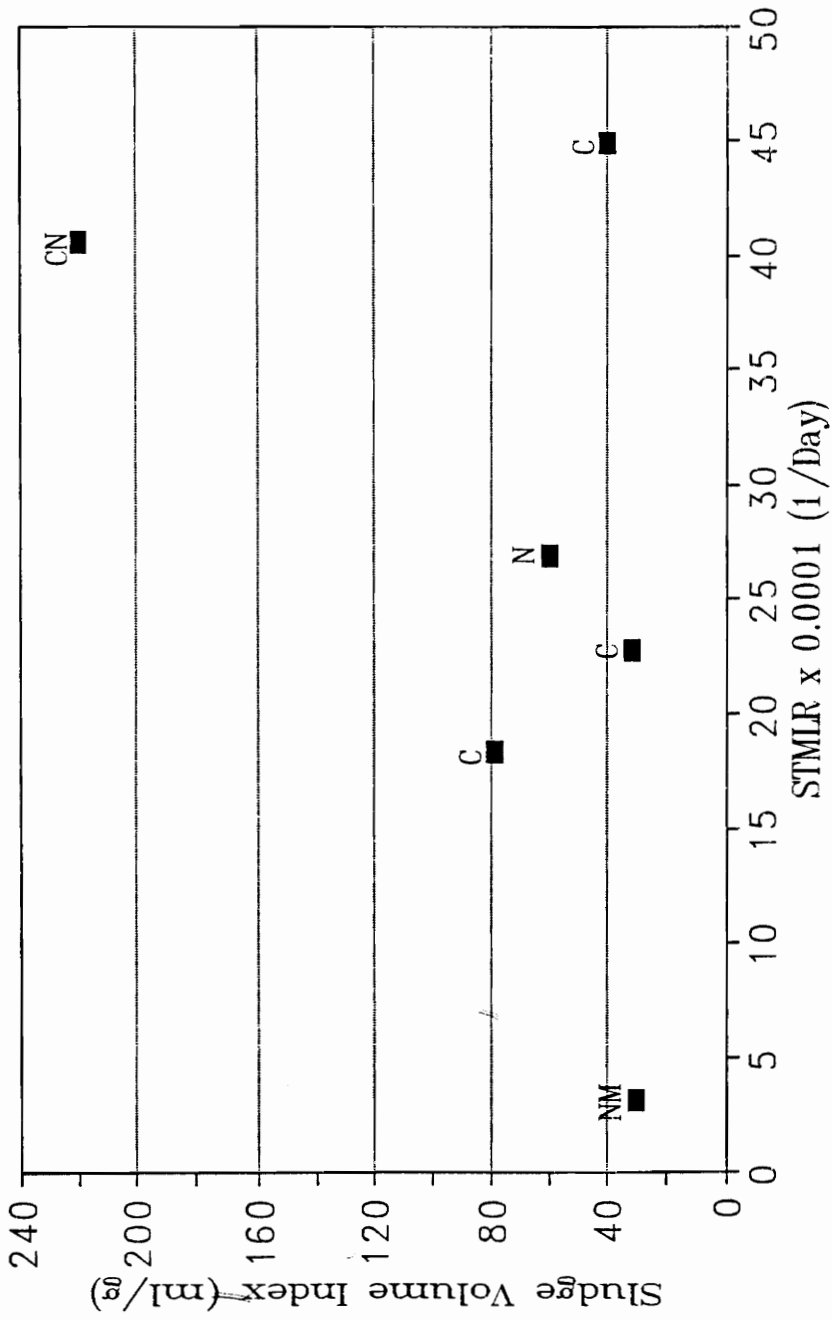
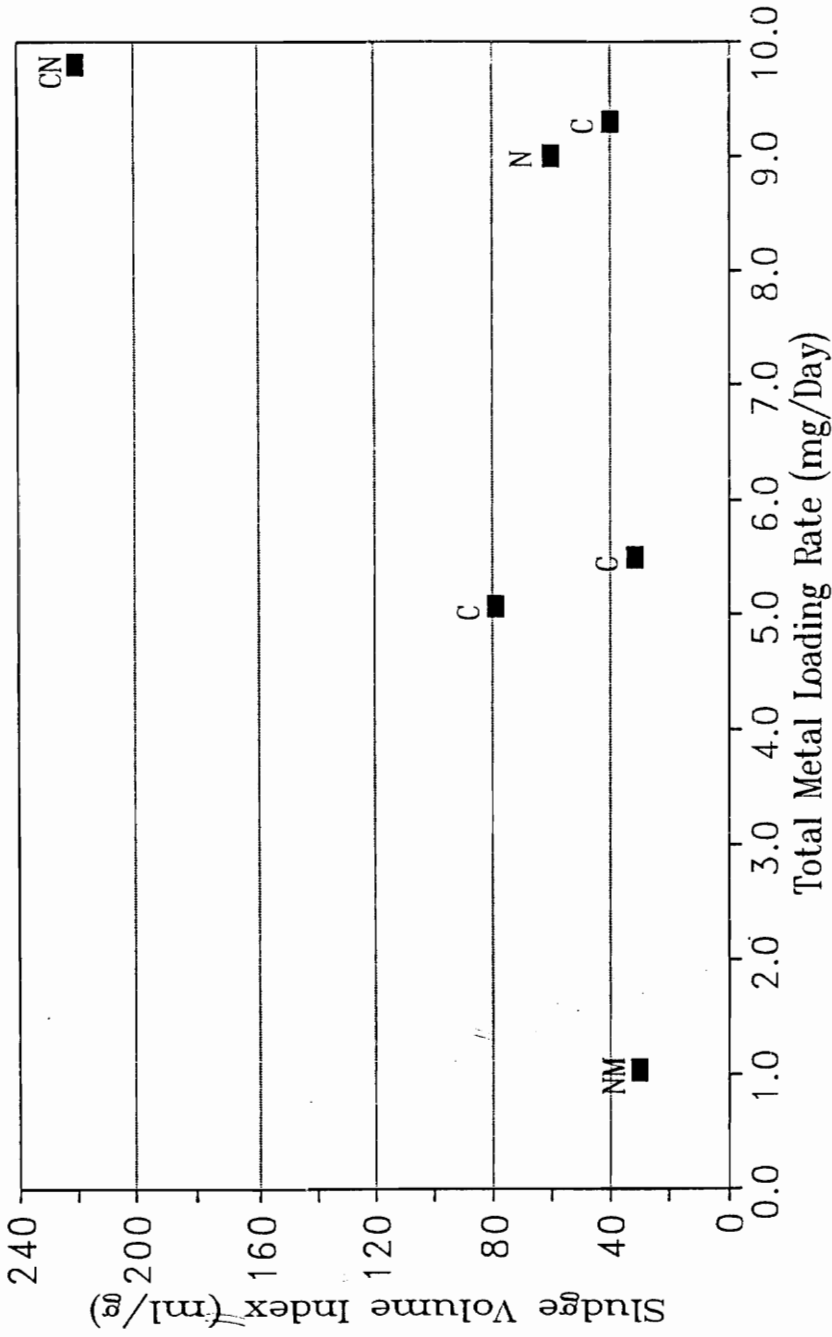


Figure 5.26 Variation of SVI with SUM



NM = No Metal : C = Copper : N = Nickel : CN = Copper and Nickel

Figure 5.27 Variation of SVI with STMLR



NM = No Metal : C = Copper : N = Nickel : CN = Copper and Nickel

Figure 5.28 Variation of SVI with TMLR

## CHAPTER 6

# CONCLUSIONS

The following parameters were used to analyze the data:

Specific Uptake of Metal (SUM), Dissolved Metal (DM), Total Metal Loading Rate (TMLR), and Specific Total Metal Loading Rate (STMLR).

The conclusions reached after the analysis of the research results are as follows :

1. The effluent COD and SS concentrations were not significantly affected by the presence of copper and nickel in activated sludge systems in the amounts added and observed during this investigation. The amounts added varied from 0.2 mg/L to 2 mg/L and concentrations as high as 6 mg/L were observed in the mixed liquor. It was possible that SOUR was affected by the STMLR, but the results were inconclusive.
2. The accumulation of metals in the activated sludge system was a function of the metal loading rate. The

accumulation was modeled using a second order equation.

3. The increase in dissolved metal concentrations in the mixed liquor were a linear function of the metal loading rates.
4. The uptake of copper and nickel by the activated sludge were independent of each other.
5. The settling characteristics improved significantly when copper or nickel was added separately but the combination of copper and nickel addition worsened the sludge settling characteristics.
6. Pretreatment of the influent feed for metals precipitation reduced the influent SS; but did not significantly reduce the influent COD.

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DAY	DATE	EFFLUENT COD		INFLUENT COD	
		EXPERIMENT	CELCO	EXPERIMENT	CELCO
1	05/31	76	36	1720	1967
3	06/02	68	90	2120	1764
4	06/03	79		1967	
5	06/04	87	67	1652	2044
7	06/06	150		2243	3174
9	06/08	153	114	1928	2700
11	06/10	153	149	1883	2184
13	06/12	168	170	2000	1840
15	06/14	136	90	2000	1997
17	06/16	124	51	2200	1843
19	06/18	128	55	2490	2350
21	06/20		70		2332
22	06/21	120		2400	
23	06/22		77		2249
25	06/24	116	115	2972	3456
27	06/26	173	110	2743	3078
29	06/28	196	117	2522	2500
31	06/30	212	110	2479	2509
33	07/02	189	114	2125	2113
35	07/04	130	144	2125	2129
38	07/07	136		3440	
39	07/08		123		3341
40	07/09	165	165	3423	3462
42	07/11	145	208	3580	3540
44	07/13	149	171	2400	2305
46	07/15	145	133	2321	2124
48	07/17	153	133	2321	2125
50	07/19	248	107	2090	1853
52	07/21	171	115	2929	2731
54	07/23	150	134	2597	2518
56	07/25	146	107	2278	2392
58	07/27	146	104	2197	2400
60	07/29	155	106	2359	2366
62	07/31	205	171	2379	1888

DAY	DATE	EFFLUENT COD		INFLUENT COD	
		EXPERIMENT	CELCO	EXPERIMENT	CELCO
64	08/02	175	49	2359	2600
66	08/04	175	85	2237	2481
68	08/06	161	53	2282	2517
70	08/08	172	82	2107	2185
72	08/10	175	65	1944	1740
74	08/12	151	67	2023	2063
76	08/14	156	62	2040	2075
78	08/16	135	61	2090	1865
80	08/18	131	81	2380	2261
82	08/20		44		2431
83	08/21	156		2240	
84	08/22		64		2404
86	08/24	156	64	2480	2640
88	08/26	140	45	2278	2481
90	08/28	134	70	2440	2661
92	08/30	141	64	2102	2582
94	09/01	129	56	2142	2182
96	09/03	92	72	2120	2160
98	09/05		96		2141
99	09/06	88		2240	
100	09/07		77		2174
101	09/08	98		2164	
102	09/09		58		2623
104	09/11	90	59	2479	2479
106	09/13	91	55	2539	2499
108	09/15	76	52	2520	2440
110	09/17	83	72	2499	2630
112	09/19	75	60	2539	2720
114	09/21	80	88	2760	2934
116	09/23	96	56	2640	2737
118	09/25	111	91	2420	2496
120	09/27	128	73	2600	2443
122	09/29	108	60	2440	2440
124	10/01	103	55	2539	2725
126	10/03	107	58	2460	2116

DAY	DATE	MLSS (=g/L)		MLVSS (=g/L)	
		EXPERIMENT	CELCO	EXPERIMENT	CELCO
1	05/31	4545	2954	3845	
3	06/02	4305	3265	3575	2690
4	06/03	4140		3365	
5	06/04	4020	2930	3175	2350
7	06/06	5020	2930	3540	2700
9	06/06	5091	3305	3518	2970
11	06/10	5463	3140	3354	2640
13	06/12	5100	3122	3440	2514
15	06/14	5499	2900	3437	2660
17	06/16	5481	2960	3222	2500
19	06/16	5185	2685	3162	2350
21	06/20		3090		2640
22	06/21	5500		3262	
23	06/22		3235		2675
25	06/24	5450	3155	3200	2635
27	06/26	5014	3530	2695	2980
29	06/26	5200	3350	2240	2690
31	06/30	5120	3560	2190	2900
33	07/02	5150	3060	2200	2490
35	07/04	4890	3180	2780	2570
36	07/07	5500		3400	
39	07/08		3760		2950
40	07/09	6150	4726	3550	3630
42	07/11	4890	4380	2780	3380
44	07/13	5600	3410	2580	3010
46	07/15	5580	3950	2420	3060
48	07/17	5850	4010	2350	3160
50	07/19	5820	3160	2100	2520
52	07/21	5530	3690	2250	2720
54	07/23	5550	3350	3370	2500
56	07/25	5550	2820	3370	2340
58	07/27	4970	2857	2640	2286
60	07/29	4720	3270	2580	2530
62	07/31	4680	2850	1840	2440

DAY	DATE	MLSS (=g/L)		MLVSS (=g/L)	
		EXPERIMENT	CELCO	EXPERIMENT	CELCO
64	08/02	4150	3560	2450	2690
66	08/04	4310	3440	2490	2990
68	08/06	3970	3450	2060	2860
70	08/08	3570	3740	2170	2750
72	08/10	3355	2830	1970	2430
74	08/12	2900	3330	1790	2450
76	08/14	2760	3140	1905	2720
78	08/16	3390	3350	2320	2770
80	08/18	3250	3390	2390	2770
82	08/20		3130		2560
83	08/21	2970		2030	
84	08/22		3230		2660
86	08/24	3460	4180	2530	3360
88	08/26	3200	3690	2300	2890
90	08/28	3280	3310	2440	2790
92	08/30	3490	3640	2460	3110
94	09/01	3475	3600	2325	3090
96	09/03	3480	3155	2550	2695
98	09/05		3420		2980
99	09/06	3930		2690	
100	09/07		3550		2960
101	09/08	3780		2490	
102	09/09		3770		3110
104	09/11	4140	4490	3120	3580
106	09/13	4440	4670	3200	3780
108	09/15	4710	4620	3200	3740
110	09/17	5310	3960	3140	3390
112	09/19	6580	4870	4100	3890
114	09/21	6770	4220	4310	3600
116	09/23	6420	4940	3940	3890
118	09/25	5270	4070	3250	3410
120	09/27	5550	3980	3470	3550
122	09/29	5460	4800	3610	3850
124	10/01	4410	4140	3170	3350
126	10/03	4880	4010	3330	3490

DAY	DATE	F/M (per day)		MLVSS/MLSS	
		EXPERIMENT	CELCO	EXPERIMENT	CELCO
1	05/31	0.22		0.85	
3	06/02	0.30	0.33	0.83	0.82
4	06/03	0.29		0.61	
5	06/04	0.23	0.43	0.79	0.80
7	06/06	0.32	0.59	0.71	0.92
9	06/08	0.27	0.45	0.69	0.90
11	06/10	0.28	0.41	0.61	0.84
13	06/12	0.29	0.37	0.67	0.81
15	06/14	0.29	0.38	0.63	0.92
17	06/16	0.34	0.37	0.59	0.84
19	06/18	0.39	0.50	0.61	0.81
21	06/20		0.44		0.85
22	06/21	0.37		0.59	
23	06/22		0.42		0.83
25	06/24	0.45	0.66	0.59	0.84
27	06/26	0.51	0.52	0.54	0.84
29	06/28	0.56	0.46	0.43	0.80
31	06/30	0.57	0.45	0.43	0.79
33	07/02	0.48	0.42	0.43	0.81
35	07/04	0.38	0.41	0.57	0.81
38	07/07	0.51		0.62	
39	07/08		0.59		0.76
40	07/09	0.48	0.48	0.56	0.77
42	07/11	0.64	0.52	0.57	0.77
44	07/13	0.47	0.38	0.46	0.88
46	07/15	0.48	0.35	0.43	0.77
48	07/17	0.49	0.34	0.40	0.79
50	07/19	0.44	0.35	0.40	0.83
52	07/21	0.65	0.50	0.41	0.74
54	07/23	0.39	0.50	0.61	0.75
56	07/25	0.34	0.51	0.61	0.83
58	07/27	0.42	0.52	0.53	0.80
60	07/29	0.46	0.47	0.55	0.77
62	07/31	0.65	0.39	0.39	0.86

DAY	DATE	F/M (per day)		MLVSS/MLSS	
		EXPERIMENT	CELCO	EXPERIMENT	CELCO
64	08/02	0.48	0.48	0.59	0.76
66	08/04	0.45	0.41	0.58	0.87
68	08/06	0.55	0.44	0.52	0.83
70	08/08	0.49	0.40	0.61	0.74
72	08/10	0.49	0.36	0.59	0.86
74	08/12	0.57	0.42	0.62	0.74
76	08/14	0.54	0.38	0.69	0.87
78	08/16	0.45	0.34	0.68	0.83
80	08/18	0.50	0.41	0.74	0.82
82	08/20		0.47		0.82
83	08/21	0.55		0.68	
84	08/22		0.45		0.82
86	08/24	0.49	0.39	0.73	0.80
88	08/26	0.50	0.43	0.72	0.78
90	08/28	0.50	0.48	0.74	0.84
92	08/30	0.43	0.42	0.70	0.85
94	09/01	0.46	0.35	0.67	0.86
96	09/03	0.42	0.40	0.73	0.85
98	09/05		0.36		0.87
99	09/06	0.42		0.68	
100	09/07		0.37		0.83
101	09/08	0.43		0.66	
102	09/09		0.42		0.82
104	09/11	0.40	0.35	0.75	0.80
106	09/13	0.40	0.33	0.72	0.81
108	09/15	0.39	0.33	0.68	0.81
110	09/17	0.40	0.39	0.59	0.86
112	09/19	0.31	0.35	0.62	0.80
114	09/21	0.32	0.41	0.64	0.85
116	09/23	0.34	0.35	0.61	0.79
118	09/25	0.37	0.37	0.62	0.84
120	09/27	0.37	0.34	0.63	0.89
122	09/29	0.34	0.32	0.66	0.80
124	10/01	0.40	0.41	0.72	0.81
126	10/03	0.37	0.30	0.68	0.87

		CELCO		
DAY	DATE	INFLUENT pH	EFFLUENT pH	MIXED LIQUOR pH
1	05/31	4.72	8.30	8.33
3	06/02	4.57	8.34	
4	06/03			
5	06/04	4.45	7.91	8.12
7	06/06	4.29	8.00	8.05
9	06/08	4.33	7.95	7.72
11	06/10	4.50	8.04	8.14
13	06/12	4.55	8.06	8.25
15	06/14	4.58	8.20	8.37
17	06/16	4.81	8.10	8.40
19	06/18			
21	06/20	4.51	8.08	8.09
22	06/21			
23	06/22	4.53	7.99	8.02
25	06/24	4.34	8.09	8.10
27	06/26	4.40	7.77	7.90
29	06/28	4.36	7.91	8.08
31	06/30	4.74	8.24	8.25
33	07/02			
35	07/04	4.10	8.00	8.06
38	07/07			
39	07/08	4.46	8.01	8.36
40	07/09	4.69	8.00	8.03
42	07/11	4.60	7.18	8.02
44	07/13	4.32	8.22	8.32
46	07/15	4.58	8.21	8.32
48	07/17	4.42	7.95	8.15
50	07/19	4.95	8.25	8.46
52	07/21	4.31	8.40	8.40
54	07/23	4.48	8.27	8.33
56	07/25	4.47	8.35	8.50
58	07/27	4.55	8.32	8.45
60	07/29	4.60	8.17	8.30
62	07/31	4.91	8.33	8.55

		CELCO		
DAY	DATE	INFLUENT pH	EFFLUENT pH	MIXED LIQUOR pH
64	08/02	4.41	8.30	8.35
66	08/04	4.53	8.28	8.35
68	08/06	4.42	8.43	8.34
70	08/08	4.73	8.39	8.30
72	08/10	5.10	8.41	8.51
74	08/12	4.82	8.27	8.34
76	08/14	4.33	8.37	8.40
78	08/16		8.29	8.40
80	08/18			
82	08/20	4.41	8.24	8.07
83	08/21			
84	08/22	4.40	8.34	8.37
86	08/24	4.48	8.29	8.34
88	08/26	4.47	8.33	8.42
90	08/28	4.31	8.27	8.29
92	08/30	4.40	8.16	8.21
94	09/01	4.48	8.22	8.27
96	09/03			
98	09/05	4.40	8.19	8.29
99	09/06			
100	09/07	4.32	8.14	8.24
101	09/08			
102	09/09		8.11	8.22
104	09/11	4.38	8.19	8.28
106	09/13			
108	09/15	4.41	8.18	8.22
110	09/17	4.45	8.09	8.22
112	09/19	4.49	8.12	7.97
114	09/21	4.44	8.17	8.22
116	09/23	4.46	8.14	8.24
118	09/25	4.41	8.12	8.12
120	09/27	4.39	8.09	8.02
122	09/29	4.47	8.21	8.29
124	10/01	4.51	8.10	8.23
126	10/03	4.50	8.04	7.99



## EXPERIMENT

DAY	DATE	INFLUENT pH	EFFLUENT pH	MIXED LIQUOR pH
1	05/31	7.45	8.04	8.29
3	06/02	6.03	8.32	8.44
4	06/03	6.05	8.22	8.27
5	06/04	6.05	8.19	8.25
7	06/06	6.00	7.97	8.08
9	06/08	6.40	8.00	7.95
11	06/10	6.67	7.85	8.16
13	06/12	6.08	7.90	8.19
15	06/14	5.97	8.10	8.22
17	06/16	6.20	8.00	8.12
19	06/18	6.18	8.15	8.23
21	06/20			
22	06/21	6.12	8.11	8.18
23	06/22			
25	06/24	6.28	7.95	8.05
27	06/26	6.11	7.86	8.00
29	06/28	6.12	8.02	8.22
31	06/30	6.08	8.10	8.19
33	07/02	6.00	8.11	8.21
35	07/04	6.05	8.15	8.25
38	07/07	6.10	8.00	8.18
39	07/08			
40	07/09	4.60	7.80	7.99
42	07/11	4.61	8.01	8.11
44	07/13	4.55	8.10	8.22
46	07/15	4.54	8.30	8.35
48	07/17	4.50	8.12	8.29
50	07/19	4.52	7.98	8.19
52	07/21	4.56	8.21	8.25
54	07/23	4.55	8.18	8.28
56	07/25	4.45	8.30	8.33
58	07/27	4.52	8.25	8.34
60	07/29	4.50	8.32	8.41
62	07/31	4.40	8.23	8.33

		EXPERIMENT		
DAY	DATE	INFLUENT pH	EFFLUENT pH	MIXED LIQUOR pH
64	08/02	4.44	8.22	8.27
66	08/04	4.48	8.37	8.40
68	08/06	4.53	8.40	8.40
70	08/08	4.55	8.29	8.33
72	08/10	4.60	8.06	8.30
74	08/12	4.57	8.10	8.15
76	08/14	4.50	8.30	8.27
78	08/16	4.55	8.22	8.29
80	08/18	4.45	8.23	8.40
82	08/20			
83	08/21	4.53	8.08	8.30
84	08/22			
86	08/24	4.52	8.34	8.33
88	08/26	4.55	8.27	8.39
90	08/28	4.59	8.24	8.28
92	08/30	4.50	8.05	8.11
94	09/01	4.51	8.10	8.19
96	09/03	4.55	8.24	8.25
98	09/05			
99	09/06	4.46	8.11	8.22
100	09/07			
101	09/08	4.56	8.04	8.28
102	09/09			
104	09/11	4.51	7.98	8.09
106	09/13	4.55	8.05	8.15
108	09/15	4.40	8.02	8.05
110	09/17	4.45	8.13	8.13
112	09/19	4.46	7.91	7.99
114	09/21	4.47	8.10	8.19
116	09/23	4.51	8.08	8.09
118	09/25	4.44	8.10	8.11
120	09/27	4.60	7.90	8.00
122	09/29	4.57	7.85	8.05
124	10/01	4.55	8.09	8.10
126	10/03	4.52	8.11	8.12

DAY	DATE	INFLUENT SS (mg/L)		INFLUENT VSS (mg/L)	
		EXPERIMENT	CELCO	EXPERIMENT	CELCO
1	05/31	27		15	
3	06/02	63	66	24	47
4	06/03	28		13	
5	06/04	27	73	13	46
7	06/08	20	104	14	97
9	06/08	32	190	22	150
11	06/10	102	69	70	63
13	06/12	28	67	13	56
15	06/14	113	37	95	30
17	06/16	96	277	60	223
19	06/18	43	70	35	49
21	06/20		101		89
22	06/21	35		26	
23	06/22		403		349
25	06/24	123	121	47	98
27	06/26	12	40	7	28.6
29	06/28	19	21	11	15
31	06/30	50	297	36	250
33	07/02	14	103	12	100
35	07/04	24	73	12	
38	07/07	16		10	
39	07/08		224		183
40	07/09	20	632	16	541
42	07/11	24	123	47	104
44	07/13	63	70	40	59
46	07/15	22	635	14	562
48	07/17	33	86	21	69
50	07/19	36	76	23	68
52	07/21	67	92	44	73
54	07/23	30	246	19	218
56	07/25	30	224	19	185
58	07/27	95	271	77	220
60	07/29	22	423	13	355
62	07/31	23	55	13	51

DAY	DATE	INFLUENT SS (=g/L)		INFLUENT VSS (=g/L)	
		EXPERIMENT	CELCO	EXPERIMENT	CELCO
64	08/02	44	152	35	131
66	08/04	36	802	27	718
68	08/06	23	61	14	42
70	08/08	50	102	30	78
72	08/10	59	125	44	54
74	08/12	47	97	32	77
76	08/14	22	38	14	34
78	08/16	36		24	
80	08/18	56	69	32	57
82	08/20		81		67
83	08/21	44		26	
84	08/22		51		42
86	08/24	45	86	27	59
88	08/26	23	89	13	72
90	08/28	60	71	37	60
92	08/30	34	54	13	47
94	09/01	35	59	17	44
96	09/03	49	65	28	43
98	09/05		33		26
99	09/06	81		65	
100	09/07		36		25
101	09/08	77		58	
102	09/09		26		18
104	09/11	102	156	79	125
106	09/13	43	65	24	40
108	09/15	43	72	24	63
110	09/17	47	61	29	50
112	09/19	47	146	27	110
114	09/21	74	57	39	46
116	09/23	59	106	32	63
118	09/25	37	32	19	19
120	09/27	56	36	23	25
122	09/29	113	131	90	100
124	10/01	35	65	20	40
126	10/03	66	60	33	51

DAY	DATE	OUR (mg/L/day)		SOUR (mg O / mg MLVSS/day)	
		EXPERIMENT	CELCO	EXPERIMENT	CELCO
1	05/31	576	504	0.15	
3	06/02	576	432	0.16	0.16
4	06/03	580		0.17	
5	06/04	547	547	0.17	0.23
7	06/06	600	403	0.17	0.15
9	06/08	504	504	0.14	0.17
11	06/10	576	518	0.17	0.20
13	06/12	576	432	0.17	0.17
15	06/14	576	360	0.17	0.14
17	06/16	597	346	0.19	0.14
19	06/18	638	475	0.20	0.20
21	06/20		619		0.23
22	06/21	720		0.22	
23	06/22		475		0.18
25	06/24	687	706	0.21	0.27
27	06/26	495	691	0.18	0.23
29	06/28	297	677	0.13	0.25
31	06/30	342	331	0.16	0.12
33	07/02	450	648	0.20	0.26
35	07/04	355		0.13	
38	07/07	522		0.15	
39	07/08		547		0.19
40	07/09	698	562	0.20	0.15
42	07/11	360	475	0.13	0.14
44	07/13	480	432	0.19	0.14
46	07/15	480	302	0.20	0.10
48	07/17	443	331	0.19	0.10
50	07/19	387	432	0.16	0.16
52	07/21	411	475	0.18	0.17
54	07/23	597	475	0.18	0.19
56	07/25	597	461	0.18	0.20
58	07/27	576	504	0.22	0.22
60	07/29	480	432	0.19	0.17
62	07/31	370	360	0.20	0.15

DAY	DATE	OUR (mg/L/day)		SOUR (mg O /mg MLVSS/day)	
		EXPERIMENT	CELCO	EXPERIMENT	CELCO
64	08/02	432	432	0.18	0.16
66	08/04	504	403	0.20	0.13
68	08/06	560	490	0.27	0.17
70	08/08	761	432	0.35	0.16
72	08/10	504		0.26	
74	08/12	400	432	0.22	0.18
76	08/14	360	547	0.19	0.20
78	08/16	432	475	0.19	0.17
80	08/18	540	346	0.23	0.12
82	08/20		432		0.17
83	08/21	550		0.27	
84	08/22		504		0.19
86	08/24	702	475	0.28	0.14
88	08/26	684	446	0.30	0.15
90	08/28	480	907	0.20	0.33
92	08/30	368	590	0.15	0.19
94	09/01	514	634	0.22	0.21
96	09/03	560	576	0.22	0.21
98	09/05		403		0.14
99	09/06	403		0.15	
100	09/07		403		0.14
101	09/08	540		0.22	
102	09/09		518		0.17
104	09/11	552	504	0.18	0.14
106	09/13	486	475	0.15	0.13
108	09/15	486	576	0.15	0.15
110	09/17	712	706	0.23	0.21
112	09/19	810	763	0.20	0.20
114	09/21	864	576	0.20	0.16
116	09/23	878	792	0.22	0.20
118	09/25	821	664	0.25	0.19
120	09/27	630	589	0.18	0.17
122	09/29	594	576	0.16	0.15
124	10/01	580	576	0.18	0.17
126	10/03	705	643	0.21	0.18

DAY	DATE	SVI (ml/g)		ZSV (F-r-r)	
		EXPERIMENT	CELCO	EXPERIMENT	CELCO
1	05/31	229	254	0.27	0.57
3	06/02	259	101	0.17	1.52
4	06/03	272		0.19	
5	06/04	224	90	0.23	1.66
7	06/08	155	96	0.5	1.63
9	06/08	63	94	1.53	1.56
11	06/10	42	105	1.74	1.52
13	06/12	39	120	1.81	1.41
15	06/14	33		1.86	
17	06/16	35	118	1.83	1.47
19	06/18	33	120	1.88	1.48
21	06/20		251		0.51
22	06/21	30		1.89	
23	06/22		111		1.45
25	06/24	29	269	1.9	0.34
27	06/26	32	242	1.9	0.33
29	06/28	29	254	1.92	0.11
31	06/30	37	270	1.84	0.09
33	07/02	38	289	1.82	0.26
35	07/04	41	101	1.81	1.54
38	07/07	155		0.34	
39	07/08		258		0.07
40	07/09	149	204	0.19	0.08
42	07/11	40	220	1.82	0.08
44	07/13	38	274	1.79	0.15
46	07/15	32	246	1.86	0.07
48	07/17	31	172	1.86	0.70
50	07/19	27	130	1.91	1.34
52	07/21	29	263	1.91	0.07
54	07/23	155	280	0.32	0.14
56	07/25	155	339	0.32	0.10
58	07/27	36	100	1.86	1.62
60	07/29	31	83	1.94	1.65
62	07/31	29	105	1.96	1.58

DAY	DATE	SVI ( $\frac{m}{s}$ )		ZSV ( $\frac{F}{v}$ )	
		EXPERIMENT	CELCO	EXPERIMENT	CELCO
64	08/02	37	93	1.91	1.52
66	08/04	34	90	1.94	1.56
68	08/06	40	188	1.90	0.79
70	08/08	35	222	1.98	0.38
72	08/10	43			
74	08/12	55	219	1.90	0.61
76	08/14	80	92	1.77	1.61
78	08/16	83	99	1.63	1.52
80	08/18	86	165	1.63	1.00
82	08/20		265		0.38
83	08/21	71			
84	08/22		257		0.38
86	08/24	95	189	1.52	0.48
88	08/26	103	247	1.52	0.20
90	08/28	117	275	1.39	0.20
92	08/30	218	271	0.54	0.03
94	09/01	222	250	0.52	0.23
96	09/03	106	241	1.43	0.54
98	09/05		238		0.42
99	09/06	78		1.57	
100	09/07		218		0.51
101	09/08	82		1.56	
102	09/09		221		0.37
104	09/11	77	196	1.54	0.27
106	09/13	81	182	1.45	0.34
108	09/15	161	184	0.54	0.34
110	09/17	168	218	0.25	0.31
112	09/19	137	180	0.23	0.28
114	09/21	133	209	0.23	0.27
116	09/23	137	185	0.27	0.19
118	09/25	153	200		
120	09/27	77	217		
122	09/29	64	183	1.47	0.27
124	10/01	60	210	1.66	0.29
125	10/03	61	209	1.58	0.36



DAY	DATE	COPPER (in mg/L) CELCO			
		TOTAL Cu in INFLUENT	TOTAL Cu in EFFLUENT	TOTAL Cu in MIX LIQUOR	SOL Cu in MIX LIQUOR
1	05/31	0.32	0.33		
3	06/02	0.38	0.32		
4	06/03				
5	06/04	0.31	0.35		
7	06/06	0.38	0.32		
9	06/08	0.34	0.28		
11	06/10	0.36	0.3	1.05	0.29
13	06/12	0.33	0.31	0.98	0.3
15	06/14	0.32	0.29	0.99	0.28
17	06/16	0.3	0.29	0.88	0.28
19	06/18	0.34	0.3	0.9	0.3
21	06/20	0.33	0.33	0.92	0.31
22	06/21				
23	06/22	0.36	0.31	0.95	0.3
25	06/24	0.33	0.34	0.89	0.32
27	06/26	0.27	0.28	0.9	0.25
29	06/28	0.24	0.24	0.85	0.22
31	06/30	0.25	0.24	0.81	0.23
33	07/02	0.28	0.25	0.79	0.24
35	07/04	0.3	0.27	0.78	0.25
38	07/07				
39	07/08	0.33	0.3	0.81	0.29
40	07/09	0.42	0.36	0.82	0.34
42	07/11	0.4	0.4	0.96	0.38
44	07/13	0.36	0.39	0.99	0.36
46	07/15	0.34	0.35	1	0.33
48	07/17	0.28	0.31	0.95	0.25
50	07/19	0.4	0.33	0.89	0.31
52	07/21	0.41	0.38	1.04	0.36
54	07/23	0.37	0.36	1	0.34
56	07/25	0.4	0.39	1.05	0.36
58	07/27	0.33	0.39	0.95	0.33
60	07/29	0.36	0.38	0.78	0.34
62	07/31	0.38	0.37	0.86	0.36

DAY	DATE	COPPER (in mg/L)			
		CELCO			
		TOTAL Cu in INFLUENT	TOTAL Cu in EFFLUENT	TOTAL Cu in MIX LIQUOR	SOL Cu in MIX LIQUOR
64	08/02	0.4	0.39	0.88	0.37
66	08/04	0.38	0.38	1.02	0.36
68	08/06	0.33	0.34	1.05	0.32
70	08/08	0.34	0.33	0.99	0.31
72	08/10	0.39	0.31	1	0.34
74	08/12	0.3	0.32	0.92	0.29
76	08/14	0.34	0.33	0.93	0.31
78	08/16	0.33	0.31	0.96	0.29
80	08/18	0.25	0.27	0.9	0.25
82	08/20	0.28	0.25	0.78	0.24
83	08/21				
84	08/22	0.27	0.25	0.72	0.24
86	08/24	0.4	0.36	0.82	0.34
88	08/26	0.48	0.4	1.03	0.4
90	08/28	0.5	0.41	1.1	0.44
92	08/30	0.44	0.45	1.12	0.42
94	09/01	0.41	0.42	1.01	0.4
96	09/03	0.33	0.36	1.06	0.34
98	09/05	0.28	0.3	0.95	0.29
99	09/06				
100	09/07	0.29	0.28	0.88	0.27
101	09/08				
102	09/09	0.27	0.24	0.81	0.23
104	09/11	0.22	0.24	0.78	0.2
106	09/13	0.24	0.27	0.68	0.22
108	09/15	0.38	0.3	0.7	0.3
110	09/17	0.33	0.33	0.83	0.31
112	09/19	0.36	0.34	0.85	0.32
114	09/21	0.43	0.37	0.94	0.37
116	09/23	0.42	0.33	1.05	0.36
118	09/25	0.34	0.36	1.05	0.34
120	09/27	0.29	0.34	0.92	0.3
122	09/29	0.36	0.33	0.88	0.31
124	10/01	0.33	0.33	0.9	0.31
126	10/03	0.32	0.31	0.96	0.29

DAY	DATE	NICKEL (in mg/L) CELCO			
		TOTAL Ni in INFLUENT	TOTAL Ni in EFFLUENT	TOTAL Ni in MIX LIQUOR	SOL Ni in MIX LIQUOR
1	05/31	0.4	0.36		
3	06/02	0.44	0.41		
4	06/03				
5	06/04	0.5	0.48		
7	06/06	0.56	0.46		
9	06/08	0.48	0.49		
11	06/10	0.5	0.49	1.5	0.47
13	06/12	0.52	0.51	1.56	0.5
15	06/14	0.55	0.54	1.66	0.52
17	06/16	0.61	0.52	1.82	0.56
19	06/18	0.54	0.56	1.82	0.52
21	06/20	0.5	0.51	1.62	0.49
22	06/21				
23	06/22	0.46	0.46	1.4	0.45
25	06/24	0.39	0.45	1.22	0.39
27	06/26	0.4	0.43	1.2	0.37
29	06/28	0.55	0.49	1.66	0.5
31	06/30	0.61	0.58	1.8	0.57
33	07/02	0.78	0.66	2.36	0.69
35	07/04	0.74	0.69	2.22	0.73
38	07/07				
39	07/08	0.65	0.69	1.96	0.67
40	07/09	0.6	0.61	1.8	0.6
42	07/11	0.63	0.6	1.9	0.57
44	07/13	0.72	0.56	2.16	0.67
46	07/15	0.7	0.69	2.1	0.66
48	07/17	0.69	0.69	2	0.67
50	07/19	0.65	0.64	1.94	0.62
52	07/21	0.5	0.54	1.5	0.54
54	07/23	0.52	0.52	1.56	0.5
56	07/25	0.49	0.5	1.48	0.48
58	07/27	0.46	0.56	1.38	0.45
60	07/29	0.42	0.46	1.26	0.42
62	07/31	0.49	0.46	1.48	0.45

DAY	DATE	NICKEL (in mg/L)			
		TOTAL Ni in INFLUENT	TOTAL Ni in EFFLUENT	TOTAL Ni in MIX LIQUOR	SOL Ni in MIX LIQUOR
64	08/02	0.41	0.45	1.22	0.41
66	08/04	0.4	0.45	1.2	0.4
68	08/06	0.45	0.43	1.36	0.42
70	08/08	0.46	0.45	1.38	0.43
72	08/10	0.42	0.42	1.26	0.41
74	08/12	0.51	0.47	1.54	0.46
76	08/14	0.54	0.52	1.62	0.5
78	08/16	0.46	0.47	1.38	0.46
80	08/18	0.48	0.46	1.44	0.45
82	08/20	0.5	0.49	1.5	0.46
83	08/21				
84	08/22	0.42	0.43	1.26	0.41
86	08/24	0.46	0.45	1.38	0.43
88	08/26	0.46	0.45	1.4	0.45
90	08/28	0.4	0.41	1.22	0.39
92	08/30	0.5	0.46	1.54	0.43
94	09/01	0.51	0.48	1.52	0.46
96	09/03	0.64	0.59	1.92	0.57
98	09/05	0.66	0.63	1.98	0.61
99	09/06				
100	09/07	0.6	0.61	1.9	0.59
101	09/08				
102	09/09	0.64	0.63	1.92	0.6
104	09/11	0.69	0.6	2	0.64
106	09/13	0.55	0.57	1.66	0.55
108	09/15	0.54	0.56	1.62	0.52
110	09/17	0.5	0.55	1.5	0.49
112	09/19	0.59	0.55	1.78	0.54
114	09/21	0.71	0.65	2	0.64
116	09/23	0.72	0.63	2.2	0.66
118	09/25	0.64	0.66	1.92	0.64
120	09/27	0.63	0.63	1.9	0.61
122	09/29	0.6	0.6	1.8	0.57
124	10/01	0.55	0.56	1.64	0.54
126	10/03	0.59	0.57	1.8	0.55

		NICKEL (in mg/L)			
		EXPERIMENT			
DAY	DATE	TOTAL Ni in INFLUENT	TOTAL Ni in EFFLUENT	TOTAL Ni in MIX LIQUOR	SOL. Ni in MIX LIQUOR
1	05/31	0.19	0.25		
3	06/02	0.3	0.35		
4	06/03				
5	06/04	0.33	0.35	0.78	
7	06/06				
9	06/08	0.34	0.3	0.83	0.27
11	06/10	0.39	0.38	0.80	0.36
13	06/12	0.3	0.25	0.74	0.23
15	06/14	0.28	0.27	0.77	0.23
17	06/16	0.21	0.25	0.68	0.2
19	06/18	0.25	0.26	0.62	0.24
21	06/20				
22	06/21	0.23	0.23	0.60	0.21
23	06/22				
25	06/24	0.24	0.22	0.59	0.21
27	06/26	0.28	0.27	0.65	0.27
29	06/28	0.22	0.27	0.65	0.27
31	06/30	0.2	0.29	0.60	0.28
33	07/02	0.23	0.3	0.68	0.3
35	07/04	0.26	0.26	0.58	0.29
38	07/07	0.28	0.26	0.59	0.27
39	07/08				
40	07/09	0.25	0.25	0.60	0.31
42	07/11	0.26	0.29	0.60	0.3
44	07/13	0.31	0.34	0.62	0.29
46	07/15	0.3	0.3	0.65	0.28
48	07/17	0.24	0.26	0.66	0.26
50	07/19	0.21	0.26	0.62	0.22
52	07/21	0.18	0.23	0.59	0.18
54	07/23	0.23	0.24	0.60	0.2
56	07/25	0.22	0.21	0.54	0.19
58	07/27	0.27	0.23	0.66	0.22
60	07/29	0.25	0.24	0.59	0.16
62	07/31	0.24	0.28	0.60	0.28

DAY	DATE	NICKEL (in mg/L)			
		TOTAL Ni in INFLUENT	TOTAL Ni in EFFLUENT	TOTAL Ni in MIX LIQUOR	SOL Ni in MIX LIQUOR
64	08/C2	0.17	0.22	0.56	0.22
66	08/C4	0.19	0.19	0.57	0.18
68	08/C6	0.22	0.2	0.53	0.15
70	08/C8	0.21	0.2	0.60	0.22
72	08/10	0.22	0.21	0.59	0.15
74	08/12	1.35	0.78	1.34	0.66
76	08/14	1.33	0.91	1.52	0.81
78	08/16	1.29	1.1	1.86	0.95
80	08/18	1.36	1.19	2.01	1.1
82	08/20				
83	08/21	1.27	1.2	2.27	1.13
84	08/22				
86	08/24	1.31	1.18	2.72	1.16
88	08/26	1.35	1.23	2.78	1.14
90	08/28	1.29	1.2	2.87	1.2
92	08/30	1.41	1.25	2.78	1.2
94	09/01	1.36	1.31	2.85	1.22
96	09/03	0.24	0.96	2.12	1
98	09/05				
99	09/06	0.18	0.78	1.85	0.81
100	09/07				
101	09/08	0.16	0.65	1.49	0.65
102	09/09				
104	09/11	0.18	0.34	1.08	0.41
106	09/13	2.2	0.29	0.90	0.33
108	09/15	2.24	1.02	2.28	0.96
110	09/17	2.18	1.37	3.30	1.45
112	09/19	2.2	1.49	3.98	1.55
114	09/21	2.31	1.65	4.50	1.62
116	09/23	2.28	1.82	4.95	1.79
118	09/25	2.26	2	5.42	1.95
120	09/27	2.18	2.12	5.84	2
122	09/29	2.2	2.1	5.67	2.05
124	10/01	2.22	2.18	5.55	1.98
126	10/03	2.21	2.12	5.70	2.06

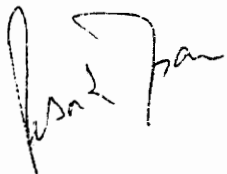
DAY	DATE	COPPER (in mg/L)			
		TOTAL Cu in INFLUENT	TOTAL Cu in EFFLUENT	TOTAL Cu in MIX LIQUOR	SOL Cu in MIX LIQUOR
1	05/31	0.04	0.16		
3	06/02	0.15	0.4		
4	06/03				
5	06/04	0.04	0.1	0.36	
7	06/06				
9	06/08	0.02	0.08	0.26	0.06
11	06/10	0.03	0.09	0.3	0.08
13	06/12	0.03	0.04	0.25	0.04
15	06/14	0.02	0.05	0.23	0.06
17	06/16	0.03	0.04	0.23	0.04
19	06/18	0.04	0.05	0.24	0.04
21	06/20				
22	06/21	0.03	0.05	0.22	0.05
23	06/22				
25	06/24	0.02	0.04	0.2	0.04
27	06/26	1.05	0.07	0.47	0.06
29	06/28	1.06	0.16	0.66	0.18
31	06/30	1.1	0.22	1.3	0.15
33	07/02	0.91	0.26	1.64	0.19
35	07/04	1.01	0.54	1.75	0.41
38	07/07	0.96	0.8	1.8	0.67
39	07/08				
40	07/09	0.9	0.91	1.61	0.84
42	07/11	1.05	0.95	1.65	0.88
44	07/13	1.1	1	1.55	0.9
46	07/15	1.08	1	1.65	0.89
48	07/17	1.1	1.01	1.68	0.99
50	07/19	2.2	1.3	2.31	1.21
52	07/21	2.18	1.66	3.23	1.54
54	07/23	2.11	1.89	3.99	1.77
56	07/25	1.87	1.89	4.15	1.69
58	07/27	1.99	1.95	4.12	1.91
60	07/29	2.13	2	4.23	1.89
62	07/31	2.01	1.88	4.11	1.9

		COPPER (in mg/L)			
		EXPERIMENT			
DAY	DATE	TOTAL Cu in INFLUENT	TOTAL Cu in EFFLUENT	TOTAL Cu in MIX LIQUOR	SOL. Cu in MIX LIQUOR
64	08/02	2.04	1.9	4.01	2
66	08/04	2.18	2	4.05	1.89
68	08/06	2.07	1.83	3.96	1.82
70	08/08	2.11	1.92	4.12	1.88
72	08/10	2.14	2.1	3.98	1.93
74	08/12	1.1	1.9	3.67	1.83
76	08/14	1.07	1.65	3.01	1.56
78	08/16	0.95	1.43	2.74	1.41
80	08/18	1.12	1.45	2.45	1.3
82	08/20				
83	08/21	1.05	1.2	2	1.12
84	08/22				
86	08/24	1.15	1.11	1.9	1.12
88	08/26	1.1	1.16	1.88	1.09
90	08/28	1.16	1.14	1.8	1.1
92	08/30	1	1.09	1.85	1.4
94	09/01	1.11	1.1	1.75	1.02
96	09/03	1.05	1.05	1.7	1.06
98	09/05				
99	09/06	1.06	1.04	1.73	1.04
100	09/07				
101	09/08	1.1	1.09	2	1.09
102	09/09				
104	09/11	1.09	1.05	1.72	1.1
106	09/13	0.06	1	1.65	1.01
108	09/15	0.05	0.85	1.31	0.86
110	09/17	0.07	0.66	1.1	0.7
112	09/19	0.03	0.6	0.82	0.39
114	09/21	0.04	0.22	0.64	0.24
116	09/23	0.05	0.16	0.45	0.14
118	09/25	0.02	0.11	0.33	0.13
120	09/27	0.03	0.06	0.3	0.09
122	09/29	0.07	0.07	0.3	0.1
124	10/01	0.05	0.03	0.28	0.06
126	10/03	0.04	0.03	0.29	0.05



### VITA

Rishi S. Sadagopan was born on December 17, 1964 in India. He received his undergraduate degree in Civil Engineering from the Indian Institute of Technology (IIT) Madras in 1986. Next he worked in a consulting firm in Madras, India for two years in the fields of Civil and Environmental Engineering. Then he joined Virginia Tech for his graduate studies in Environmental Engineering. In 1990, he accepted a job with SEC Donohue (then known as Donohue & Associates), an Environmental Engineering consulting firm. Currently the author is an environmental engineer in the process division, working at Fairfax, Virginia. The author is a member of the Water Environment Federation and American Water Works Association.

  
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