THE EFFECTS OF COPPER AND CHROMIUM IN TERMS OF RECOVERY TIME FOR SOLUBLE BIOLOGICAL OXYGEN DEMAND REMOVAL ON A BIOLOGICAL TOWER

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TABLE OF CONTENTS

LIST OF TABLES

Table		Page

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Microorganisms growing on the media surface in fixed-film biological treatment processes may be seriously inhibited by the toxicity of heavy metals. Domestic wastewater and especially industrial wastewater contain various kinds of metal compounds. These compounds may cause changes in the cell metabolism of microorganisms which could result in a perturbation of the biological treatment processes. The extent of the disturbance in treatment processes depends on the quantity and species of the metal compounds. A small amount of a metal compound usually does not interfere with the treatment processes but allows the microorganisms to acclimate to the toxicity. High concentrations of metal compounds can cause a rapid deterioration in the fixed-film thickness and diversity up to death of the entire fixed film. The toxic effect of metal compounds also depends on the organic loading rate. Bagby and Sherrard (1981) documented that bacteria and other microorganisms had more tolerance to the toxic effects of metal compounds under high organic loading conditions than at low loading conditions because the large microbial population and abundance of substrate materials decrease the harmful effects of the toxic compound on the treatment system.

The presence of metallic waste in the influent to a wastewater treatment plant can have an important effect on the treatment efficiency of organic pollutants by the biological treatment processes. Lewandowski (1987) considered microorganism respiration rate to be closely connected with the substrate conversion rate. He documented that toxicity of metallic waste adversely affected microorganism respiration, causing reduction of growth rate and changes in the composition of the microbial population.

Excessive concentrations of chromium and copper in the soluble form are toxic to enzyme and bacterial systems. The toxicity of hexavalent chromium and copper, as copper sulfate, can change the metabolism of the enzymes in microorganisms and slow down the mechanisms of BOD removal. The objectives of this study were to investigate how long it takes a biological tower to recover from the inhibitory effects of copper and chromium in terms of the overall tower performance based on soluble five-day BOD under slug dose (short term) conditions except for one continuous (long term) addition of copper, and examine the fate of copper and chromium in a biological tower system by using domestic wastewater.

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

An extensive amount of information on the effects of heavy metals on activated sludge, trickling filters, rotating biological contactors (RBC), and anaerobic treatment process is available in the scientific literature; however, studies concerning the toxic effects of heavy metals on a biological tower system are virtually nonexistent. Therefore, the following reviews of the scientific literature concern the removal mechanisms and the effects of metals on activated sludge, trickling filters, RBC systems, and anaerobic process with no previous history of receiving metal (except as noted).

The removal of BOD in a trickling filter results from the biological reaction between the biofilm and wastewater. Williamson and McCarty (1976) considered diffusion and transformation as the actions required for removal of organic pollutants. Soluble constituents in the wastewater diffuse into the biofilm and are transformed by the microorganisms on the filter slimes. These two processes are dependent upon influent BOD, hydraulic loading rate and the source of wastewater. Influent BOD and the type of wastewater are important factors in establishing the biological reaction rate. Eckenfelder (1961) considered contact time, which is related to hydraulic loading, between the biofilm and liquid phase of a waste to be a significant factor contributing to the BOD removal in trickling filters.

Different species of bacteria in the biological treatment system have different abilities to remove organic matter as well as metal ions in their cell matrix. The removal of soluble metal in activated sludge is conducted by three processes: adsorption to sites on the extracellular polymers, accumulation in the cytoplasm of the bacterial cell, and adsorption on the cell wall (Brown and Lester, 1979). Lion *et al.* (1988) studied trace metal removal processes in biofilm. They stated that the inorganic surface of the support media was modified into an organic surface which was coated with attached organisms and their extracellular polymeric materials, and soluble metal was bound to the bacterial cells and their polymers by means of adsorption. Rudd, *et al.* (1984) concluded that bacterial extracellular polymers are important because of their high affinity for soluble metals. Wilkinson (1958) reported that extracellular polymers occurred in two forms, a loose slime which was nonadherent to the cell and microcapsules or capsules which adhere to the cell. These polymers have an important role in protecting bacteria from an abnormal environment. Extracellular polymers have a specific characteristic that enhances metal removal, the negative surface charge due to uronic acids that are oxidation products of sugars (Wilkinson, 1958). Therefore, soluble cation forms of metals such as Cu^{2+} and Cr^{6+} combine with the extracellular polymer by interactions with negatively charged polymer.

Properties of copper and chromium are shown in Table I (Friberg *et al.* 1979). Copper is one of the transition elements with four possible oxidation states; Cu(0), Cu(I), Cu(II), and Cu(III) (Sanchez, 1971).

TABLE I

PROPERTIES OF COPPER AND CHROMIUM

Characteristics	Copper	Chromium
Symbol	Cu	Cr
Atomic weight	63.5	52
Atomic number	29	24
Density	8.9 g/cc	7.2 g/cc
Melting point	1083.4°C	1857±20°C
Boiling point	2567°C	2672°C
Color	crystalline form redish metal	crystalline form steel-grey
Shape	cubic	cubic

Cu(II) is the only stable state in aqueous solution and Cu(III) is a strong oxidant (Sanchez, 1971). Copper may be found in aquatic water systems in several different forms such as soluble, colloidal, and particulate phases. Copper complexes of carbonate, cyanide, amino acids and polypeptides, and humic substances as well as free cupric ion are present in soluble form. Colloidal matter includes polypeptide material and some clays and metallic hydroxide precipitates. Oxide, sulphide, and malachite ($Cu_2(OH)_2CO_3$) precipitates as well as insoluble organic complexes and copper adsorbed on clays and on other mineral solids could be present in particulate forms of copper (Stiff, 1971). The soluble copper is removed from the aquatic system by adsorption, both abiotic and biotic, and precipitation. The pH has a great effect on adsorption and precipitation (Sylva, 1975). Copper salts, especially the sulfate and acetate, are more toxic than copper itself (NAS, 1977).

Chromium is usually found as trivalent and hexavalent forms in nature. The oxidation potential of hexavalent to trivalent chromium is strong. Hexavalent chromium in the natural aquatic system is stable and persists for long periods under aerobic conditions. However, hexavalent chromium reduces to trivalent chromium under anaerobic conditions, whose salts in neutral or weakly alkaline solution hydrolyze. (Cheremisinoff and Habib, 1972). The trivalent state of chromium is mainly present in the insoluble form (NAS, 1974). In the oxidized state, the hexavalent form, chromium is very toxic and is water soluble (Langard, 1982).

McDermott *et al.* (1963), and Moore *et al.* (1961) studied the effects of heavy metals on a pilot scale activated sludge system, investigating the toxic effects of chromium and copper using two types of influent feeding processes: continuous feed and slug doses.

McDermott *et al.* (1963) studied the effects of three concentrations (10, 15, and 25 mg/l) of copper, as copper sulfate, continuously fed for periods up to four months with an average influent BOD of 319 mg/l and organic loading rate of 42-58 lb/day/1000 ft^3. The effect of copper in terms of BOD removal efficiency is summarized in Table II.

Table II shows that the three concentrations of copper lowered the effluent quality in terms of BOD of the test units as compared to the control units. They found the removal of copper over the concentration range from 10 to 25 mg/l averaged 75-79 percent. They also investigated the effects of four hour slug doses of copper, as copper sulfate, at dosages of 66 to 410 mg/l on an activated sludge system with average influent BOD of 264 mg/l (Table II). They found that concentrations of more than 100 mg/l caused severe effects in terms of treatment efficiency over the first 48 hours in the activated sludge unit. They concluded that at the 100 and 410 mg/l doses, BOD removal efficiency fell off to about 50 percent and recovered to normal operation in about 120 hours and 100 hours, respectively.

Moore *et al.* (1961) investigated the toxic effects of hexavalent chromium in domestic wastewater under continuous feed and slug dose operations in a pilot scale activated sludge system with an influent BOD of 260 mg/l. Five concentrations (0.5, 2, 5, 15, and 50 mg/l) of hexavalent chromium were continuously fed for one month (two lowest concentrations) and a six week period (the other three concentrations)

TABLE II

SUMMARY OF METAL EFFECT IN ACTIVATED SLUDGE

Metal used	Concentration	Metal injection period	Activated Sludge (% BOD Removal)
Copper[1]	10 mg/l	4 months	3.4 % drop
Copper[1]	15 mg/l	4 months	5.3 % drop
Copper[1]	25 mg/l	4 months	2.5 % drop
Copper[2]	66 mg/l	4 hours	slight effect
Copper[2]	100 mg/l	4 hours	severe effect for the first 48 hours. Recovery: in 120 hours
Copper[2]	410 mg/l	4 hours	severe effect for the first 48 hours. Recovery: in 100 hours
Chromium[3]	0.5 mg/l	1 months	no effect
Chromium[3]	2 mg/l	1 months	no effect
Chromium[3]	5 mg/l	6 weeks	2 % increase
Chromium[3]	15 mg/l	6 weeks	no effect
Chromium[3]	50 mg/l	6 weeks	3 % drop
Chromium[4]	10 mg/l	4 hours	no effect
Chromium[4]	100 mg/l	4 hours	3 % drop for the first 24 hours. Recovery: within 48 hours (2 days).
Chromium[4]	500 mg/l	4 hours	8.5 % drop for the first 32 hours. Recovery: within 72 hours (3 days).

1: Continuous dose of copper; influent BOD = 319 mg/l (McDermott *et al.*)
2: Slug dose of copper; influent BOD = 264 mg/l (McDermott *et al.*)
3: Continuous dose of chromium; influent BOD = 260 mg/l (Moore *et al.*)
4: Slug dose of chromium; influent BOD 260 mg/l (Moore *et al.*)

to the activated sludge process.

Table II shows the effect of hexavalent chromium in terms of BOD removal efficiency. The four lowest concentrations (0.5, 2, 5, and 15 mg/l) did not cause a decrease of BOD removal efficiency. However, with the 50 mg/l chromium dose, BOD removal efficiency dropped about 3 percent.

The effects of three concentrations (10, 100, and 500 mg/l) administered as slug doses of hexavalent chromium were investigated. These concentrations were fed over a period of four hours to the activated sludge. As shown in Table II, treatment efficiency was not affected at the feed concentration of 10 mg/l. When a slug dose of 100 mg/l was fed, BOD removal efficiency dropped about 3 percent during the first 24 hours and the system performance recovered within 2 days. With the feed concentration of 500 mg/l of chromium, BOD removal efficiency dropped about 9 percent for 32 hours and the treatment performance was restored to normal after 3 days.

Furtado (1981) studied the effect of chromium and copper in an activated sludge system. A synthetic wastewater with an influent BOD of around 323 mg/l was fed to the system at a flow rate of 5.6 ml/min. The total volume of the system was 4.76 liters: 2.8 liters of aeration tank and 1.96 liters of settling tank. Hexavalent chromium fed in a continuous dose for 15 days and 14 days duration at a concentration of 5 mg/l and 10 mg/l, respectively, had no effect on the BOD removal efficiency and were not removed in the system. With the 5 mg/l dose of copper for 22 days, efficiency of BOD removal decreased by 9 percent. The 20 mg/l dose of copper for 30 days duration reduced the BOD removal efficiency by 30 percent. He indicated that the amount of copper in the effluent increased with time. At the 5 mg/l copper dose, removal efficiency of copper was about 95.4 percent at the beginning of spiking and 45.8 percent just before the injection of copper stopped. In the case of the 20 mg/l copper dose, the removal efficiency of copper at the beginning was about 98.7 percent and the removal efficiency just before the injection stopped was 89 percent.

Reid *et al* (1968) investigated the effect of hexavalent chromium on a trickling filter pilot plant. The trickling filter was 4 ft in diameter and 6 ft deep with 2 inch rock media and with a normal flow rate of 4.0 gpm and a designed organic loading of 0.074 lb BOD/day/ft^3. They concluded that domestic sewage containing 2 mg/l or less of hexavalent chromium did not significantly affect BOD removal efficiency of the trickling filter pilot plant.

Chang *et al.* (1985) studied the toxic effects of cadmium and copper in terms of the dissolved organic carbon (DOC) in an RBC system which operated with a synthetic wastewater feed at the hydraulic loading rate of 1.35 gal/day/ft^2 with influent DOC of 140 to 160 mg/l. They also studied cadmium and copper toxicities in an activated sludge system with the same influent DOC concentrations as those for the RBC system. Two concentrations (5 and 20 mg/l) of cadmium, as $CdCl_2$, were injected into the influent of the RBC. Table III summarizes the effect of cadmium and copper in each biological treatment process. The DOC removal efficiency was restored 6 days and 8 days after the injection stopped at the 5 and 20 mg/l cadmium doses, respectively. They believed that there was not much difference in removal efficiency between the

TABLE III

SUMMARY OF METAL EFFECT IN TERMS OF % DOC REMOVAL ON RBC SYSTEM AND ACTIVATED SLUDGE UNIT

Metal Conc. used		Injection period	RBC system# (% DOC Removal)	Activated Sludge+ (% DOC Removal)
Cadmium	5 mg/l	24 hours	8 % drop for 5 days. Recovery: 144 hours (6 days) after the injection stopped.	7 % drop for 2 days. Recovery: 72 hours (3 days) after the injection stopped.
Cadmium	20 mg/l	3 days	6.5 % drop for 4 days. Recovery: 192 hours (8 days) after the injection stopped.	12 % drop for the first day spiking. Recovery: instantly after the injection stopped.
Copper	1 mg/l	9 days	no effect	no effect*
Copper	5 mg/l	9 days	no effect	no effect*
Copper	10 mg/l	11 days	no effect	no effect*
Copper	25 mg/l	7 days	10 % drop for 7 days. Recovery: 336 hours (14 days) after the injection stopped.	-
Copper	50 mg/l	5 days	7 % drop for 10 days.	-

#: Operating condition of RBC unit;

Hydraulic loading rate = 1.35 gal/day/ft^2
Influent DOC = 140 mg/l for cadmium
160 mg/l for copper

+: Operating condition of Activated Sludge;

Influent DOC = 140 mg/l for cadmium
160 mg/l for copper
MLSS = 2,500 mg/l
Hydraulic retention time = 6 hours
Sludge age = 8 days

*: The biological sludge did not settle well, and a substantial amount of MLSS was lost from the system.

two doses of cadmium because the unit was acclimated by the first feeding of cadmium.

Toxic effects of copper were also investigated in their study. Five concentrations (1, 5, 10, 25, and 50 mg/l) of copper, as copper sulfate, were fed to the influent of an RBC (Table III). Three lowest concentrations (1, 5, and 10 mg/l) of copper did not produce any noticeable toxic effects on the RBC system. At a copper dose of 25 mg/l for 7 days, the treatment efficiency recovered within 14 days. When 50 mg/l of copper was dosed for 5 days, the unit showed a 20 percent reduction in the DOC removal efficiency on the first day, but the average suppression of the DOC removal efficiency was about 7 percent for 10 days. The 1, 5, and 10 mg/l slug doses also did not reduce the DOC removal efficiency in the activated sludge, however these copper doses disturbed the settling of the biological sludge system. This RBC unit averaged from 85 to 95 percent efficiency in the removal of soluble cadmium and 30 to 90 percent efficiency in soluble copper removal, depending on the influent metal concentration.

Keihani (1980) concluded that the long-term effects of the 10 mg/l chromium dose for 15 days duration and the 10 mg/l copper dose for 20 days duration on an RBC system were the same as the short-term effects. He investigated the toxic effects on an RBC system which was fed synthetic wastewater (BOD = 200 mg/l) at a hydraulic loading of 2 gal/day/ft^2. He found that the suppression of BOD removal efficiency was about 23 percent at both 5 mg/l (feeding for 38 days) and 10 mg/l of hexavalent chromium. However, in the case of copper, as copper sulfate, the BOD removal efficiency was little affected at 3 mg/l (feeding for 20 days) and 10 mg/l. The average metal reduction varied from over 90 percent for the copper experiments to 93-97 percent for the chromium experiments.

Dehkordi (1980) studied changes in the performance of an RBC system treating synthetic wastewater (COD = 460 mg/l), as a result of the toxic effects of hexavalent chromium (1, 2, 3, and 20 mg/l) and copper (0.5, 1, 4, and 10 mg/l). Hexavalent chromium at 20 mg/l decreased COD removal efficiency by 3 percent at the hydraulic loading rate of 2.8 gal/day/ft^2. At the hydraulic loading rate of 0.7 and 3 gal/day/ft^2, copper, as copper sulfate, at 10 mg/l did not affect the COD removal efficiency of the system. The removal efficiency of hexavalent chromium was 65 to 80 percent in the RBC. In the case of copper, the removal efficiency was very low (0 to 36 percent) at a hydraulic loading rate of 0.7 gal/day/ft^2. However, copper removal efficiencies of 80 to 96 percent were achieved at a hydraulic loading rate of 3.0 gal/day/ft^2.

Moore *et al.* (1961) noted the effects of chromium in anaerobic digesters fed with varying levels of the metal. Three different concentrations of hexavalent chromium (50 mg/l, 300 mg/l, and 500 mg/l) were fed to a digester which had previously received chromium containing sludge. When 50 mg/l of chromium (based on the digester contents) was fed to a digester daily for 42 days, gas (CO_2) production dropped off rapidly. In feeding the digester a 300 mg/l slug dose of chromium, gas production ceased to 7 days. The digester then gradually recovered. A slug dose of 500 mg/l caused the digester to stop all gas production and the digester did not recover.

Mosey and Hughes (1975) analyzed raw and digested sludge and the volume of gases produced daily and per unit of volatile matter destroyed by digestion in order to investigate the toxicity of heavy metals to anaerobic digestion. The total metal concentrations in the digesting sludge (noted in Table IV) when failure of digester started decrease in the sequence: Fe, Cr(III), Cr(IV), Cu, Cd, and Zn, respectively. Table IV also illustrates that heavy metals are toxic to digestion at very low soluble concentrations.

Chian and DeWalle (1977) studied the removal of heavy metals from a laboratory-scale anaerobic filter with a filter height of 6.5 ft. The surface area of the plastic media was 63 ft^2/ft^3 column volume with a porosity of 94 percent. Flow rates used were 0.5, 1.0, 1.6, and 4.2 gal/day which resulted in detention times of 34, 17, 11.3 and 4.2 days, respectively. The recirculation was 8.14 gal/day. As shown in Table V, total removal percentages vary between 30 percent and 96 percent, while the soluble metal removals vary between 52 percent and 97 percent, depending on the rate of inflow, hydraulic detention time, and loading of the filter.

Lawrence and McCarty (1965) reported that sulfides play a significant role in preventing toxicity of most heavy metals in anaerobic treatment because sulfides formed metal sulfides, which are extremely insoluble salts, in a digester containing heavy metals. The metal removals in anaerobic digesters have been attributed to the formation of metal sulfide precipitates.

In biological treatment processes, metal toxicity is mainly attributed to the soluble metal ion (Sujarittanonta and Sherrard,

TABLE IV

TOTAL CONCENTRATIONS OF METALS WHEN DIGESTION STARTED TO FAIL AND CONCENTRATIONS OF METAL IONS EXHIBITING 50 % INHIBITION OF DIGESTERS

Metals	Total conc. of metals in digesting sludge (mg/l)	Conc. of metal ions metal ions	Conc. of metal ions (mg/l)
Zinc	163	Zn^{++}	10^{-4}
Cadmium	180	Cd^{++}	10^{-7}
Copper	170	Cu^{++} Cu^{+}	10^{-16} 10^{-12}
Iron	1750	Fe^{++}	1-10
Chromium III	530		
Chromium VI	450		

TABLE V

CONCENTRATION OF HEAVY METALS IN INFLUENT AND EFFLUENT OF THE ANAEROBIC FILTER*

Element	Influent conc. (mg/l)	Average effluent conc. (mg/l)	Average soluble effluent conc. (mg/l)	Percentage metal present as SS (%)	Average metal removal (%)	Average soluble metal removal (%)
Fe	430	19.4	12.6	35	95.5	97.1
Zn	16	1.3	0.96	27	92.0	94.1
Cu	5.6	1.47	0.67	54	73.8	88.1
Cr	1.7	0.24	0.15	27	85.9	91.2
Ni	1.2	0.33	0.20	39	72.5	83.7
Pb	0.38	0.08	0.06	25	78.9	84.2
Cd	0.027	0.019	0.013	32	29.6	51.9

*: Data from Chian and Dewalle (1977)

1981). Metal uptake by the biomass depends on several factors including solubility of metal ions, metals concentration, pH, concentration of organic matter, and the amount of biomass present in the system. Solubility of metal ions is closely related to pH of the metal containing wastewater. Cheng *et al* (1975) reported that the uptake capacity of metal increased with increasing pH because of the greater number of free binding sites on the sludge functional groups and the formation of more metal-organic complexes.

CHAPTER III

MATERIALS AND METHODS

During this study the effects of copper, added as copper sulfate ($CuSO_4$), and chromium, added as potassium dichromate ($K_2Cr_2O_7$), on a biological tower were investigated.

All experiments were performed at room temperature of 20°-25°C in the Oklahoma State University Environmental Engineering pilot plant laboratory. The experimental equipment was composed of a biological tower reactor, three different kinds of pumps, one wet well, two inlet and two distribution systems, sampling wand, and several 25 liter glass carboys.

A schematic of the experimental treatment system is shown in Figure 1. The pilot scale biological tower system was constructed of plexiglass. This unit consisted of two three-cubic-foot sections each with a horizontal cross section area of one square foot. The sections were separated by spacing units that were five inches deep. The bottom of the tower served as the major source of air for the unit and was set up to aerate the unit by natural draft. Plastic filter media was used in this study. The filter media provided a surface area of 42 ft^2/ft^3 for microorganisms to grow on. A fine screen was set up to collect the biological solids at the 3 ft and 6 ft depth of the reactor.

The inlet system for the tower was made of one inch inside

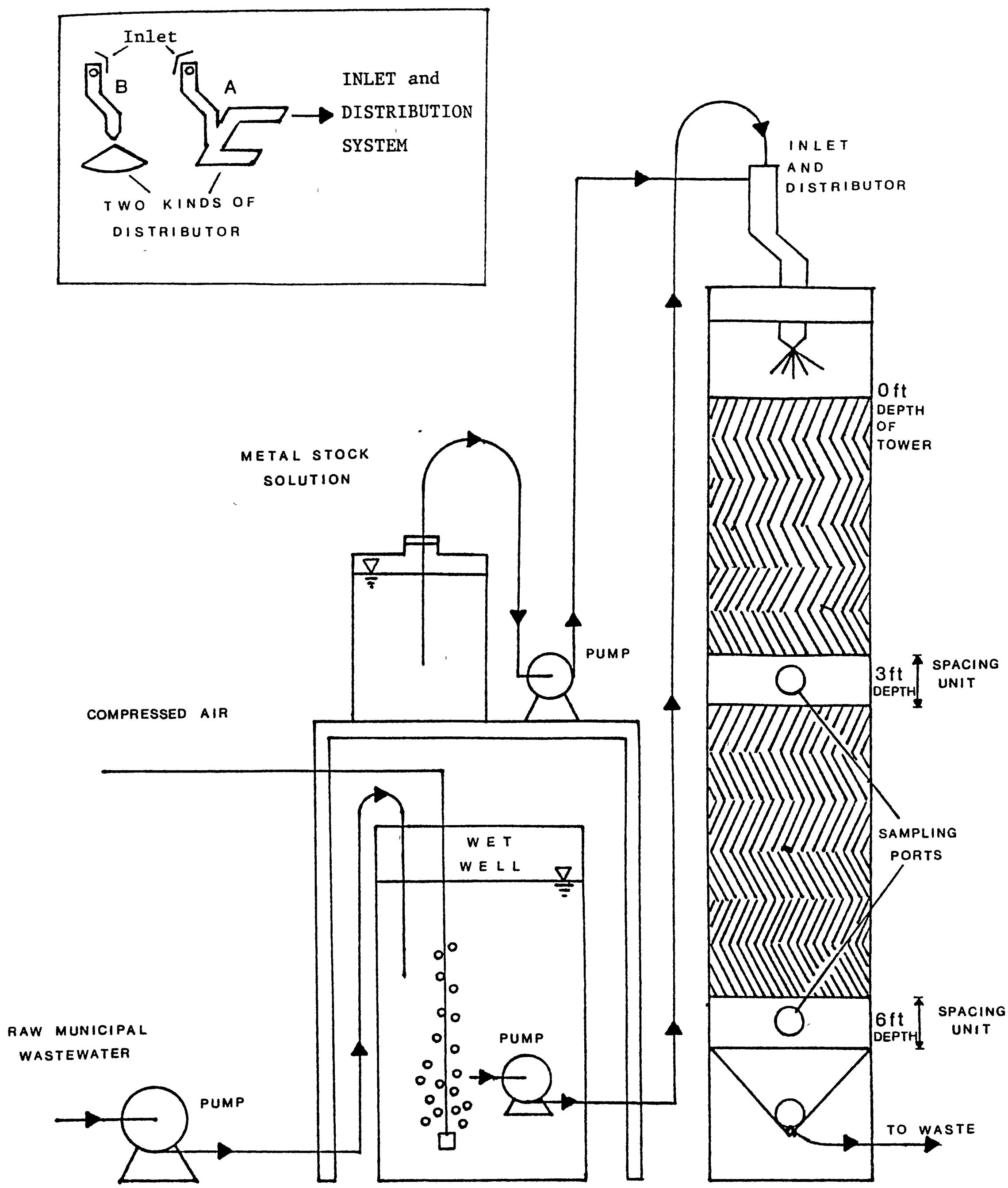

Figure 1: Experimental Biological Tower Unit

diameter P.V.C. pipe which had three successive 90° bends to enhance complete mixing of the domestic wastewater and the metal solutions.

Two kinds of distributor discharge devices which were attached to the bottom of the inlet system were used in the experiment (Fig. 1). Distributor "A" had two branches constructed of one inch inside diameter P.V.C. pipe which contained 14 holes for even flow distribution. This distributor was used during the copper experiment. Distributor "B" was used during the chromium experiment and consisted of an inverted metal cone instead of branches. Distributor "A" was changed after the copper experiment because it clogged up frequently. Distributor "B" provided better distribution of the wastewater and clogged up less than distributor "A".

Feed solution to the unit consisted of Stillwater municipal wastewater. The raw municipal wastewater was pumped into a 180 gallon wet well by a Hydramatic Sewage Lift pump (1.5 HP and 1725 rpm.). Temperature of wastewater in the wet well ranged between 18°C-23°C in all seasons. The pH of the wastewater was between 7.0 and 8.5. The wastewater in the wet well was pumped to the biological tower through the inlet and distribution system by a Tecumsen Products Co. (model 5-MSP) pump. The hydraulic loading rate of the pilot scale tower was maintained at 0.9 gal/min/ft^2 (1296 gal/day/ft^2) during the experiments conducted using copper, but was increased for the chromium experiments to 1 gal/min/ft^2 (1440 gal/day/ft^2) because the lower flow rate caused the adjusting valve above the distributor to clog. Samples for analyses were collected at a location ahead of the inlet system and from the two sampling ports. A sampling wand was used to collect samples from the two ports located at the 3 ft and 6 ft tower depths. The wand was made of a 15-inch long P.V.C. pipe, which had been cut in half to form a semicircle.

Carbonaceous inhibition screening tests for the effects of the metals were conducted as preliminary studies. Dilutions of the domestic wastewater sample were prepared in BOD bottles. The dilution water was prepared according to the procedure in Standard Methods (APHA, 1985). The wastewater volume added to the BOD bottles was 30 ml and 16 ml for copper and chromium, respectively. Different concentrations of either copper or chromium were individually added to the BOD bottles in order to investigate the BOD inhibition level of these two heavy metals, as shown in Table VI. The dilution water was added to each bottle as required to fill the 300 ml volume of the BOD bottles. Then, the BOD bottles were incubated in a BOD incubator at 20°C for 5 days. The initial (day 0) and final (day 5) dissolved oxygen concentration in each bottle were measured using a oxygen electrode (Orion Research Inc.). This experiment followed Stover's (1980) inhibition screening test procedure.

The copper experiment was conducted first. After its completion the tower and filter media were cleaned thoroughly before starting the chromium study. It took about four weeks for the biological tower system to reach a pseudo-steady state condition with respect to biological tower performance for $sBOD_5$ removal. Pseudo-steady state conditions are illustrated as follows; the influent $sBOD_5$ closely parallels the effluent $sBOD_5$ and the $sBOD_5$ removal efficiency of the biological tower was almost constant. That is, the treatment of $sBOD_5$

TABLE VI

COPPER AND CHROMIUM CONCENTRATIONS IN WASTEWATER SAMPLES AND WASTEWATER VOLUME FOR INHIBITION SCREENING TEST

Metal Conc. in Wastewater Volume (mg/l)	Wastewater Volume for Cu Experiment (ml)	Wastewater Volume for Cr Experiment (ml)
0.00*	30	16
0.10	30	16
0.25		16
0.50	30	16
0.75		16
1.00	30	16
2.00	30	
5.00	30	16
10.00	30	16
25.00		16
50.00		16
75.00		16
100.00		16

*: Control (no containing metal)

by microorganisms on the surface of media is fairly constant during the continuous flow of the domestic wastewater. After a pseudo-steady state condition had been achieved, either copper or chromium solutions were fed individually at controlled rates (Table VII) to investigate the toxic effects of these metals. Concentrated copper and chromium solutions were prepared in 25 liter glass carboys. Table VII shows the feeding rates of the metal solutions which were fed to the unit by a Milton Roy Co. (model DB-2-117R) controlled volume pump. Stock solutions of the metals were prepared for copper ($CuSO_4$) and chromium ($K_2Cr_2O_7$) in distilled water.

During the experiments, the following parameters were measured: filterable BOD_5, pH, total suspended solids (TSS), volatile suspended solids (VSS), concentration of soluble metal and total metal in solution, and metal concentration in the biological solids. BOD_5 tests were performed in accordance with Standard Methods on the collected filtrate of the sample after it passed through a Whatman 934-AH glass microfiber filter (APHA, 1985). An Orion Oxygen electrode and Orion Research analog pH meter (model 301) were used to measure dissolved oxygen. The pH of the samples was measured using a Fisher Scientific pH Meter Model 900 and a glass electrode. The procedures followed for TSS and VSS were those set in Standard Methods (APHA, 1985). The soluble metal concentration in this project was defined as the metal concentration in the liquid phase following filtration of the sample through a 0.45 micrometer pore membrane filter. Total metal concentration was determined on samples following a nitric acid digestion, and the metal concentration in the solids was measured on

TABLE VII

FEED RATE OF METAL STOCK SOLUTIONS

Injection stage	Duration (hours)	Conc. of stock solution (mg/l)	Flow rate of metal stock solution (ml/min)
3 mg/l, Cu	135 hours	806 mg/l as Cu	18
56 mg/l, Cu	10 hours	11,279 mg/l as Cu	18
9 mg/l, Cr	4 hours	2,013 mg/l as Cr	18
38 mg/l, Cr	4 hours	8,499 mg/l as Cr	18
96 mg/l, Cr	4 hours	21,470 mg/l as Cr	18

samples put through the dry ashing method in Standard Methods (APHA, 1985). The concentrations of copper and chromium were measured on a Perkin Elmer Model 5000 atomic absorption spectrophotometer using the flame method. The detection limits of this atomic absorption spectrophotometer for copper and chromium were 0.01 mg/l.

CHAPTER IV

RESULTS AND DISCUSSION

Preliminary Studies

Preliminary studies were conducted in order to determine the time of day the samples should be taken, to investigate the rate at which copper and chromium partitioned to the solid phase in the wastewater, and to find the inhibitory concentration level of metals in the BOD bottle. This last set of tests was conducted to help establish metal doses for the biological tower.

The organic strength and constituents of raw municipal wastewater vary over time because of its inherently changeable characteristics. Figure 2 represents a typical variation of the $sBOD_5$ removal efficiency at the 3 ft and 6 ft tower depths, and $sBOD_5$ at the 0 ft, 3 ft, and 6 ft tower depths for one day. This sampling event consisted of grab samples (Fig. 2) and was conducted at a hydraulic loading rate of 0.9 gal/min/ft^2 while the filter medium was covered with a prolific growth of microorganisms. The influent $sBOD_5$ showed an increase starting from 6:00 a.m.. The influent $sBOD_5$ concentration reached a plateau value between 2:00 p.m. and 10:00 p.m., and then decreased through the night time. The influent $sBOD_5$ value fell to its lowest point at 6:00 a.m., however, the performance of the biological tower in terms of $sBOD_5$ removal efficiency was almost constant throughout this period.

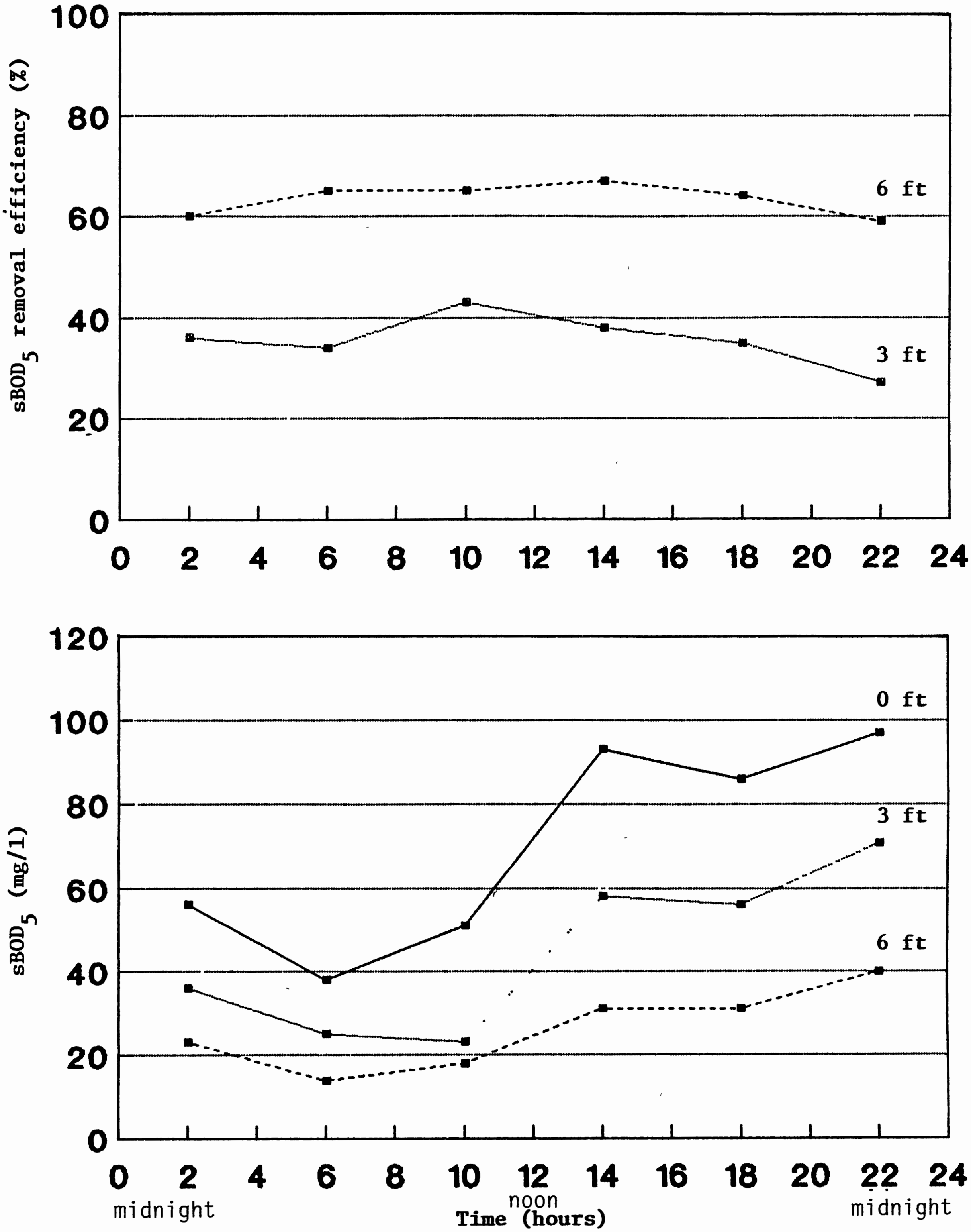

Figure 2: Variation of sBOD5 Removal Efficiency and sBOD5 Concentrations of Municipal Wastewater for One Day

Figure 3 shows the $sBOD_5$ removal efficiency at the 6 ft tower depth for samples taken three times a day between day 23 and day 36. The $sBOD_5$ removal efficiency was monitored for 14 days in order to investigate the variation of $sBOD_5$ removal efficiency throughout the day. Grab samples were taken over a time interval of 10 minutes in the sequence: effluent at the 6 ft tower depth, effluent at the 3 ft tower depth, and influent at the 0 ft tower depth, respectively. Grab samples were collected three times a day, but samples taken at midnight on days 23, 25, 34, and 36 were lost in a lab accident. During the 14 day period, the $sBOD_5$ removal efficiency averaged 62(±4) percent at 10:00 a.m., 64(±6) percent at 6:00 p.m., and 58(±6) percent at midnight.

Figure 3 shows that the $sBOD_5$ removal efficiency of the system was almost constant throughout each day during the period of 14 days. Even though the organic loading of the feeding solution was not constant, the remainder of the experiment was arranged to collect the samples at a fixed time during the day. The collection time of the grab samples was chosen to be 6:00 p.m. because the strength of municipal wastewater was relatively high at this time.

The concentration of soluble metals in the wastewater may change between the time interval of sampling and measurement. Two experiments were conducted to investigate changes in the copper and chromium concentrations through the inlet and distributor, and to study reduction of the soluble metal concentration in the wastewater. In the first experiment, either a 78 mg/l soluble concentration of copper or a 40 mg/l soluble concentration of chromium were added to the domestic wastewater at the top of the inlet system at the hydraulic loading rate

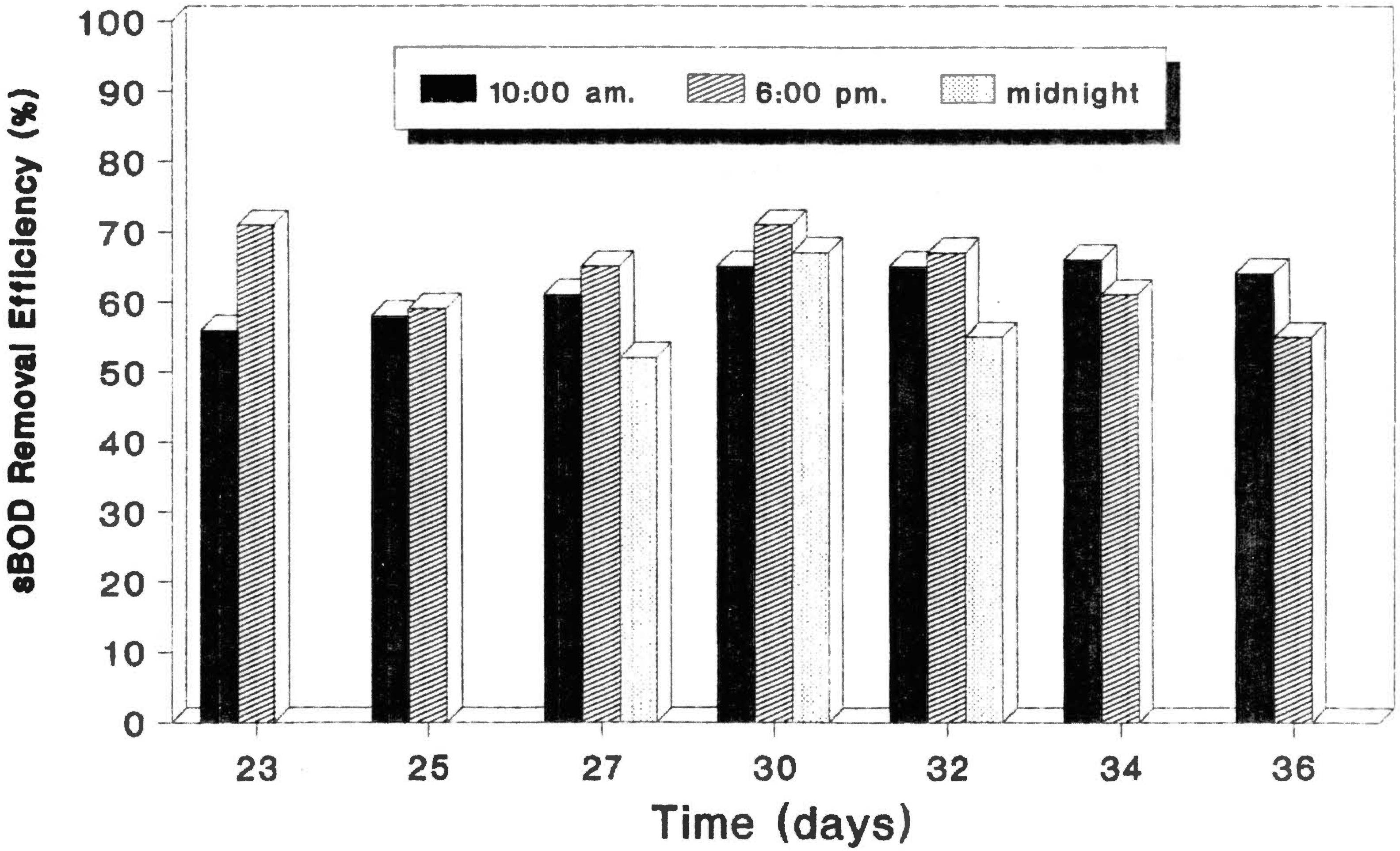

Figure 3: sBOD5 Removal Efficiency at 10:00 a.m., 6:00 p.m., and Midnight under the Steady State Condition

of 1 gal/min/ft^2. Samples of the wastewater were collected at locations ahead of the inlet and behind the distributor. The concentrations of soluble copper and soluble chromium behind the distributor were 17.7 mg/l and 39.6 mg/l, respectively. A 77 percent reduction in the soluble copper concentration was seen through the distributor, but only a 1 percent drop in the soluble chromium concentration in the feed was measured.

From the first experiment, over 70 percent of the soluble copper was converted to the particulate form. Therefore, it became necessary to investigate the reduction of the soluble copper concentration with the passing of time. In most cases, more than 5 minutes was required to take and filter samples. The second experiment was conducted to investigate changes in the soluble copper concentration in the wastewater 5 minutes, 10 minutes, 1 hour, and 24 hours after soluble copper contacted the wastewater.

Table VIII indicates the time requirement for establishment of equilibrium between soluble and particulate copper. When a 66 mg/l concentration of the soluble copper was contacted with the wastewater for intervals of 5 minutes, 10 minutes, and 1 hour prior to filtering the samples, the soluble copper concentration was reduced by 75 to 79 percent. During the contact time of 24 hours, a 73 mg/l concentration of the soluble copper was reduced by 82 percent. The results indicate that the liquid phase concentration of copper changes quickly into the solid phase in wastewater and the partition equilibrium persisted over 24 hours. The reduction of the soluble copper concentration is not due to the inlet and distribution system, but due to the wastewater itself

TABLE VIII

TIME REQUIREMENT FOR ESTABLISHMENT OF EQUILIBRIUM
BETWEEN SOLUBLE AND PARTICULATE COPPER

Elapsed Time	Total Cu conc. (mg/l)	Soluble Cu conc. (mg/l)	Reduction rate (%)
5 minutes	66.4	14.0	79
10 minutes	66.2	16.4	75
1 hours	69.0	15.4	78
24 hours	73.4	13.2	82

and copper's tendency to partition rapidly to the solid phase by adsorption and precipitation processes. Therefore, if a sample was not filtered for 1 hour after it was taken, it can be concluded that the percentage of metal in the particulate form would be no different than a sample filtered immediately (5 minutes) after it was taken.

Precipitation of soluble copper in municipal wastewater (alkalinity = 240 mg/l $CaCO_3$ and pH = 7.8), which was filtered through 0.45 micrometer pore membrane filter, was investigated as a preliminary study. The soluble copper concentrations of 3.3 mg/l and 11.4 mg/l decreased to 2.86 mg/l and 4 mg/l, respectively, after 5 minutes of contact with the filtered wastewater. Thirteen percent of soluble copper was changed to an insoluble form by precipitation at the 3.3 mg/l soluble concentration, while sixty five percent of soluble copper was changed in the case of the 11.4 mg/l soluble concentration. The soluble copper removal is dependent upon the initial soluble concentration and the wastewater characteristics such as alkalinity and pH.

Inhibition screening tests were conducted to investigate the threshold inhibition level of each metal for carbonaceous biological oxidation of domestic wastewater. Figure 4 shows changes in the Dissolved Oxygen (DO) concentration with different concentrations of the soluble copper and chromium on a semilog scale.

In the copper inhibition test, the five-day DO concentration of the control bottle, which did not contain copper, was 1.2 mg/l. Each sample had the same initial DO concentration of 8.4 mg/l. As shown in Figure 4, a threshold inhibition level occurred at the 1 mg/l concentration of soluble copper.

In the case of the chromium inhibition test, the initial DO concentration of each sample was 7.9 mg/l. The five-day DO concentration of the control bottle, which did not contain chromium, was 4.8 mg/l and a threshold inhibition level was observed at the 0.5 mg/l concentration of soluble chromium (Fig. 4).

These tests only provided rough estimates because the threshold levels were observed under static conditions. Two concentrations of copper and three concentrations of chromium, which were higher than the threshold level, were set as the injection dose to the biological tower to investigate the toxic effects of these two metals. Asterisks in Figure 4 show the tower wide average concentration of copper and chromium during the injection of the metal solution onto the biological tower.

Effects of Copper as Copper Sulfate

The $sBOD_5$ of the raw municipal wastewater was 89±33 mg/l at 6:00 p.m. during the copper experiments. The hydraulic loading rate to the biological tower was maintained at 0.9 gal/min/ft^2. The organic loading rate of the biological tower system was calculated at 3.82±1.41 lbs-$sBOD_5$/day/1000 ft^2. The variation of $sBOD_5$ and its $sBOD_5$ removal efficiency at each tower depth in the system development stage are shown in Figure 5.

The $sBOD_5$ removal efficiency at the 6 ft tower depth (calculated as the difference between 0 and 6 ft) increased for a period of four

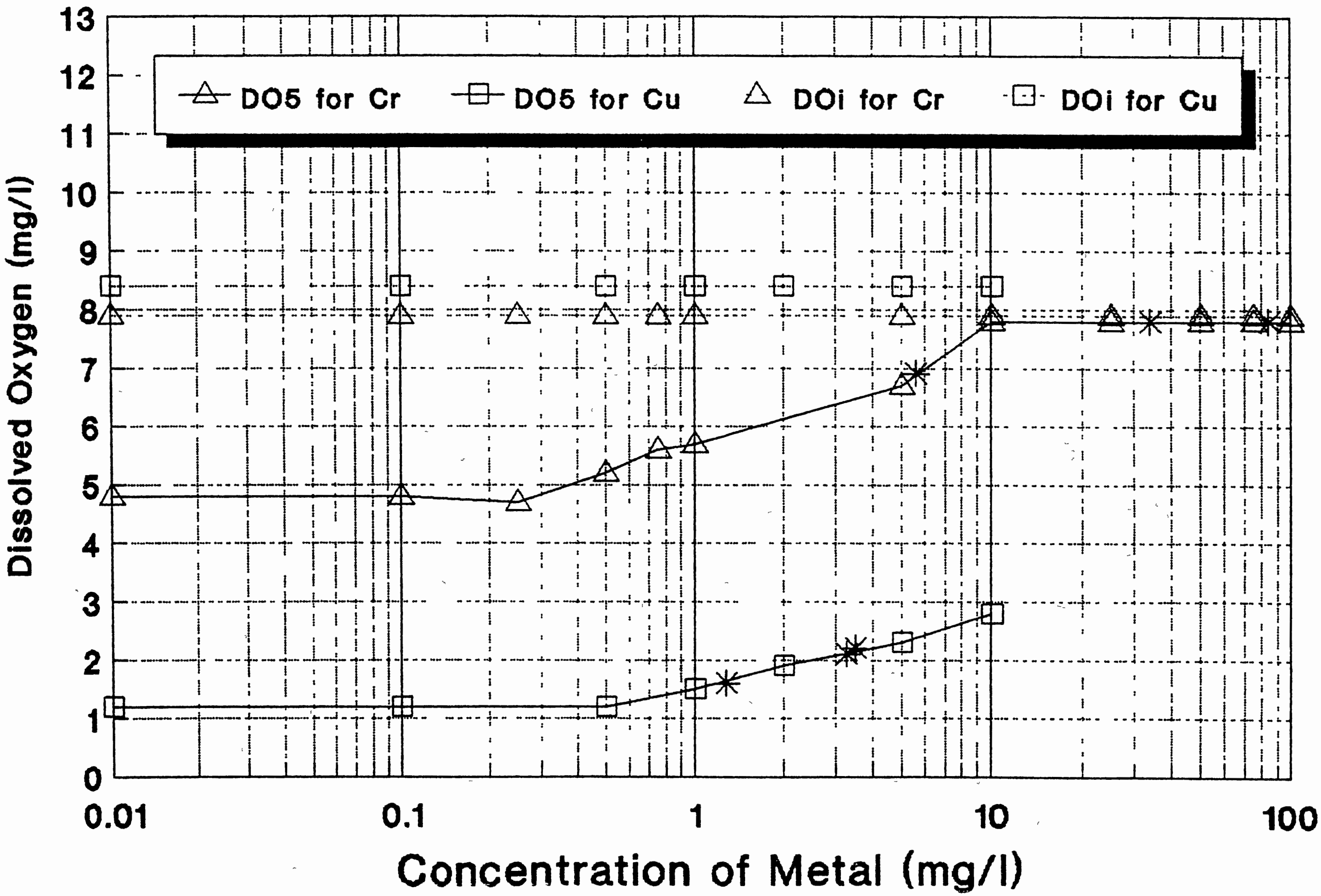

Figure 4: Results of Inhibition Screening Test for Metals
* is tower wide average conc. of soluble metals
Cu; 1.3, 3.3, and 3.5 mg/l
Cr; 5.6, 34.1, and 84.3 mg/l

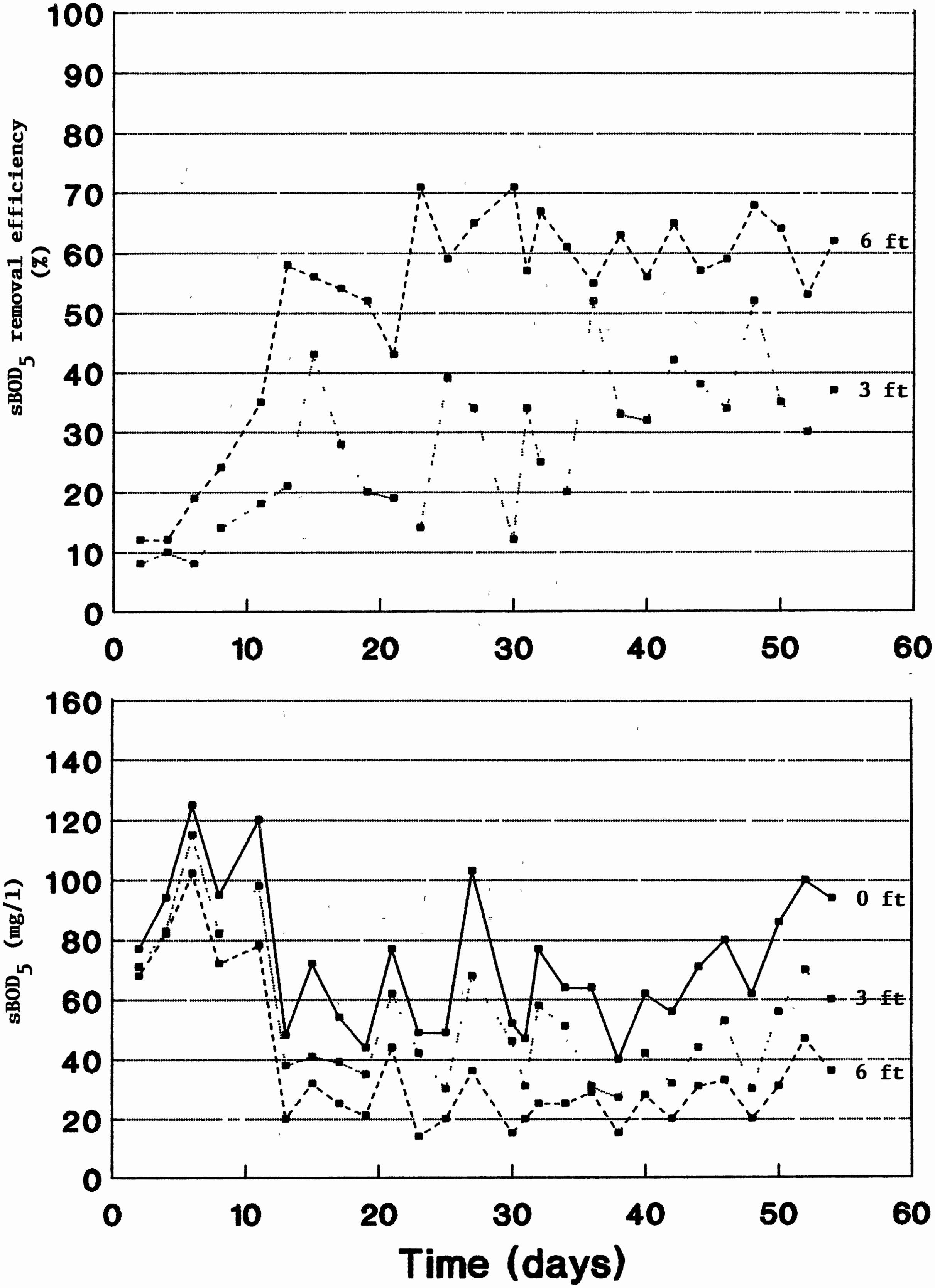

Figure 5: sBOD5 Removal Efficiency and sBOD5 Concentrations at Various Tower Depths in the System Development Stage for Cu Experiment

weeks. Then, the sBOD5 removal efficiency at 6 ft showed fluctuations between 53 and 71 percent for a period of around four weeks. During this period, the effluent sBOD5 closely paralleled the influent (Fig. 5), that is, the tower performance for sBOD5 removal was almost constant. Therefore, the biological tower was assumed to have achieved an approximate steady state condition, which was called "pseudo-steady state", in terms of sBOD5 removal efficiency after around four weeks of operation. The variation of the sBOD5 and sBOD5 removal efficiency at the 6 ft tower depth was quantified with a 99 percent confidence interval which was given as (Finney, 1980):

$$\bar{X} - 2.58 * \frac{\sigma}{\sqrt{n}} \leq \mu \leq \bar{X} + 2.58 * \frac{\sigma}{\sqrt{n}}$$

where

$\bar{X}$ = Sample mean

σ = Standard deviation

n = Sample size

μ = Population mean

The sBOD5 removal efficiency at 6 ft depth had a mean of 61 percent with a 99 percent confidence interval of 58 to 64 percent removal efficiency at the pseudo-steady state (27-54 days). SBOD5 at the 6 ft tower depth had a mean of 27 mg/l with a 99 percent confidence interval of 21 to 33 mg/l sBOD5 under the pseudo-steady state condition.

The sBOD5 removal efficiency at the 3 ft tower depth, which was calculated as the difference between 0 and 3 ft, had a mean of 37 percent with a 99 percent confidence interval of 32 to 42 percent removal efficiency for a period of 16 days (between 38-54 days in Fig. 5). Also, $sBOD_5$ at 3 ft had a mean of 46 mg/l with a 99 percent confidence interval of 34 to 58 mg/l $sBOD_5$ during the same period.

Figure 5 shows that the $sBOD_5$ removal efficiency at the 3 ft tower depth more slowly reached equilibrium than at 6 ft. The top section (0-3 ft depth) was exposed to a greater variation in the feed concentration than the bottom section (3-6 ft depth). This probably contributed to it taking longer to stabilize.

Figure 6 shows the degree of scatter of the effluent $sBOD_5$ values (vs the influent $sBOD_5$ values) from the development stage (day 27-54) relative to the 99 percent confidence interval for the pseudo-steady state period. The confidence interval is shown by the solid lines. This interval indicates the range within which the effluent $sBOD_5$ values (vs the influent $sBOD_5$ values) would be expected following the metal toxicity tests when equilibrium condition are reestablished.

Total suspended solids (TSS) obtained during the pseudo-steady state period of the system were: 112±30 mg/l at the 0 ft depth, 99±28 mg/l at the 3 ft depth, and 89±42 mg/l at the 6 ft tower depth. Volatile suspended solids (VSS) were 83±26 mg/l at the 0 ft depth, 76±25 mg/l at the 3 ft depth, and 67±32 mg/l at the 6 ft tower depth at pseudo-steady state.

The variation of pH during the system development stage is shown in Figure 7. The influent pH varied between 7.0 and 8.5, with the pH of the effluent being about 0.3 units higher than that of the influent.

Table IX contains the average value of soluble and total copper

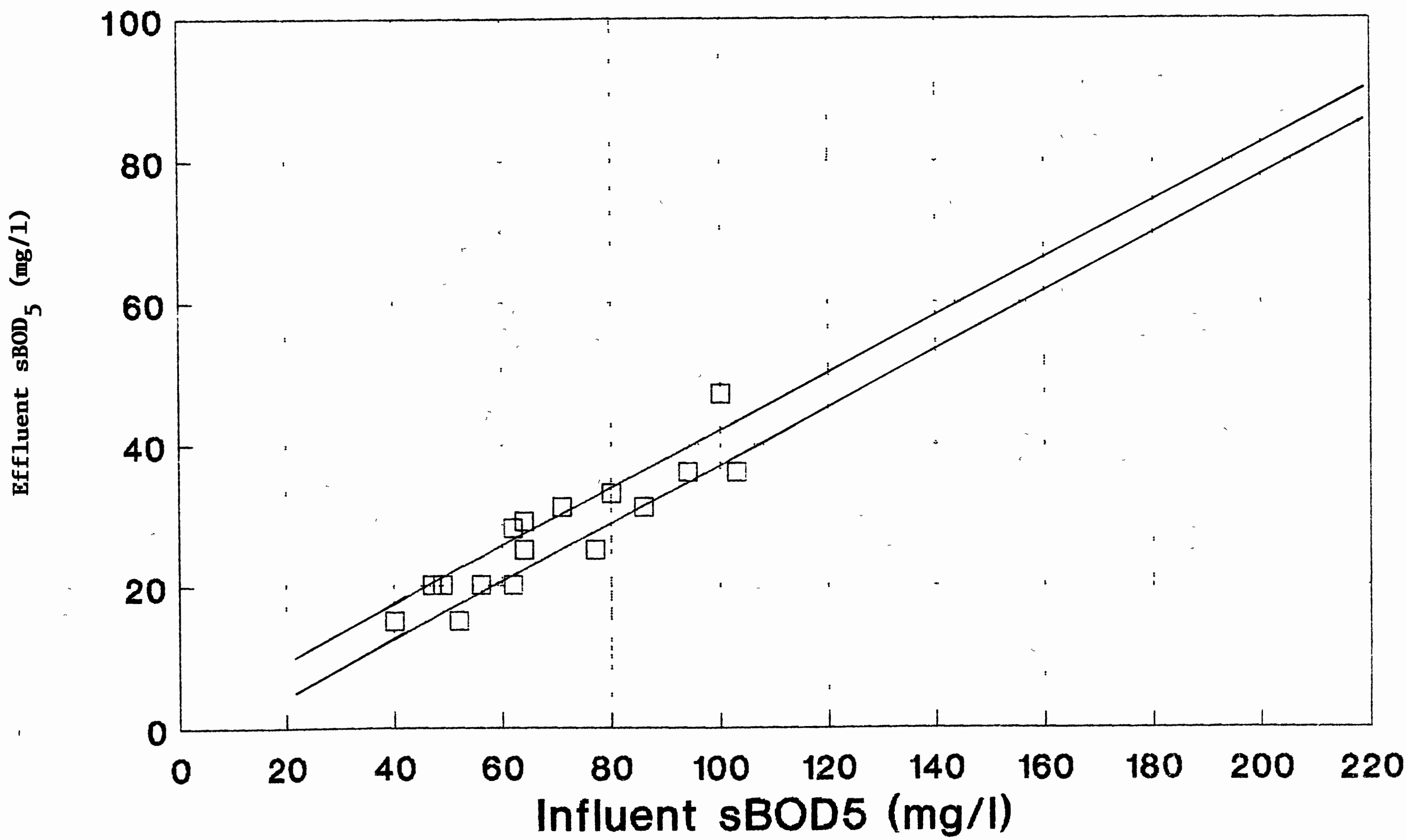

Figure 6: 99 % Confidence Interval for Influent and Effluent sBOD5 (Cu Experiment)

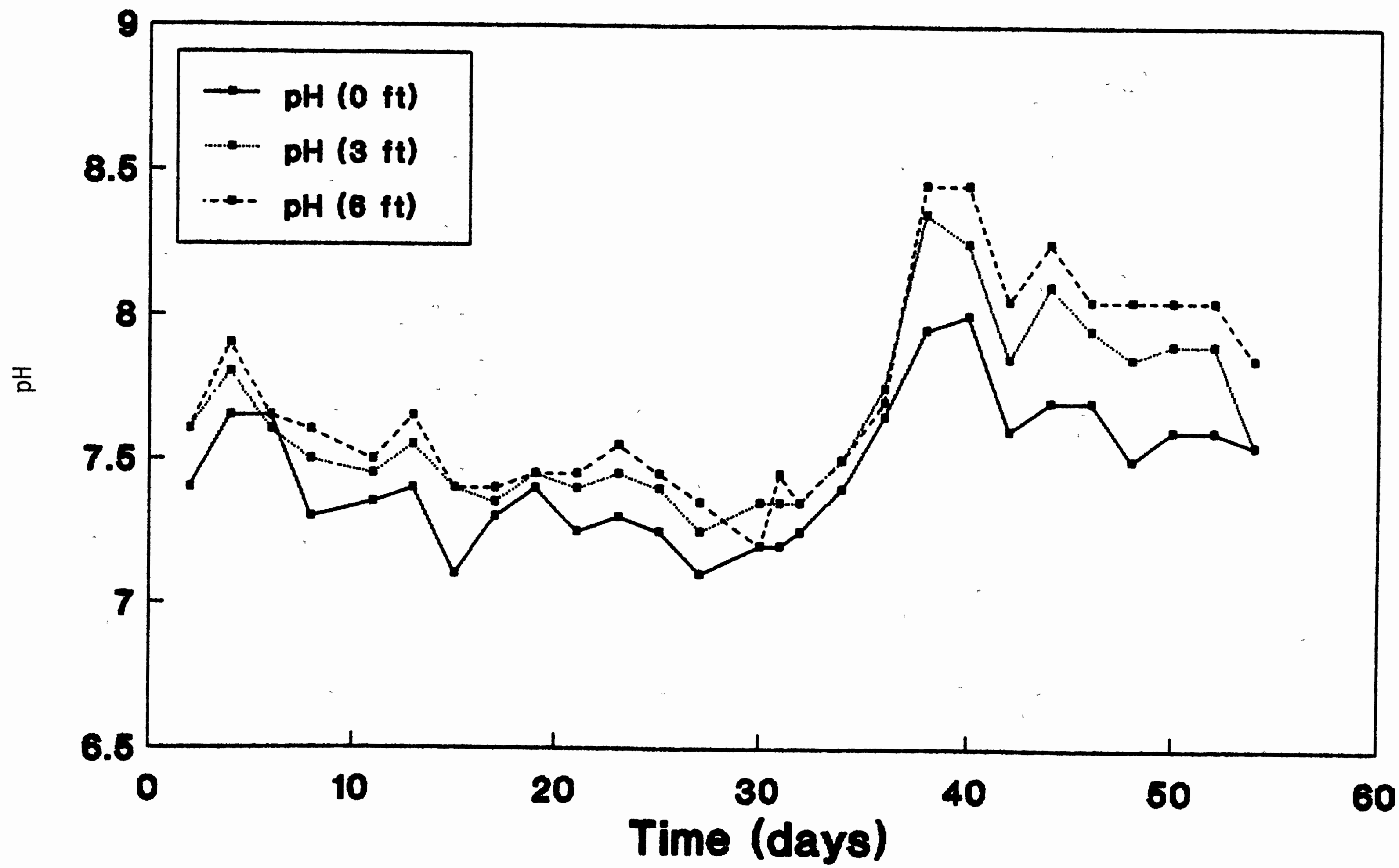

Figure 7: pH at Various Depths in the System Development Stage for Copper Experiment

TABLE IX

COPPER CONCENTRATION AT 0 FT, 3 FT, AND 6 FT DEPTH OF THE BIOLOGICAL TOWER DURING THE INJECTION PERIOD.

Injection Stage	Parameter	Copper conc. at 0 ft	3 ft	6 ft *
1st. Injection (3 mg/l for 135 hours)	Soluble conc. (mg/l)	2.08±0.68	1.09±0.42	0.64±0.23
	Total conc. (mg/l)	2.89±0.84	1.98±0.43	1.39±0.29
	Conc. in the Solids (mg/kg)	13,676±2315	10,761±2927	8,045±2741
2nd. Injection (56 mg/l for 10 hours)	Soluble conc. (mg/l)	5.00±0.80	2.68±0.65	2.08±0.32
	Total conc. (mg/l)	56.47±3.22	30.03±4.29	18.97±5.96
	Conc. in the Solids (mg/kg)	32,133±565	33,813±1723	24,626±601
3rd. Injection (47 mg/l for 10 hours)	Soluble conc. (mg/l)	4.44±0.88	3.16±0.49	2.86±0.26
	Total conc. (mg/l)	46.50±9.30	26.30±3.37	20.00±0.57
	Conc. in the Solids (mg/kg)	18,707#	14,590#	10,615#

*: Depth of the biological tower

#: Cu conc. in the solids, 2 hours after the injection stopped concentration in the liquid phase and copper concentration in the biological solids at each tower depth during the injection periods. The following figures (10, 13 , and 16), which are plotted on semilog scales to facilitate comparison of the dosage effects over time, accompany the discussion of each loading.

The first dosage of copper administered to the biological tower was 3 mg/l, which was continuously fed at a constant flow rate for 5 days and 15 hours. Samples were collected and monitored at intervals of four hours for the first 24 hours. Before the 3 mg/l copper solution was fed, the background copper concentration in the biological solids at the 0 ft tower depth was 108 mg/kg (dry-weight basis). During the experimental period for 3 mg/l copper dosage, the soluble and total copper concentration in the raw wastewater ahead of the inlet were approximately 0.08 mg/l and 0.11 mg/l, respectively. This background copper concentration in the raw wastewater did not adversely affect the biological treatment process.

At the 3 mg/l copper dose, relatively large amount of solid material was observed in the wastewater from the sampling port during the first 4 hours of the injection period because of sloughing from the surface of the media. The TSS value of the effluent increased suddenly to 942 mg/l, about 11 times higher than the effluent under the pseudo-steady state condition. Then the TSS concentration decreased gradually and returned to the pre-copper dosage level 8 hours after starting the injection of copper. However, the VSS concentration of the effluent was 52 mg/l 4 hours after the start of the copper injection. Any increase in the VSS of the effluent was not shown during the 3 mg/l copper experiment. The lack of increase in the VSS was considered to be due to an analytical error, possibly in the balance used, because the large amount of biomass sloughing should have caused some increase in the VSS concentration. Part of the TSS increase could be accounted for by inorganic copper precipitates.

During the 3 mg/l copper dose, a tower wide average soluble copper concentration was 1.27(±0.76) mg/l. The soluble copper concentration dropped below the threshold inhibition concentration of copper (1 mg/l) 21 hours after the copper spiking stopped. The 1.27 mg/l concentration of soluble copper inhibited carbonaceous biological oxidation in the inhibition screening test (Fig. 4). It is possible that the $sBOD_5$ values were affected by this soluble copper concentration during the injection period.

Figure 8 shows the variation in pH, $sBOD_5$, and $sBOD_5$ removal efficiency during the first copper toxicity test (3 mg/l copper dose). In this figure, $sBOD_5$ at the 3 ft and 6 ft depths was not extremely inhibited by the 3 mg/l copper dose during the injection period because the $sBOD_5$ values at the 3 ft depth was higher than those at the 6 ft depth. Also, the $sBOD_5$ values at each tower depth did not tract each other in a parallel fashion during the injection period, however, the $sBOD_5$ values at the various tower depths did seem to parallel each other after the injection stopped.

In Figure 8, the $sBOD_5$ removal efficiency at the 6 ft tower depth decreased to a value 8 percent lower than the mean value (61 %) of the pseudo-steady state period 21 hours after the injection stopped. Then, the $sBOD_5$ removal efficiency reached equilibrium 69 hours after the

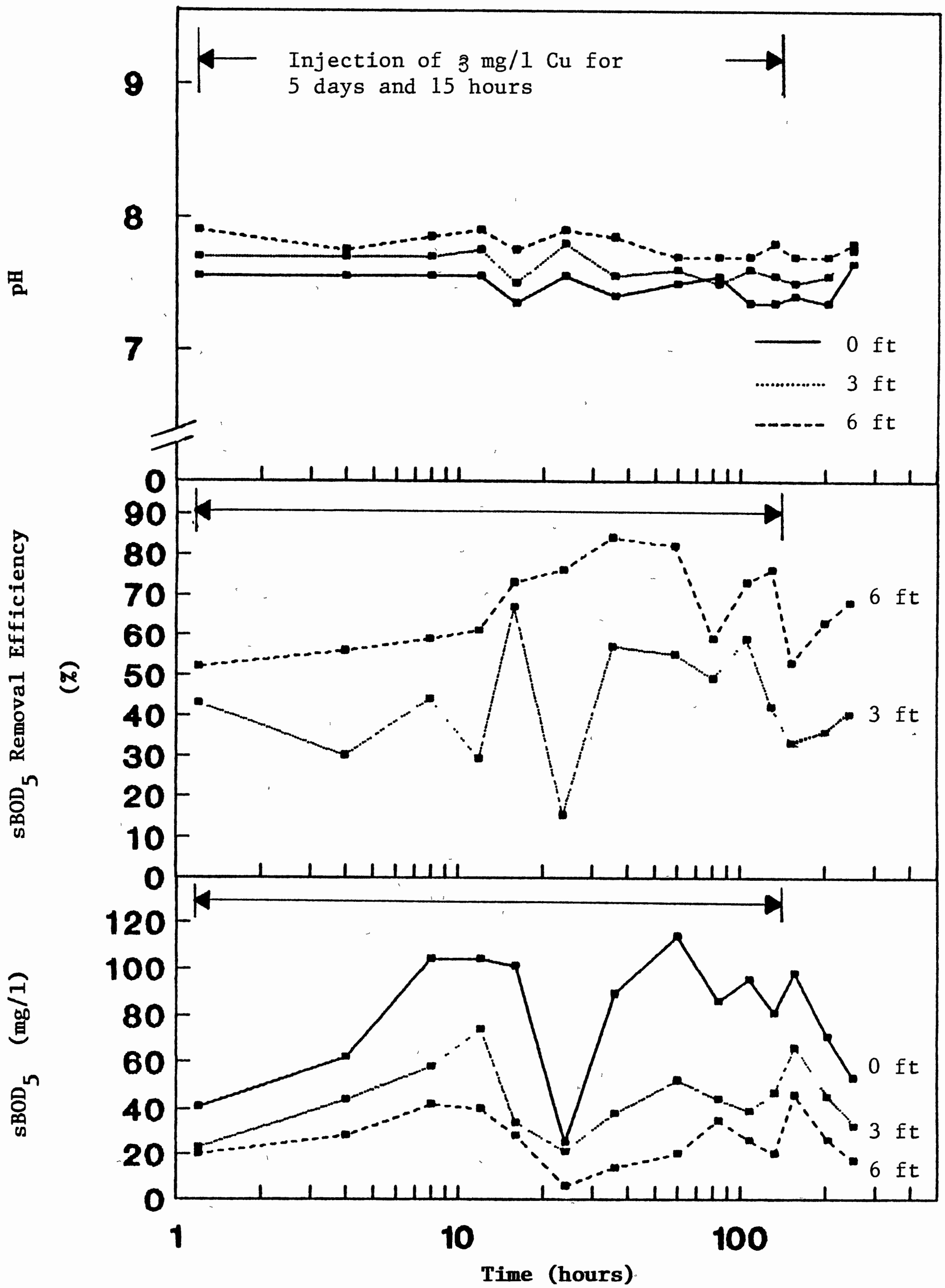

Figure 8: Effects of the 3 mg/l Cu Dose on pH, sBOD5 Removal Efficiency, and sBOD5 Concentrations at Various Tower Depths

injection stopped.

The $sBOD_5$ removal efficiency at the 3 ft depth dropped to 4 percent lower than the mean level (37 %) prior to the introduction of copper 21 hours after the injection stopped. The $sBOD_5$ removal efficiency at the 3 ft depth reached equilibrium 69 hours after the injection of copper stopped (Fig.8).

Figure 9 shows the effluent $sBOD_5$ values (vs the influent $sBOD_5$ values) which were not inhibited by the soluble copper and the range of 99 percent confidence interval. The data plotted were taken after the copper dose was stopped. The effluent $sBOD_5$ values of point 2 and 3 (Table X) are within the 99 percent confidence interval. This indicates that the tower performance in terms of $sBOD_5$ returned to the pre-dosage level 69 hours (point 2) after the injection of copper stopped.

With the 3 mg/l dose, the $sBOD_5$ removal efficiency was 33 and 53 percent at the 3 and 6 ft depths, respectively, 21 hours after the injection of copper stopped. These values were near the pseudo-steady state level of the tower. Therefore, it was considered that the 3 mg/l copper dose had no serious effect on the $sBOD_5$ removal efficiency of the biological tower.

Figure 10 shows the change of the soluble and total copper concentration and the copper concentration in the biological solids at the 3 mg/l copper dose. The removal efficiency of soluble and total copper in this system was 69 and 52 percent at the 6 ft tower depth during the injection period. In the case of the 3 ft tower depth, 48 and 31 percent removal efficiency of soluble and total copper concentration was calculated, respectively. The reason for the reported

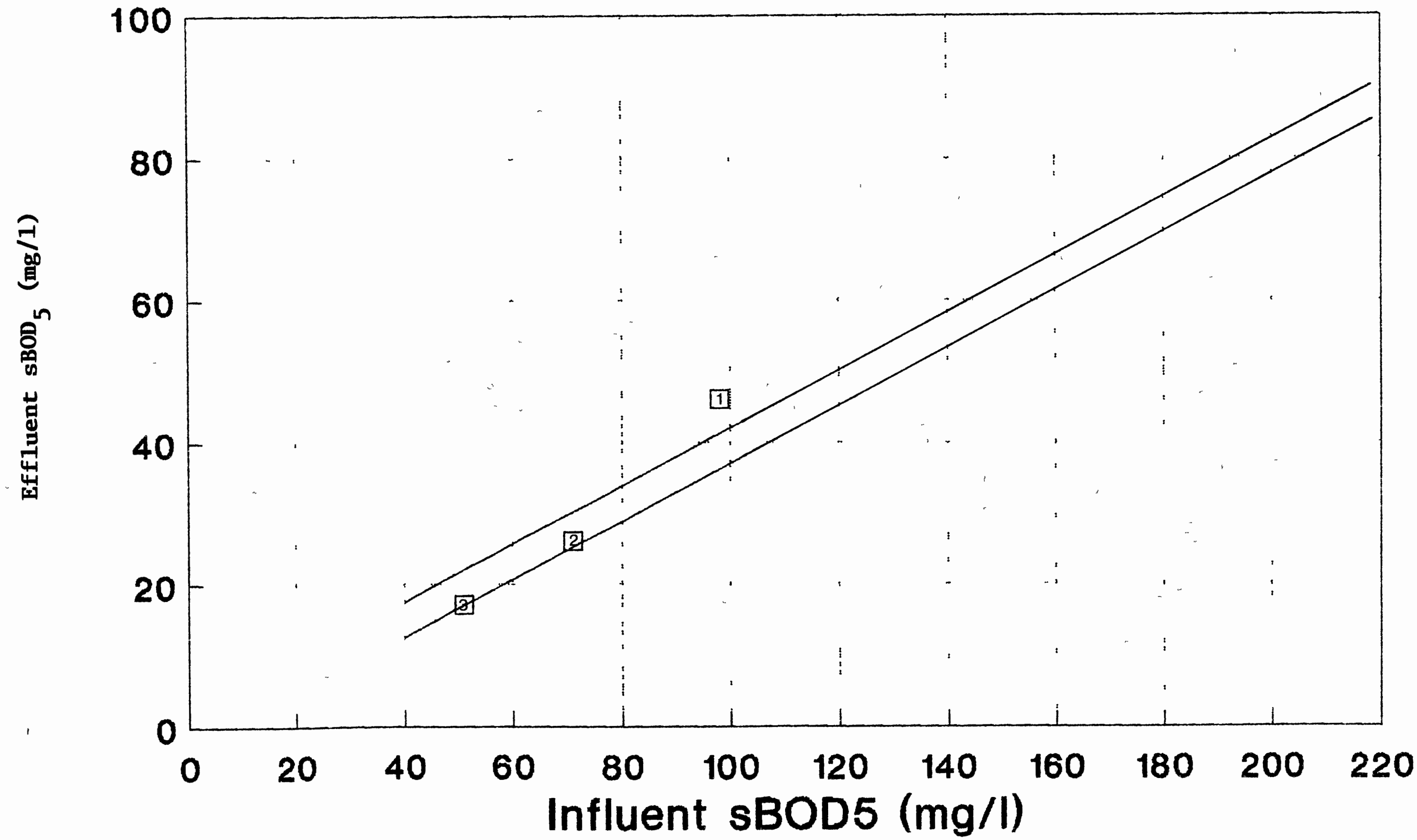

Figure 9: Hypothetical sBOD5-Response for the 3 mg/l Cu Dose
Solid Lines Represent 99 % Confidence Interval

TABLE X

INFLUENT AND EFFLUENT $sBOD_5$ VALUES AT ELAPSED TIMES IN FIGURE 9

Metal Conc.	Number in Fig.9	Elapsed time (hours)*	Influent $sBOD_5$ (mg/l)	Effluent $sBOD_5$ (mg/l)
Cu 3 mg/l	1	21	98	46
	2	69	71	26
	3	117	51	17

*: Time after the injection of copper stopped.

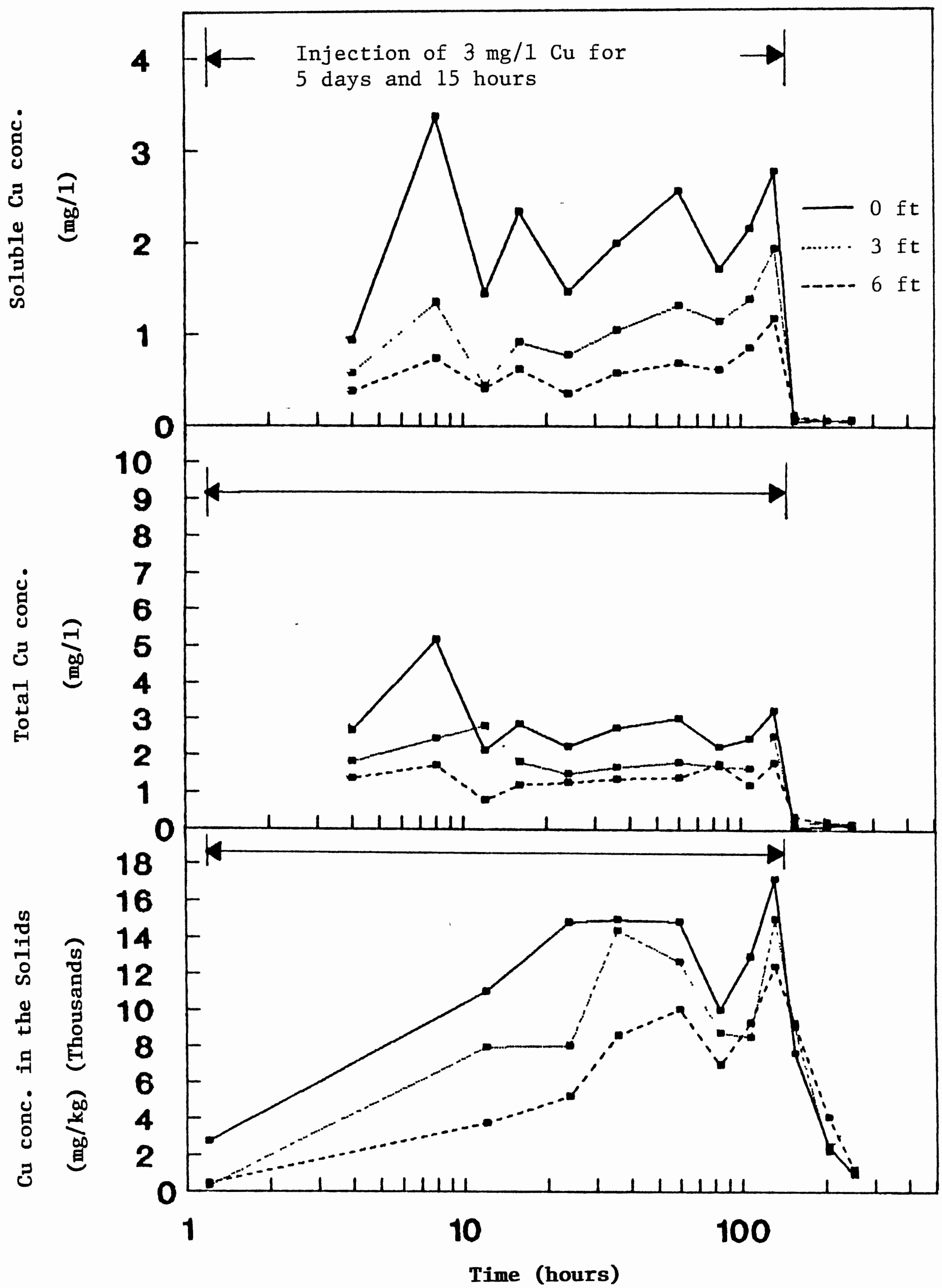

Figure 10: Cu Conc. at Various Tower Depths for the 3 mg/l Cu dose

greater removal efficiency of soluble copper as apposed to total copper could be due to analytical error.

The soluble copper may be removed by adsorption on to the biological and inorganic solids and by precipitation. The removal mechanisms of the total copper in the biological tower was considered to be absorption of the soluble and particulate portion onto the slime layer simultaneously along with precipitation.

The tower wide average copper concentration in the biological solids was 10827(±2299) mg/kg (dry-weight basis) during the injection period. The copper concentration in the biological solids of 10827(±2299) mg/kg decreased by 20 and 73 percent (calculated as tower wide average) 21 and 69 hours after the injection stopped, respectively (Fig 10 and Table XI). When the $sBOD_5$ removal efficiency was restored (69 hours after the injection stopped), the tower wide average of the copper concentration in the biological solids was 2945(±831) mg/kg (dry-weight basis).

Eleven days after the termination of the 3 mg/l copper injection, the influent copper concentration feed to the tower was increased to 56 mg/l. The 56 mg/l copper dosage was to be used during two separate experimental periods. However, the actual dosage in the second of these two experiments turned out to be less than 56 mg/l.

The 56 mg/l spiking of copper was conducted over a period of 10 hours and markedly influenced the system treatment efficiency. A large amount of solid material sloughed from the filter media. The TSS concentration of the effluent increased to 1058 mg/l 4 hours after starting the injection of 56 mg/l copper. The TSS concentration

TABLE XI

COPPER CONCENTRATION IN THE BIOLOGICAL SOLIDS
AT THE 3 MG/L COPPER DOSE

Elapsed time (hours)	/ Cu conc. in the biological solids (mg/kg) at / 0 ft depth	3 ft depth	6 ft depth
12	11,000	7,929	3,741
24	14,821	8,030	5,251
36	14,957	14,405	8,605
48	14,835	12,718	10,044
72	9,995	8,723	6,963
96	12,978	8,502	9,276
120	17,145	15,017	12,434
144 (21)*	7,611	9,033	9,277
192 (69)*	2,509	2,217	4,108
240 (117)*	939	1,121	1,229

()*: Time after the injection stopped.

decreased to 160 mg/l 8 hours after the start of the copper spiking and the TSS value returned to the pre-dosage level (89±42 mg/l) 10 hours after the injection of copper stopped. The VSS concentration of the effluent was 222 mg/l, instantly (within 10 minutes for sampling) after the start of the copper injection. Four hours after the start of the copper injection, the VSS concentration of the effluent was 154 mg/l. Then the VSS of the effluent decreased and returned to the pre-dosage level (67±32 mg/l) 10 hours after the injection stopped. The data taken four hours after the start of the copper injection showed that the VSS concentration of the effluent due to the copper dose did not result in as large increase as was the case for the TSS concentration of the effluent. The small amount of increase in the VSS concentration was considered to be an analytical error, possibly in the balance used. Part of the TSS increase could be accounted for by inorganic copper precipitates.

During the injection period of the 56 mg/l copper dose, a tower wide average of soluble copper concentration in wastewater was 3.26(±1.42) mg/l which caused inhibition of the $sBOD_5$ value in the inhibition screening test. The soluble copper concentration dropped rapidly after the injection stopped. The soluble copper concentration was 0.8 mg/l at the 6 ft tower depth 2 hours after the injection stopped. This soluble copper concentration was below the threshold level which was able to inhibit the $sBOD_5$ value in the inhibition test (Fig. 4).

In Figure 11, the $sBOD_5$ values at the 3 ft and 6 ft depths were almost same for the first 8 hours. It was surmised that the $sBOD_5$

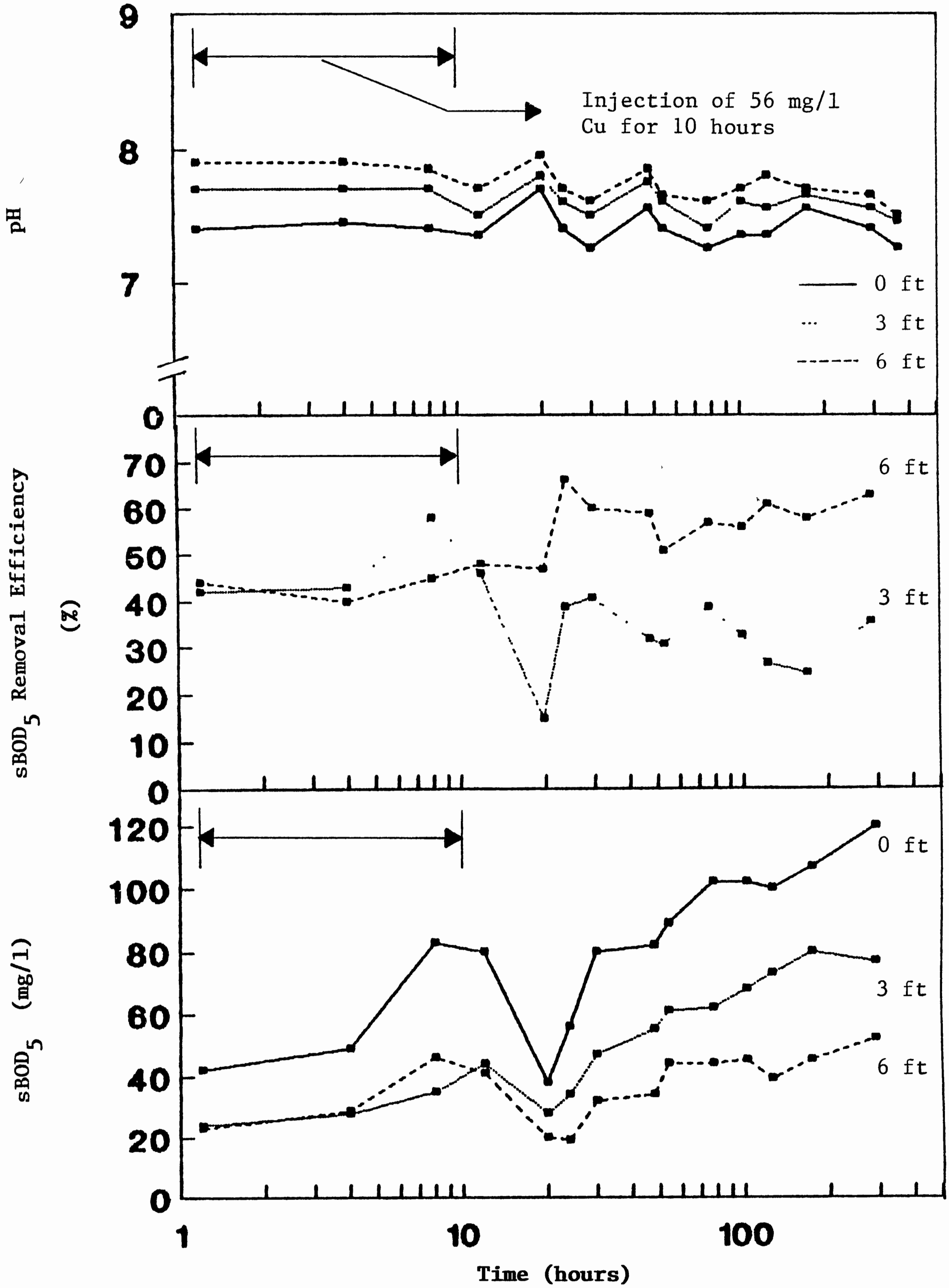

Figure 11: Effects of the 56 mg/l Cu Dose on pH, sBOD5 Removal Efficiency, and sBOD5 Concentrations at Various Tower Depths

values at the 3 ft and 6 ft tower depth (especially at the 3 ft depth) were more inhibited by the 56 mg/l copper dose than by the 3 mg/l copper dose during the injection period. The $sBOD_5$ values at 3 ft and 6 ft depths were gradually reestablished equilibrium after the copper injection stopped.

As shown in Figure 11, the $sBOD_5$ removal efficiency was around 14 percent lower than the pre-dosage level 10 hours after the injection stopped. The $sBOD_5$ removal efficiency was considered to reach equilibrium 14 hours after the copper injection stopped. In the case of the 3 ft tower depth, the $sBOD_5$ removal efficiency decreased to 15 percent 10 hours after the injection stopped, then reestablished equilibrium.

Figure 12 shows that the majority of the data points starting with number 3 exist within the range of 99 percent confidence interval (Table XII). Because of this the tower performance was considered to be restored to the level before the introduction of copper 14 hours after the spiking stopped.

Under these conditions a large amount of copper accumulated in or on the biological solids. After 8 hours of injecting the 56 mg/l copper solution, the copper concentration in the biological solids reached its maximum value for this experiment: a tower wide average of 30752±4896 mg/kg (dry-weight basis) (Fig.13). As shown in Table XIII, the copper concentration in the solids of 30752(±4896) mg/kg dropped about 50 percent (calculated as tower wide average) 2 hours after the copper spiking stopped because the raw wastewater no longer contained copper and the hydraulic loading rate of 0.9 gal/min/ft^2 was enough to wash

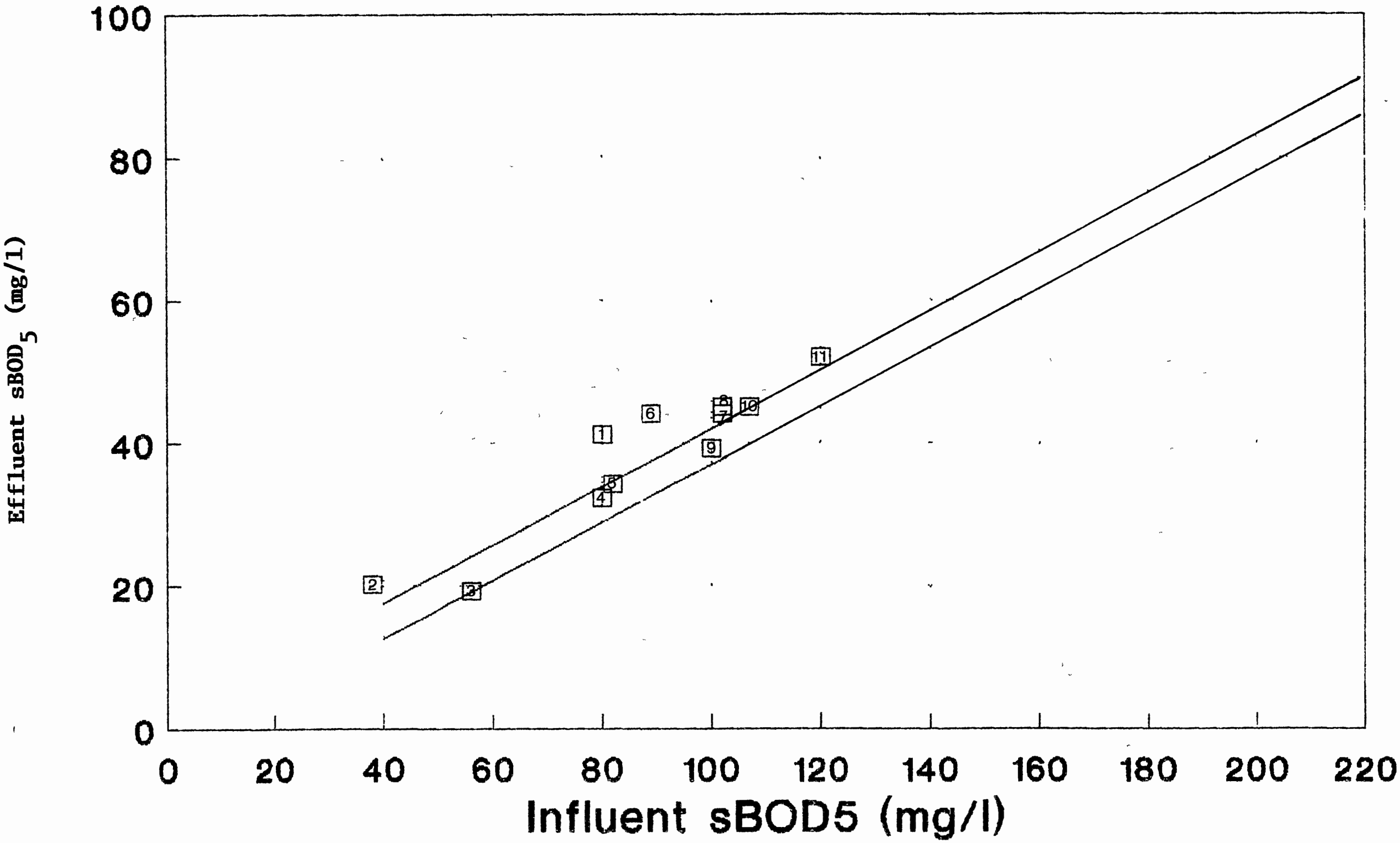

Figure 12: Hypothetical sBOD5-Response for the 56 mg/l Cu dose
Solids Lines Represent 99 % Confidence Interval

TABLE XII

INFLUENT AND EFFLUENT $sBOD_5$ VALUES AT ELAPSED TIMES IN FIGURE 12

Metal Conc.	Number in Fig.9	Elapsed time (hours)*	Influent $sBOD_5$ (mg/l)	Effluent $sBOD_5$ (mg/l)
Cu 56 mg/l	1	2	80	41
	2	10	38	20
	3	14	56	19
	4	20	80	32
	5	34	82	34
	6	44	89	44
	7	68	102	44
	8	92	102	45
	9	116	100	39
	10	164	107	45
	11	260	120	52

*: Time after the injection of copper stopped.

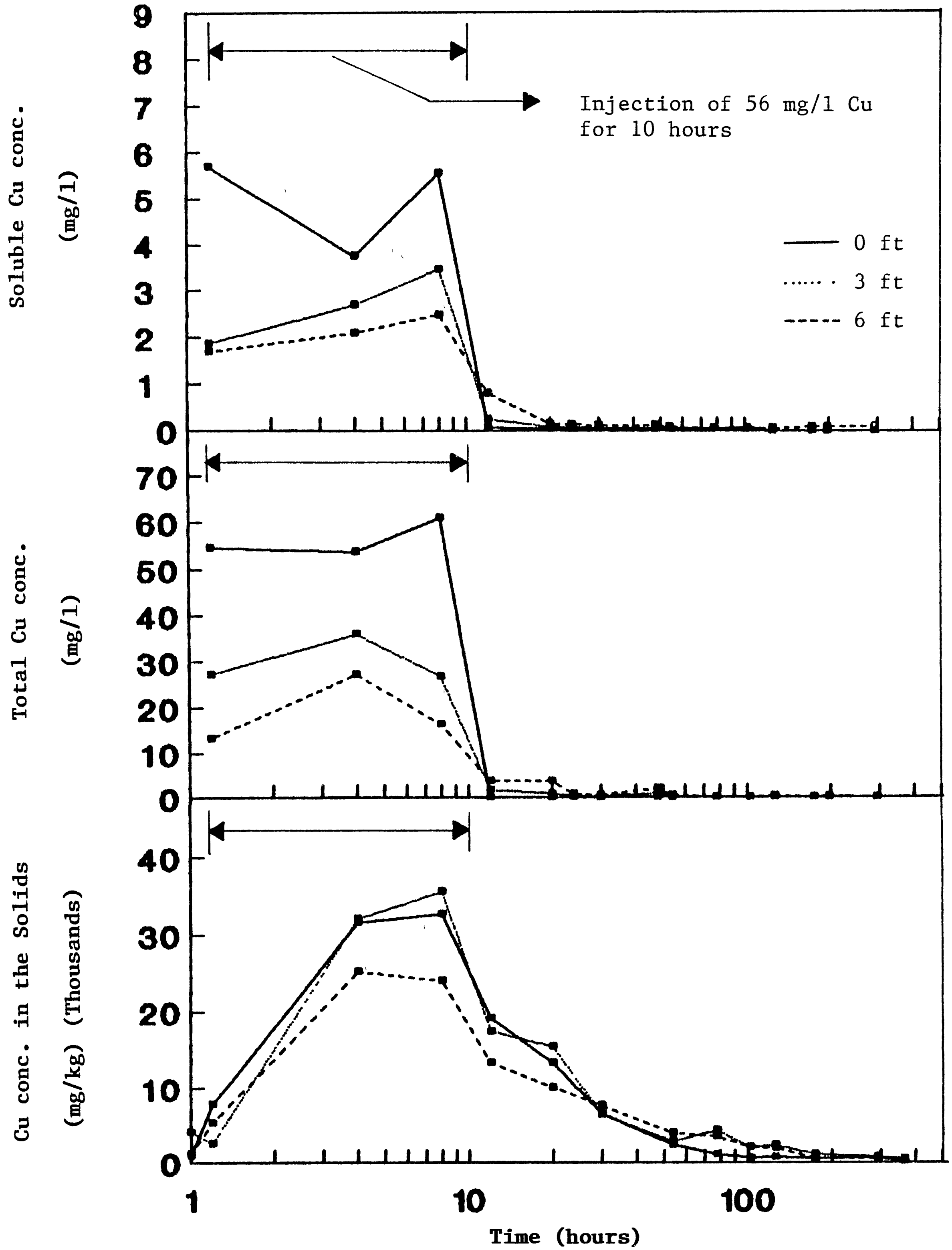

Figure 13: Cu Conc. at Various Tower Depths for the 56 mg/l Cu Dose

TABLE XIII

COPPER CONCENTRATION IN THE BIOLOGICAL SOLIDS
AT THE 56 MG/L COPPER DOSE

Elapsed time* (hours)	/ Cu conc. in the biological solids (mg/kg) at / 0 ft depth	3 ft depth	6 ft depth
During the injection period	32,697	35,535	24,025
2	19,161	17,419	13,326
10	13,359	15,425	10,060
20	6,537	6,484	7,622
44	2,442	2,906	4,007
92	664	2,085	2,081
164	570	1,138	579
260	258	454	375

*: Time after the injection of copper stopped.

out copper from the slime layer quickly due to desorption; then the copper concentration in the solids decreased to below 1000 mg/kg (dry-weight basis) 164 hours after the copper injection stopped. The tower wide average copper concentration in the slime layer was 362±81 mg/kg (dry-weight basis) 260 hours after the copper injection stopped (Table XIII).

During the period of the 56 mg/l copper dosage, background soluble and total copper concentration in the raw wastewater were around 0.07 mg/l and 0.1 mg/l, respectively. During this injection period the removal efficiency of soluble and total copper was 58 and 66 percent at the 6 ft tower depth, while removal of soluble and total copper at the 3 ft tower depth was 46 and 47 percent.

While the 47 mg/l slug dose (third dosage) of copper was administered over a 10 hour period, the inorganic solids were not sloughed from the filter media as much as during at the 56 mg/l copper dosage. The average value of the effluent TSS was 153(±23) mg/l at the 6 ft tower depth during the period of 47 mg/l copper injection. The average effluent VSS concentration was 88(±17) mg/l during the injection period. The VSS concentration of the effluent did not increase due to the injection of copper. The TSS increase during the the period of 47 mg/l copper injection could be accounted for by inorganic copper precipitates. The effluent TSS returned to the pre-dosage level 2 hours after the injection stopped.

During the 47 mg/l copper dose, the average concentration of soluble copper throughout the tower was 3.49(±0.92) mg/l. The soluble copper concentration was 0.78 mg/l at the 6 ft tower depth 2 hours after the injection stopped. This concentration did not cause the inhibition of $sBOD_5$ in the inhibition screening test because this soluble copper concentration was below 1 mg/l which was the threshold inhibition level for $sBOD_5$ (Fig. 4).

As shown in Figure 14, $sBOD_5$ at the 3 ft tower depth was inhibited more seriously than that at the 6 ft tower depth during the period of 47 mg/l copper injection because the $sBOD_5$ values at 3 ft depth were lower than at the 6 ft tower depth. These $sBOD_5$ values reached equilibrium gradually after the injection stopped.

The $sBOD_5$ removal efficiency at the 6 ft tower depth was about 5 percent lower than the mean level (61 percent) at the pseudo-steady state 10 hours after the injection stopped; then the $sBOD_5$ removal efficiency reached equilibrium (Fig. 14). At the 3 ft tower depth, the $sBOD_5$ removal efficiency reached pre-dosage level (32-42 percent) 2 hours after the injection stopped (Fig. 14).

In Figure 15, points 2 and 4 are located within the area of 99 percent confidence interval and the remainder are closely approximate to the lines defining this interval (Table XIV). However, thirty eight hours after the injection stopped (point 5), the effluent $sBOD_5$ values (vs the influent $sBOD_5$ values) seemed to establish a new pseudo-steady state level which was located a little higher than the range of the 99 percent confidence interval, possibly due to the cumulative effect of copper. Therefore, the tower performance of $sBOD_5$ removal was considered to returned to pseudo-steady state condition 38 hours after the injection stopped.

During the 47 mg/l experiment, the average background

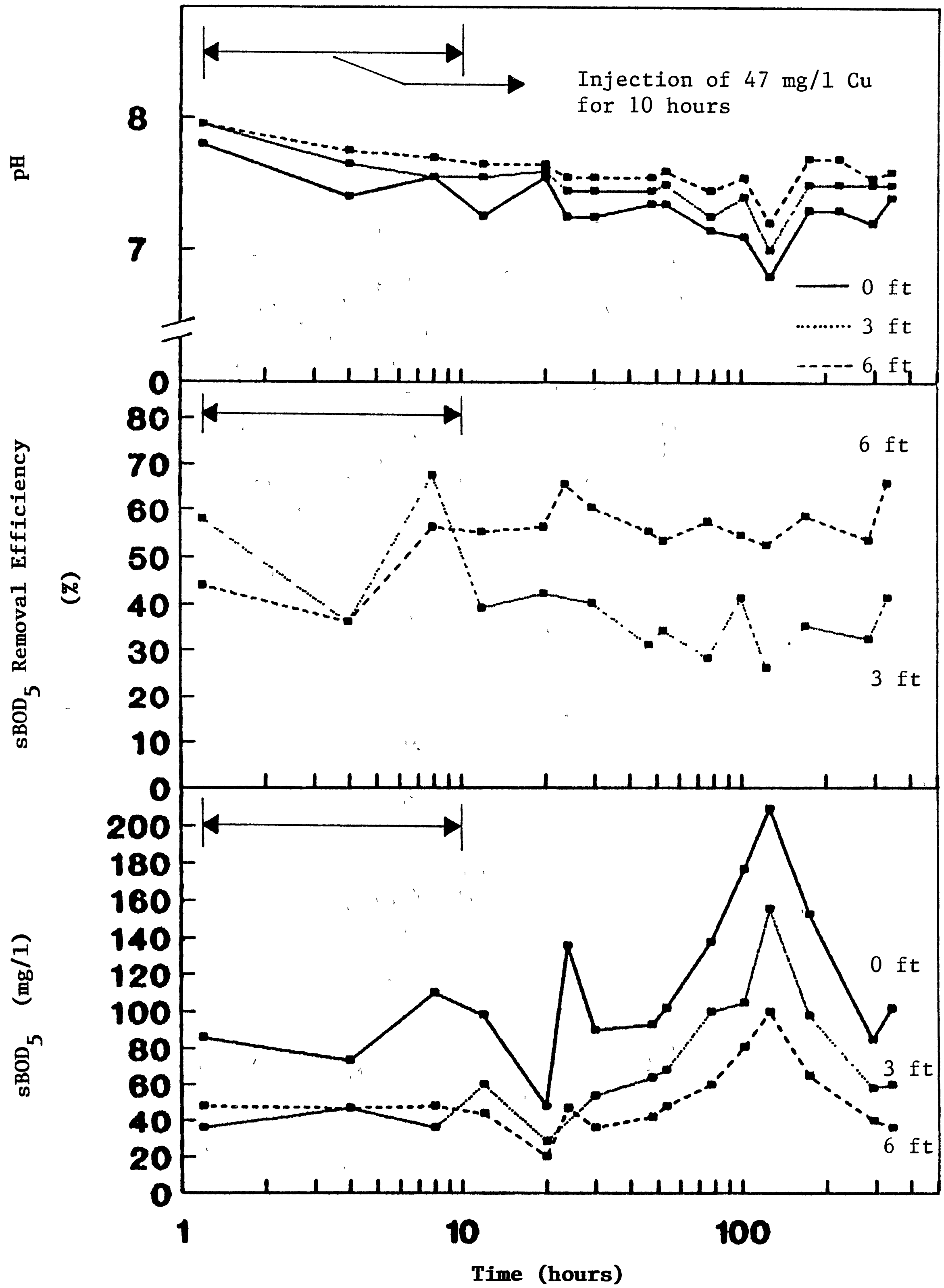

Figure 14: Effects of the 47 mg/l Cu Dose on pH, sBOD5 Removal Efficiency, and sBOD5 Concentrations at Various Tower Depths

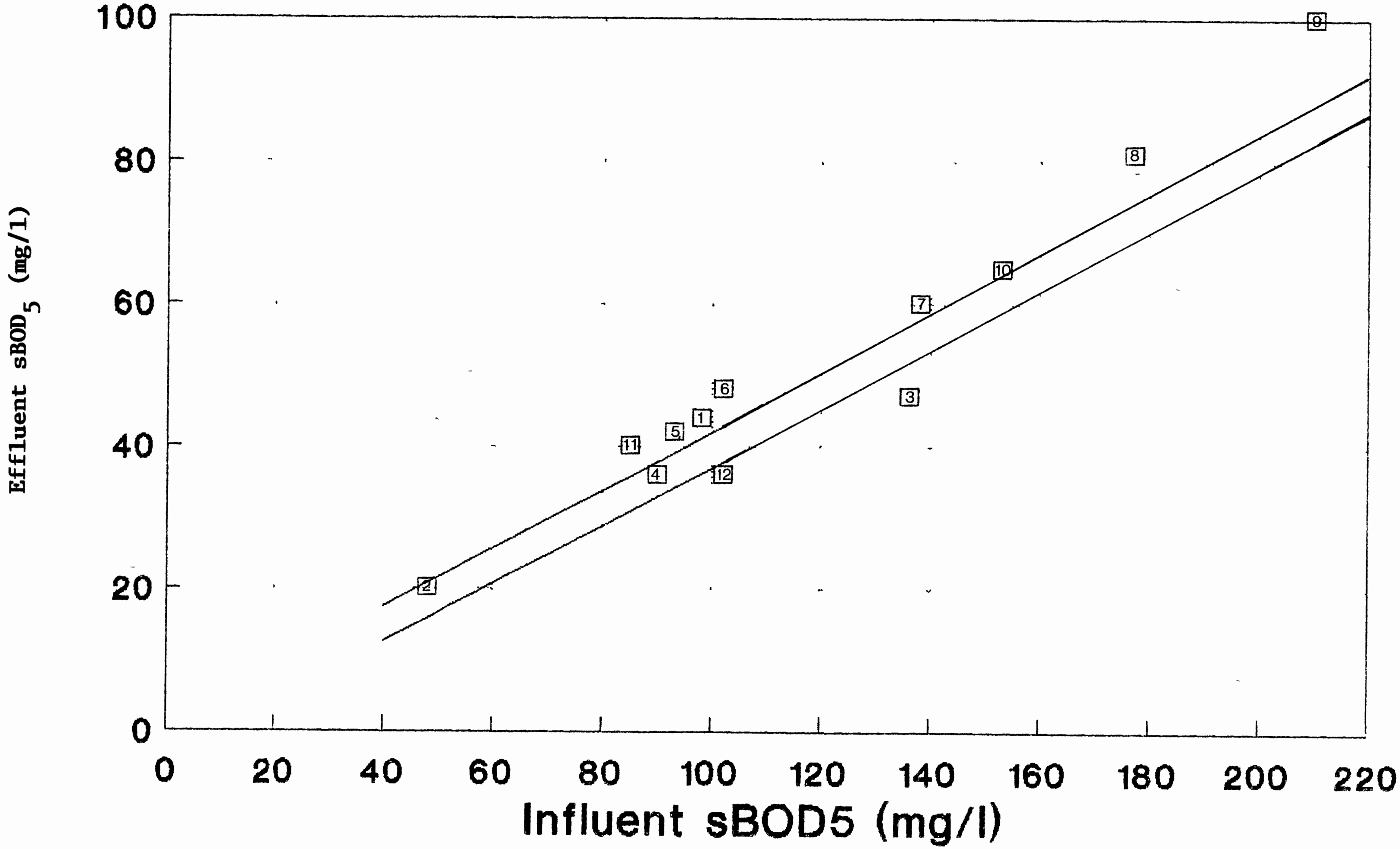

Figure 15: Hypothetical sBOD5-Response for the 47 mg/l Cu Dose
Solid Lines Represent 99 % Confidence Interval

TABLE XIV

INFLUENT AND EFFLUENT $sBOD_5$ VALUES AT ELAPSED TIMES IN FIGURE 15

Metal Conc.	Number in Fig.9	Elapsed time (hours)*	Influent $sBOD_5$ (mg/l)	Effluent $sBOD_5$ (mg/l)
Cu 47 mg/l	1	2	98	44
	2	10	48	20
	3	14	136	47
	4	20	90	36
	5	38	93	42
	6	44	102	48
	7	68	138	60
	8	92	177	81
	9	116	210	100
	10	164	153	65
	11	284	85	40
	12	332	102	36

*: Time after the injection of copper stopped.

concentrations of soluble and total copper in the raw wastewater were 0.11 mg/l and 0.14 mg/l, respectively. The removal efficiency of soluble and total copper through the biological tower was 36 and 57 percent, respectively, at the 6 ft tower depth. In the case of the 3 ft tower depth, the removal efficiency of soluble and total copper was 29 and 43 percent, respectively.

The copper concentration in the slime layer 2 days before the 47 mg/l copper dosage was initiated was 362±81 mg/kg (dry-weight basis) throughout the tower. During the 47 mg/l copper dosage, the samples taken of the slime layer after 4 hours and 8 hours of copper injection were accidentally destroyed. Therefore, it is difficult to compare the copper uptake rate during the 56 mg/l dose with that at the 47 mg/l dose. The copper concentration in the biological solids was 80±65 mg/kg (dry-weight basis) throughout the tower 332 hours after the 47 mg/l copper spiking stopped (Fig.16 and Table XV) which was close to background level of the tower before copper was added.

While the copper solution was being injected into the system, in all runs, the $sBOD_5$ values of the samples taken during this time were affected by the soluble copper concentration. The $sBOD_5$ of the influent containing copper at the 0 ft tower depth was lower than the $sBOD_5$ of raw domestic wastewater taken immediately upstream of the point of copper injection for each copper dosage. This was due to the toxicity of the soluble copper interfering with biological activity of microorganisms during the BOD test. As such, the $sBOD_5$ values measured during copper addition phase of the experiments may be of questionable value in the analysis of the performance of the biological tower.

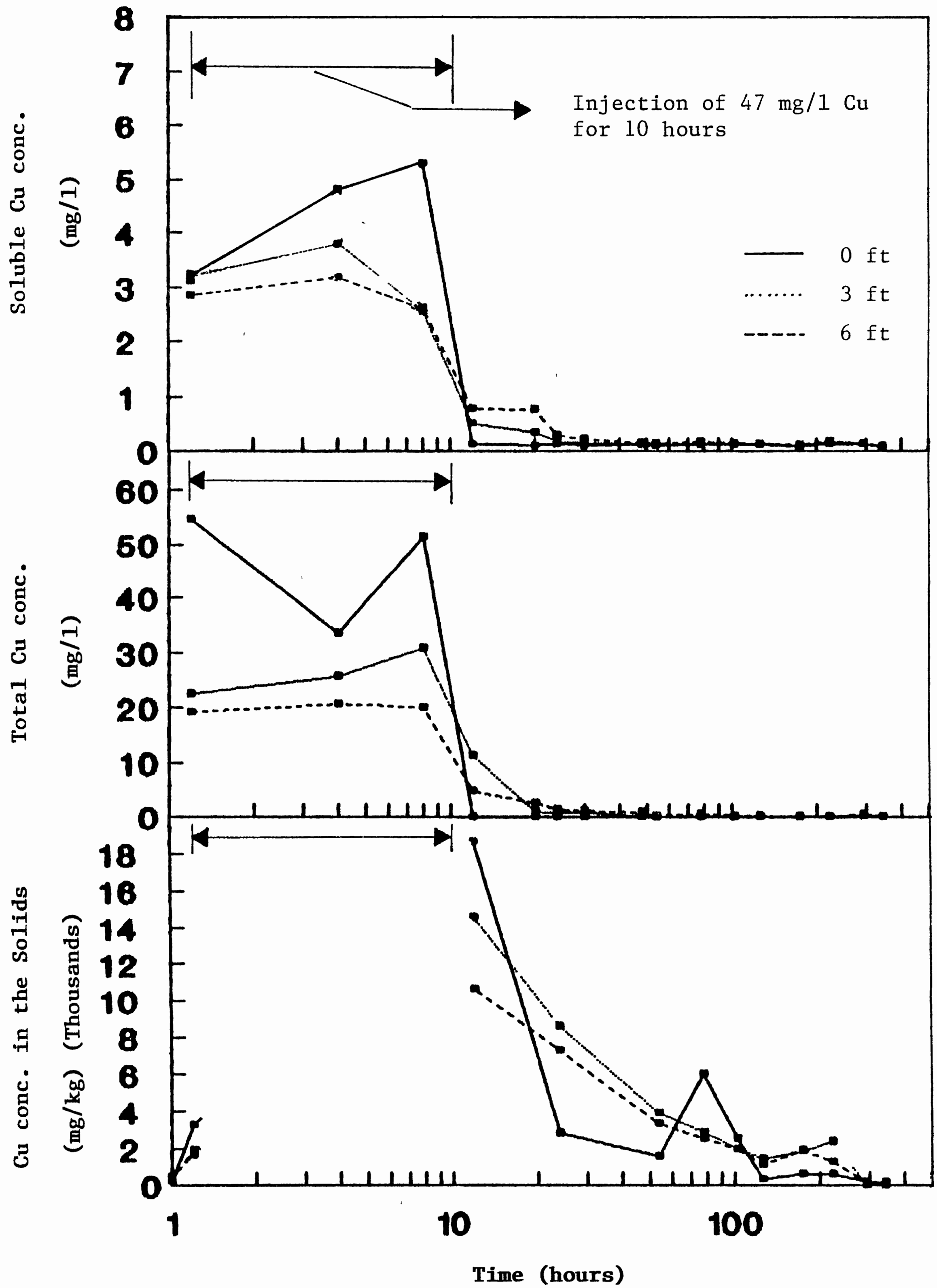

Figure 16: Cu Conc. at Various Tower Depths for the 47 mg/l Cu Dose

TABLE XV

COPPER CONCENTRATION IN THE BIOLOGICAL SOLIDS
AT THE 47 MG/L COPPER DOSE

Elapsed time* (hours)	/ Cu conc. in the biological solids (mg/kg) at / 0 ft depth	3 ft depth	6 ft depth
2	18,707	14,590	10,615
14	2,825	8,599	7,276
44	1,590	3,879	3,322
92	2,515	1,976	1,968
164	633	1,868	1,891
284	189	21	159
332	171	22	49

*: Time after the injection of copper stopped.

In the case of the 3 mg/l copper dose, the soluble copper concentration in the wastewater through the tower was below the threshold concentration, which could inhibit the $sBOD_5$ value, 21 hours after the injection stopped. In the 56 mg/l and 47 mg/l copper doses, values less than the threshold inhibition concentration were reached 2 hours after the injection stopped, respectively. The recovery time of the tower treatment efficiency using $sBOD_5$, was analyzed using data which showed the soluble metal concentration to be below the threshold inhibition level.

Since the copper stock solution was mixed with raw domestic wastewater, some amount of the soluble copper introduced into the wastewater was converted to the particulate form of copper by adsorption onto the solids and precipitation. For the 3, 56, and 47 mg/l soluble copper doses, a mean of 2.08(±0.68), 5.00(±0.80) and 4.44(±0.88) mg/l was measured in the influent from the distributor in the soluble form, respectively (Table IX). The reduction of soluble copper by adsorption and precipitation was 28 percent at the 3 mg/l dose and 91 percent at the 56 and 47 mg/l doses. In a preliminary study, 13 and 65 percent reduction of soluble copper by precipitation only were calculated at 3.3 and 11.4 mg/l doses, respectively. The difference of the reduction percentages between the 3 mg/l and 3.3 mg/l doses was considered to be caused by adsorption.

Table XVI summarizes the effects of the copper on the biological tower and the copper concentration in both the solid and liquid phases at the recovery time. It took longer time for the tower performance to recover at the third dose (47 mg/l) than at the second dose (56 mg/l).

TABLE XVI

SUMMARY OF REACTIONS TO COPPER IN THE BIOLOGICAL TOWER

Injection con. of Cu	Recovery time (% BOD removal)	Soluble con. (mg/l)	Total con. (mg/l)	Con. in the solids (mg/kg)
		/ at recovery time based on % BOD removal /		
3 mg/l (135 hr)[1]	69 hours[2]	0.07 (0 ft)[3]	0.11 (0 ft)	2,509 (0 ft)
		0.07 (3 ft)	0.23 (3 ft)	2,217 (3 ft)
		0.07 (6 ft)	0.22 (6 ft)	4,108 (6 ft)
56 mg/l (10 hr)[1]	14 hours[2]	0.05 (0 ft)	0.17 (0 ft)	6,537 (0 ft)[4]
		0.08 (3 ft)	0.94 (3 ft)	6,484 (3 ft)[4]
		0.15 (6 ft)	1.99 (6 ft)	7,622 (6 ft)[4]
47 mg/l (10 hr)[1]	38 hours[2]	0.12 (0 ft)	0.13 (0 ft)	1,590 (0 ft)[5]
		0.13 (3 ft)	0.19 (3 ft)	3,879 (3 ft)[5]
		0.16 (6 ft)	0.90 (6 ft)	3,322 (6 ft)[5]

1: Duration of copper injection
2: Recovery time after the injection of copper stopped
3: Depth of the biological tower
4: data after 6 hours (no data at this time)
5: data after 6 hours (no data at this time)

The tower performance also established new pseudo-steady state condition at the 47 mg/l copper dose. This phenomenon indicates that the microorganisms are not acclimated by the second shock load (56 mg/l copper dose), but cumulatively damaged by the first (3 mg/l copper dose), second (56 mg/l copper dose), and third shock loads (47 mg/l copper dose).

The copper concentration in the solids at the recovery time was 2945(±831), 6881(±524), 2930(±975) mg/kg (dry-weight basis) as a tower wide average at the 3, 56, 47 mg/l copper dosage (Table XVI). The soluble copper concentration in the effluent at the time of recovery was close to the background level which did not inhibit the $sBOD_5$ value. The copper concentration in the solids decreased with increase in the recovery time due to desorption of copper from the solids in the two slug doses of copper experiment (56 mg/l and 47 mg/l). It is difficult to compare the relationship of the copper concentration in the solids and the tower performance in terms of $sBOD_5$.

Table XVI also shows the soluble and the total copper concentration at each depth of the tower at the recovery time. The tower treatment of $sBOD_5$ was not affected by up to 0.16 mg/l of soluble copper concentration or 2 mg/l of total copper concentration in these copper experiments.

During the copper feedings, the pH values of raw wastewater were almost the same as those of the influent containing copper.

Effects of Chromium as Potassium Dichromate.

Following the completion of the experiments using copper the existing biofilm on the biological tower was killed by pumping a concentrated chlorine solution through the tower. The tower media, walls, and distributors were then thoroughly cleaned to remove the dead bacteria cells. Once cleaned the tower was rinsed several times with tap water, reassembled and placed back on line with its domestic wastewater feed in order to develop a new biofilm for use during the chromium experiments. The experiments run to examine the effects of slug doses of chromium on the biological tower were conducted under the same conditions as the investigation using copper except for the hydraulic loading rate. The hydraulic loading rate was increased from 0.9 to 1 gal/min/ft^2 to avoid clogging of the distributor. The average $sBOD_5$ of the raw municipal wastewater for the chromium experiments was 86±30 mg/l at the 6:00 p.m. sample time used during the chromium runs. This value gives an average loading rate of 4.10(±1.43) lbs $sBOD_5$/day/1000 ft^2.

The response of the filterable BOD_5 and filterable BOD_5 removal efficiency vs time for the system development stage of the chromium experiments is shown in Figure 17. The $sBOD_5$ removal efficiency seemed to become relatively constant and the effluent $sBOD_5$ values closely paralleled the influent $sBOD_5$ values after 4 weeks. However, the hydraulic loading rate of the system was changed to 1 gal/min/ft^2 45 days after the beginning of the experiment. The biological tower was assumed to have approached equilibrium, which was called pseudo-steady

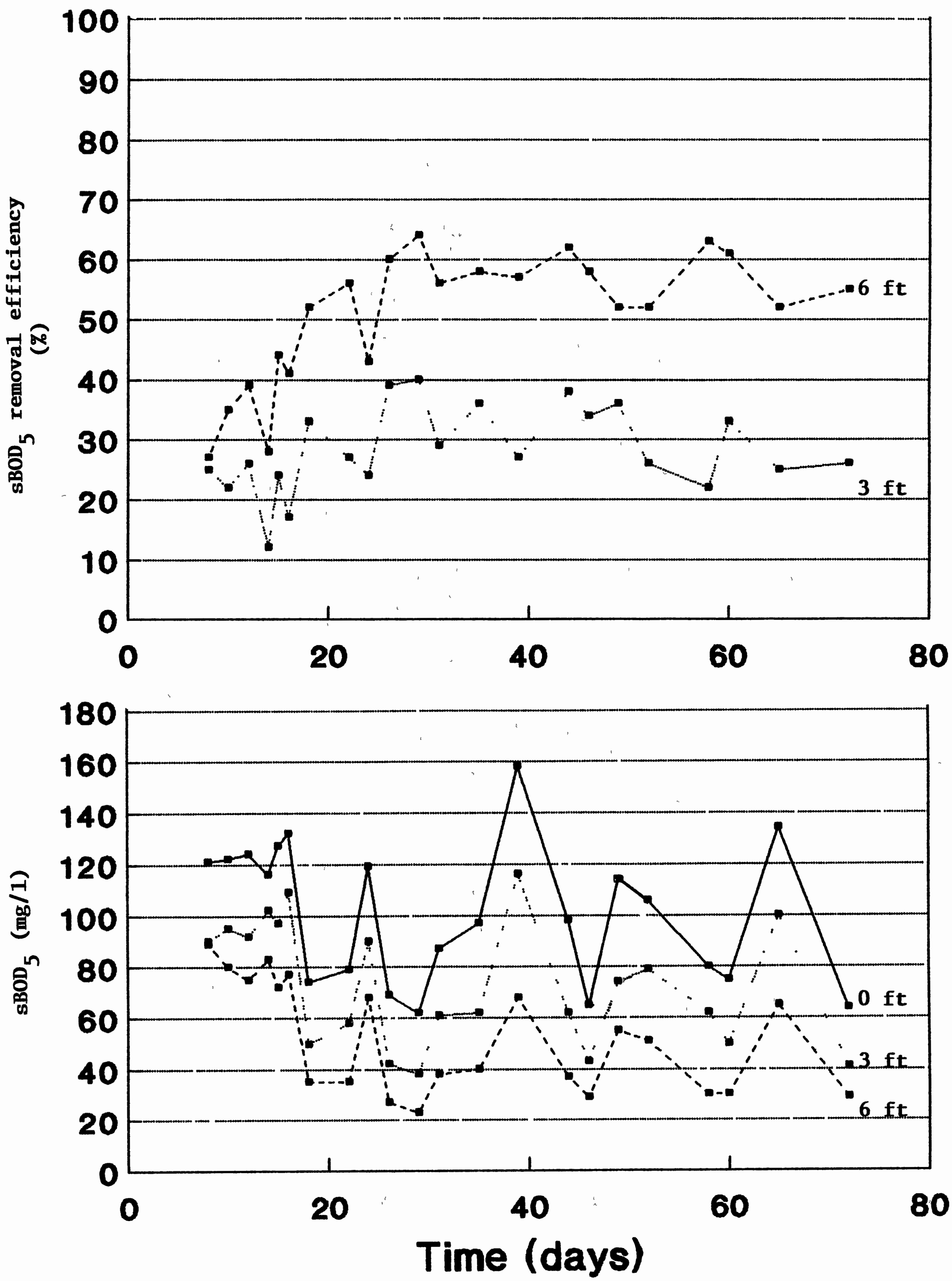

Figure 17: sBOD5 Removal Efficiency and sBOD5 Concentrations at Various Tower Depths in the System Development Stage for Cr Experiment

state, in terms of the tower performance for $sBOD_5$ removal after 49 days.

The $sBOD_5$ removal efficiency at the 6 ft tower depth had a mean of 56 percent with a 99 percent confidence interval of 51 to 61 percent removal efficiency at pseudo-steady state (49-65 days). Also, $sBOD_5$ at the 6 ft depth had a mean of 43 mg/l with 99 percent confidence interval of 30 to 56 mg/l $sBOD_5$ under the pseudo-steady state condition.

The $sBOD_5$ removal efficiency at the 3 ft tower depth seemed to reached equilibrium more slowly than at the 6 ft tower depth. The $sBOD_5$ removal efficiency at the 3 ft tower depth had a mean of 26 percent with a 99 percent confidence interval of 22 to 30 percent removal efficiency at pseudo-steady state (52-65 days). $SBOD_5$ at the 3 ft depth had a mean of 66 mg/l with a 99 percent confidence interval of 55 to 77 mg/l $sBOD_5$ at pseudo-steady state.

The mean $sBOD_5$ removal efficiency decreased by 11 percent from 37 to 26 percent at the 3 ft depth, and 5 percent from 61 to 56 percent at the 6 ft depth as compared to the removal efficiency under the pseudo-steady state condition prior to the copper experiments.

In Figure 18, the effluent $sBOD_5$ values (vs the influent $sBOD_5$ values) during the pseudo-steady state were evaluated by calculation and expressed as the 99 percent confidence interval which is shown by the solid lines. This confidence interval shows the area in which the effluent $sBOD_5$ values (vs the influent $sBOD_5$ values) would reach the same equilibrium condition after the chromium injection into the tower, as was seen prior to metal addition.

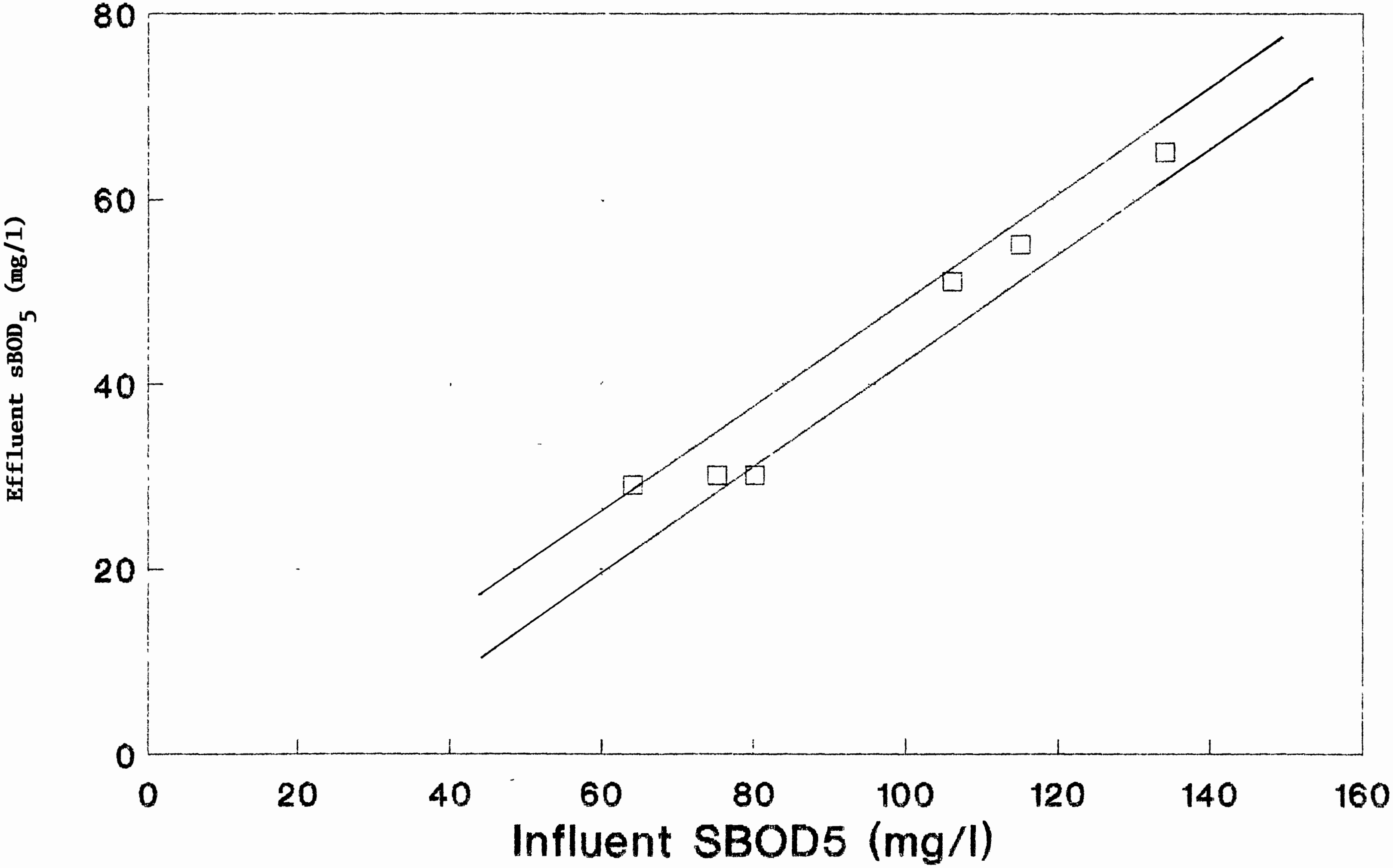

Figure 18: 99 % Confidence Interval for Influent and effluent sBOD5 (Cr Experiment)

The average TSS was 180(±60) mg/l at the 0 ft depth, 153(±45) mg/l at the 3 ft tower depth, and 143(±42) mg/l at the 6 ft tower depth during the pseudo-steady state. The average VSS concentration was 129(±29) mg/l at the 0 ft depth, 109(±29) mg/l at the 3 ft depth, and 99(±34) mg/l at the 6 ft tower depth under the pseudo-steady state condition.

The variation of pH during the development stage is shown in Figure 19. The pH of the effluent was around 0.4 units higher than that of the influent and the pH at 3 ft tower depth was about 0.2 units higher than that of the influent.

During the period of the chromium experiments, the background soluble chromium concentrations in the raw municipal wastewater were between 0.01-0.14 mg/l and the total chromium concentrations were between 0.01-0.18 mg/l. Before the chromium solution was added to the tower, the chromium concentration in the biological solids was 20 mg/kg (dry-weight basis) at the 0 ft tower depth.

Figures 20, 23, and 26 show the effects of chromium on $sBOD_5$, $sBOD_5$ removal efficiency, and pH at each depth of the tower. The variation of chromium concentrations during each chromium experiment are shown in Figures 22, 25, and 28. Table XVII illustrated the average value of soluble and total chromium concentration and chromium uptake in the biological solids.

A tower wide average of soluble chromium was 5.58(±1.33), 34.08(±4.01), and 84.25(±10.31) mg/l during the periods of the 9, 38, and 96 mg/l dose, respectively. These concentrations of soluble chromium inhibited the oxygen demand of microorganism in the inhibition

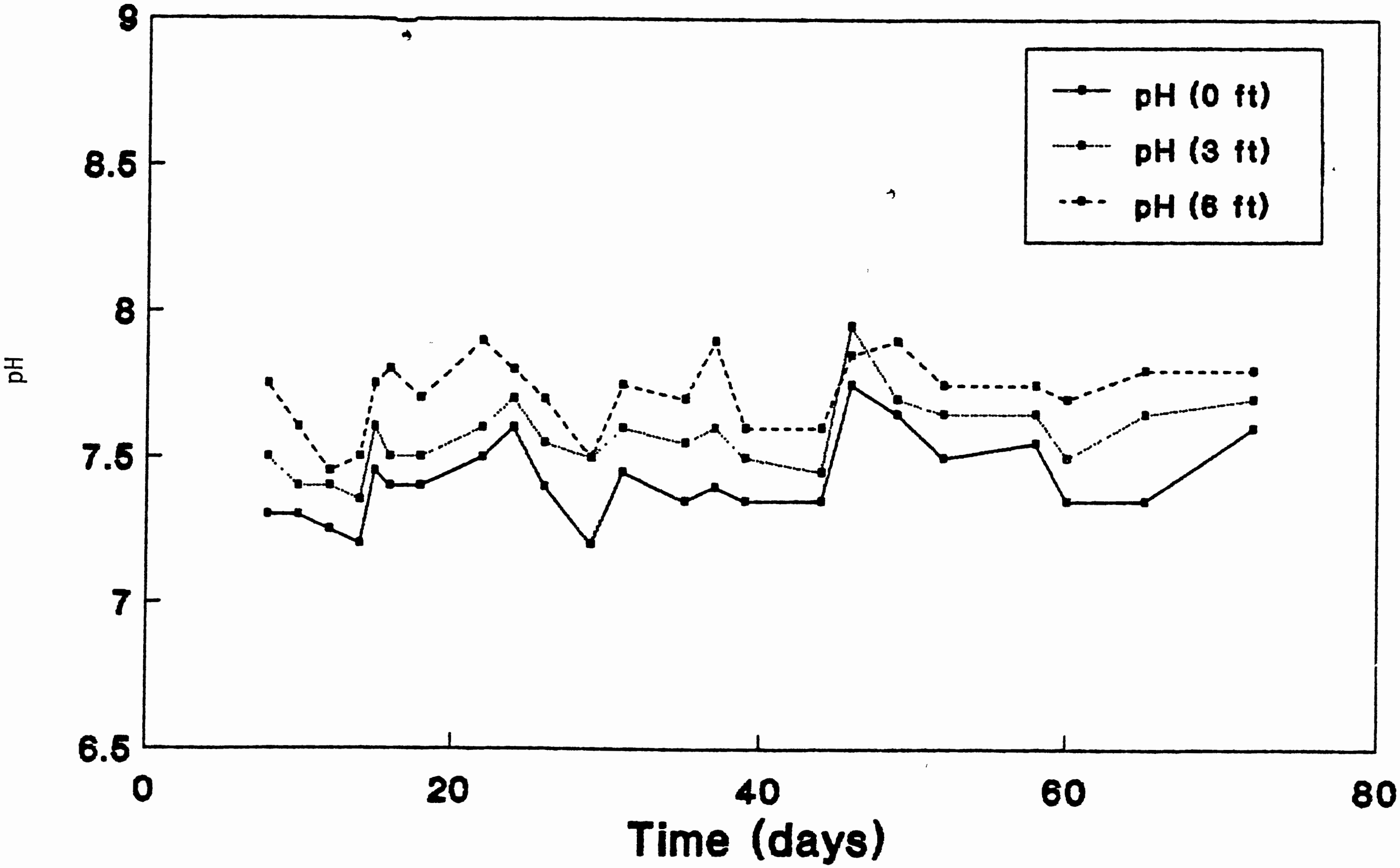

Figure 19: pH at Various Tower Depths in the System Development Stage for Cr Experiment

TABLE XVII

AVERAGE VALUE OF CHROMIUM CONCENTRATION AT 0 FT, 3 FT, AND 6 Ft TOWER DEPTH DURING THE INJECTION PERIOD

Injection Stage	Parameter	Chromium conc. at 0 ft	3 ft	6 ft *
1st. Injection (9 mg/l for 4 hours)	Soluble conc. (mg/l)	7.26	5.48	4.00
	Total conc. (mg/l)	8.75	5.75	5.10
	Conc. in the Solids (mg/kg)	3,557	1,554	1,206
2nd. Injection (38 mg/l for 4 hours)	Soluble conc. (mg/l)	37.80±0.90	32.75±2.25	24.40±3.30
	Total conc. (mg/l)	38.50±1.50	33.80±2.00	30.65±2.65
	Conc. in the Solids (mg/kg)	3,624	2,106	2,001
3rd. Injection (96 mg/l for 4 hours)	Soluble conc. (mg/l)	88.76±1.24	86.75±4.25	75.50±14.00
	Total conc. (mg/l)	96.25±1.25	93.25±7.25	82.00±18.00
	Conc. in the Solids (mg/kg)	2,591	2,894	2,320

*: Depth of the biological tower

test (Fig. 4). However, the soluble concentrations of chromium quickly dropped below 0.5 mg/l, which was the threshold inhibition level for carbonaceous biological oxidation 4 hours after the injection stopped in each experiment. Therefore, it is believed that the soluble chromium in the wastewater could inhibit $sBOD_5$ during the period of chromium injection.

When 9 mg/l of chromium was fed to the tower for 4 hours, the solids showed little detachment from the filter media due to the toxic effect of chromium. The TSS and VSS concentration of the effluent during the injection period was similar to that measured prior to the injection of chromium.

Figure 20 shows the effects of chromium, during the 4 hours injection period, on $sBOD_5$, $sBOD_5$ removal efficiency, and pH in the biological tower at the 9 mg/l chromium dose. $SBOD_5$ at the 3 ft and 6 ft depths seemed not to be too badly inhibited during the injection period because the $sBOD_5$ values at the 3 ft depth was higher than those at the 6 ft depths (Fig. 20). After the injection stopped, the $sBOD_5$ values at the 3 ft and 6 ft depths gradually reached equilibrium.

In Figure 20, the $sBOD_5$ removal efficiency was 48 percent at the 6 ft depth 4 hours after the injection stopped. Eight hours after the injection of chromium stopped, the $sBOD_5$ removal efficiency dropped to its lowest point, 32 percent, then increased and reestablished equilibrium.

In the case of the 3 ft tower depth, the $sBOD_5$ removal efficiency was 28 percent 4 hours after the injection stopped. The $sBOD_5$ removal efficiency decreased to 19 percent 8 hours after the injection stopped,

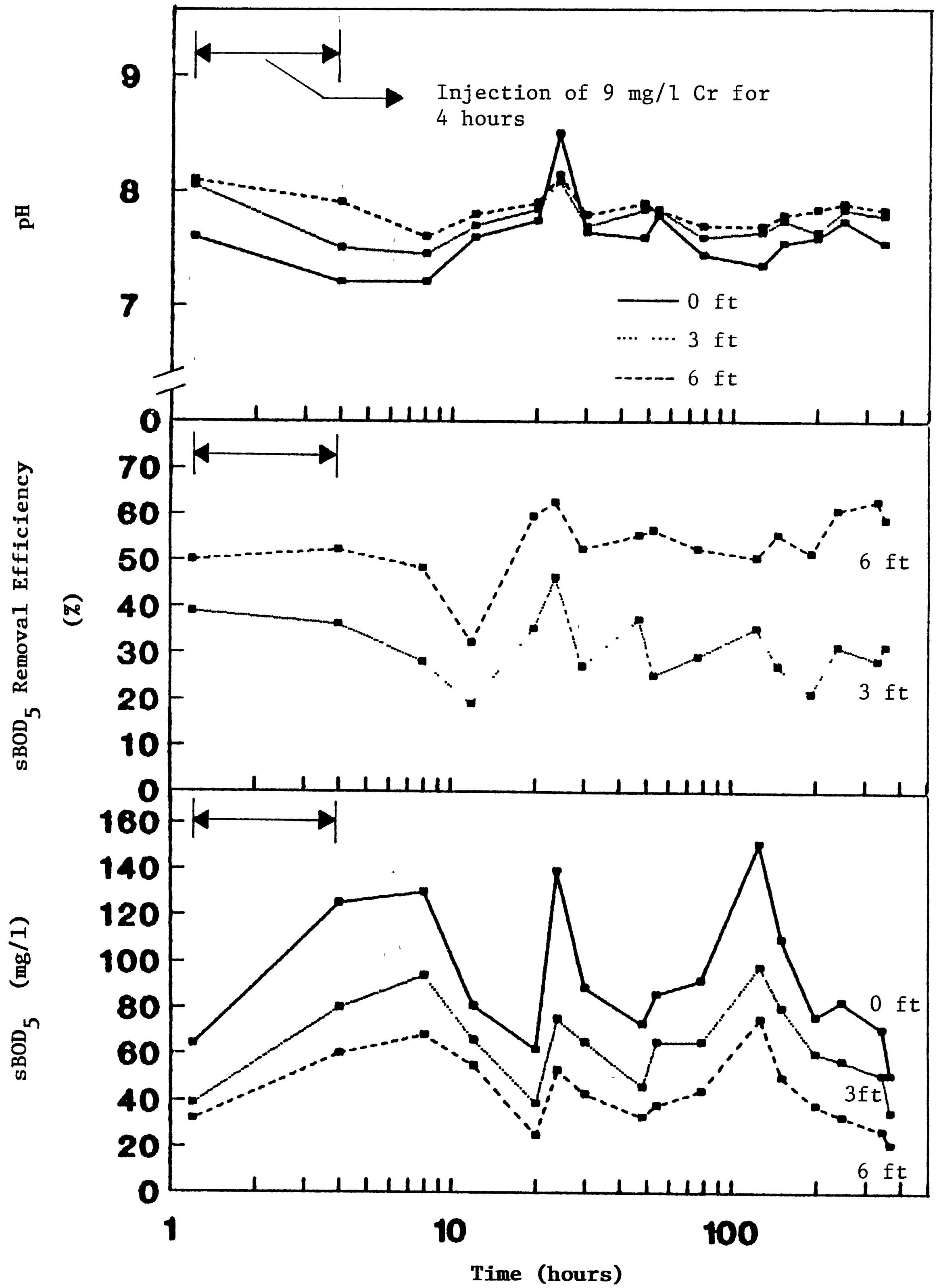

Figure 20: Effects of the 9 mg/l Cr Dose on pH, sBOD5 Removal Efficiency, and sBOD5 Concentrations at Various Tower Depths

then reached equilibrium.

In Figure 21, the effluent $sBOD_5$ (vs the influent $sBOD_5$) considered to be within the 99 percent confidence interval on and after point 5 (Table XVIII). These results indicate that the tower performance of $sBOD_5$ removal was restored to the pre-dosage level about 26 hours after the injection of chromium ceased.

The variation in the chromium concentration in the slime layer at the 9 mg/l slug dose is shown in Figure 22. Four hours after the start of the 9 mg/l chromium dosage, chromium had accumulated in the biological solids throughout the tower to 2039±943 mg/kg (dry-weight basis). After the chromium injection stopped, this chromium concentration decreased with the passing of time. Table XIX shows the chromium concentrations in the biological solids over time. The tower wide average chromium concentration in the biological solids of 2039±943 mg/kg suddenly decreased to 41 percent (842±80 mg/kg) 16 hours after the 9 mg/l chromium injection stopped. The chromium concentration in the biological solids returned to the pre-shock level 338 hours after the chromium injection stopped.

In Figure 22, the data available to graph soluble and total chromium concentrations for the first 4 hours generate a straight line because the liquid phase samples taken after 4 hours of the chromium injection were lost in a lab accident. The biological tower system achieved a removal efficiency of soluble and total chromium of 45 and 41 percent, respectively, at the 6 ft tower depth during the injection period. At the 3 ft tower depth, the removal efficiency of soluble and total chromium was 25 and 34 percent, respectively. Difference of the

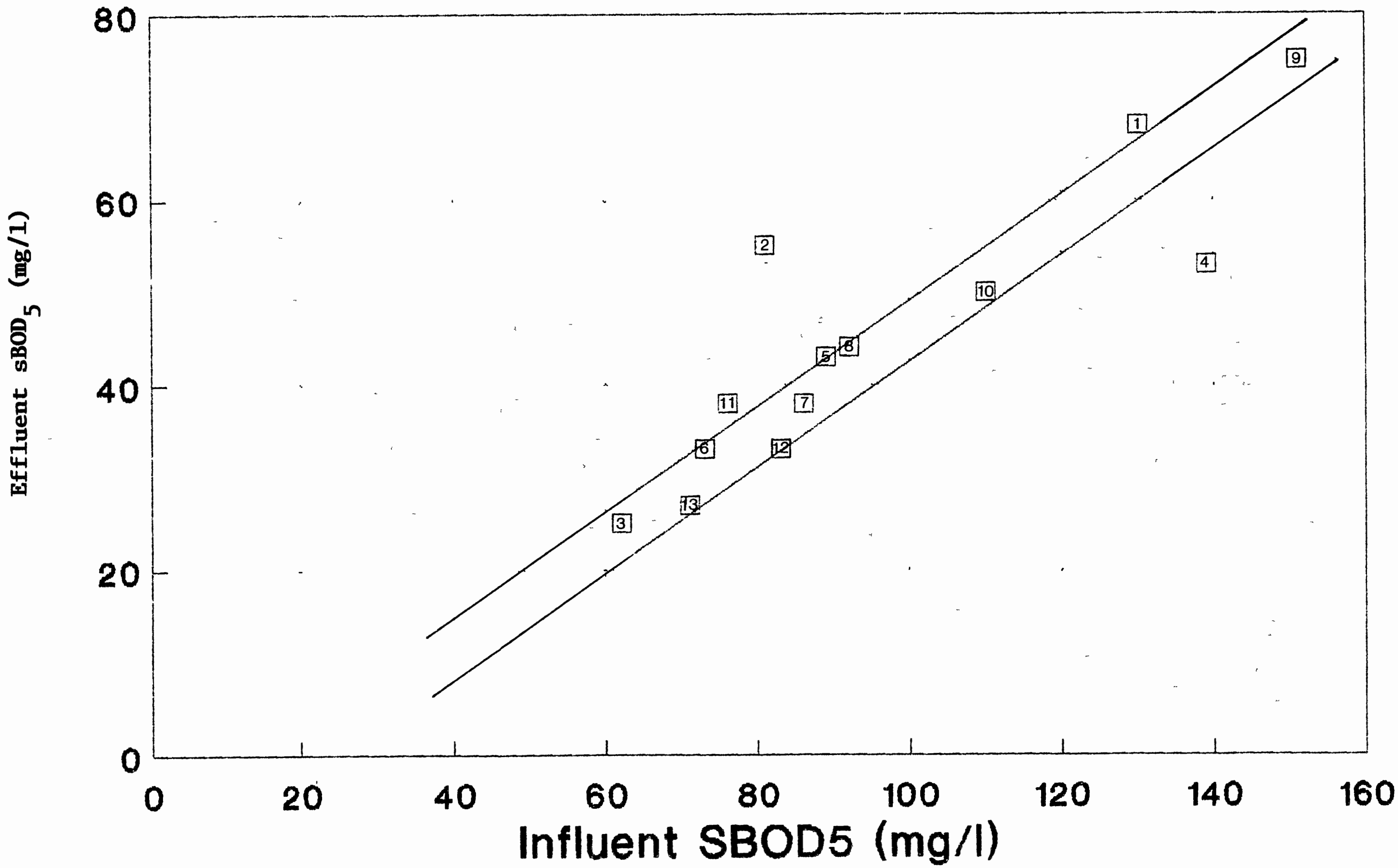

Figure 21: Hypothetical sBOD5-Response for the 9 mg/l Dose
Solid Lines Represent 99 % Confidence Interval

TABLE XVIII

INFLUENT AND EFFLUENT $sBOD_5$ VALUES AT ELAPSED TIMES IN FIGURE 21

Metal Conc.	Number in Fig.9	Elapsed time (hours)*	Influent $sBOD_5$ (mg/l)	Effluent $sBOD_5$ (mg/l)
Cr 9 mg/l	1	4	130	68
	2	8	81	55
	3	16	62	25
	4	20	139	53
	5	26	89	43
	6	44	73	33
	7	50	86	38
	8	74	92	44
	9	122	151	75
	10	146	110	50
	11	194	76	38
	12	242	83	33
	13	338	71	27

*: Time after the injection of chromium stopped.

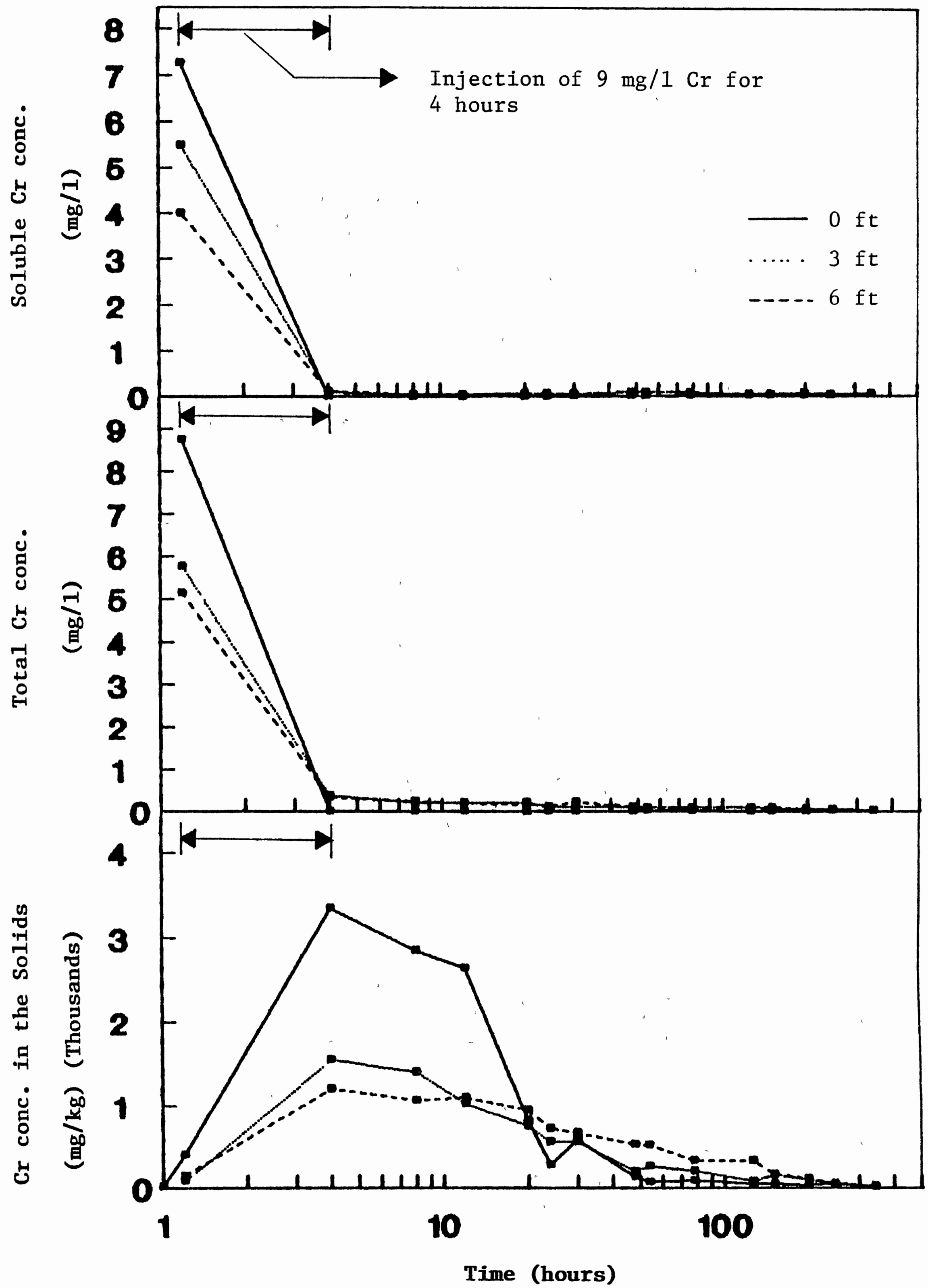

Figure 22: Cr Conc. at Various Tower Depths for the 9 mg/l Cr Dose

TABLE XIX

CHROMIUM CONCENTRATION IN THE BIOLOGICAL SOLIDS
AT THE 9 MG/L CHROMIUM DOSE

Elapsed time* (hours)	/ Cr conc. in the biological solids (mg/kg) at / 0 ft depth	3 ft depth	6 ft depth
0	3,357	1,554	1,206
4	2,857	1,407	1,070
8	2,640	1,024	1,100
16	825	754	947
26	594	571	670
50	78	275	525
122	50	88	345
194	34	102	123
242	60	56	51
338	22	18	26

*: Time after the injection of chromium stopped.

removal efficiency between soluble and total chromium at the 6 ft tower depth could be due to analytical error.

When the chromium dosage was increased to 38 mg/l, the effects on $sBOD_5$ and the $sBOD_5$ removal efficiency through the tower are shown in Figure 23. During the chromium injection, an increase in solids (TSS and VSS) sloughing due to the effect of chromium did not occur. During the injection period, $sBOD_5$ at the 3 ft and 6 ft depths was considered to be not seriously inhibited by the toxic effect of chromium because the $sBOD_5$ values were still in correct order. Figure 23 shows that the $sBOD_5$ values at 3 ft and 6 ft depths did not parallel the influent $sBOD_5$ values until 194 hours after the injection stopped. $SBOD_5$ at the 3 ft and 6 ft depths were considered to have reestablished equilibrium 242 hours after the injection stopped.

Four hours after the injection stopped, the $sBOD_5$ removal efficiency dropped to 28 percent, lower than the pre-shock level of 56 percent, at the 6 ft tower depth (Fig. 23). Then, the $sBOD_5$ removal efficiency fluctuated for about 44 hours and decreased to 22 percent 50 hours after the injection stopped. Then, The $sBOD_5$ removal efficiency increased and reestablished equilibrium.

In the case of the 3 ft tower depth, the $sBOD_5$ removal efficiency fluctuated for the 44 hours after the injection stopped and dropped to 2 percent 50 hours after the injection stopped (Fig. 23). Then, the $sBOD_5$ removal efficiency at the 3 ft tower depth increased and gradually reached equilibrium.

Figure 24 shows that most of data points starting with number 12 (Table XX) exist within the range of the 99 percent confidence

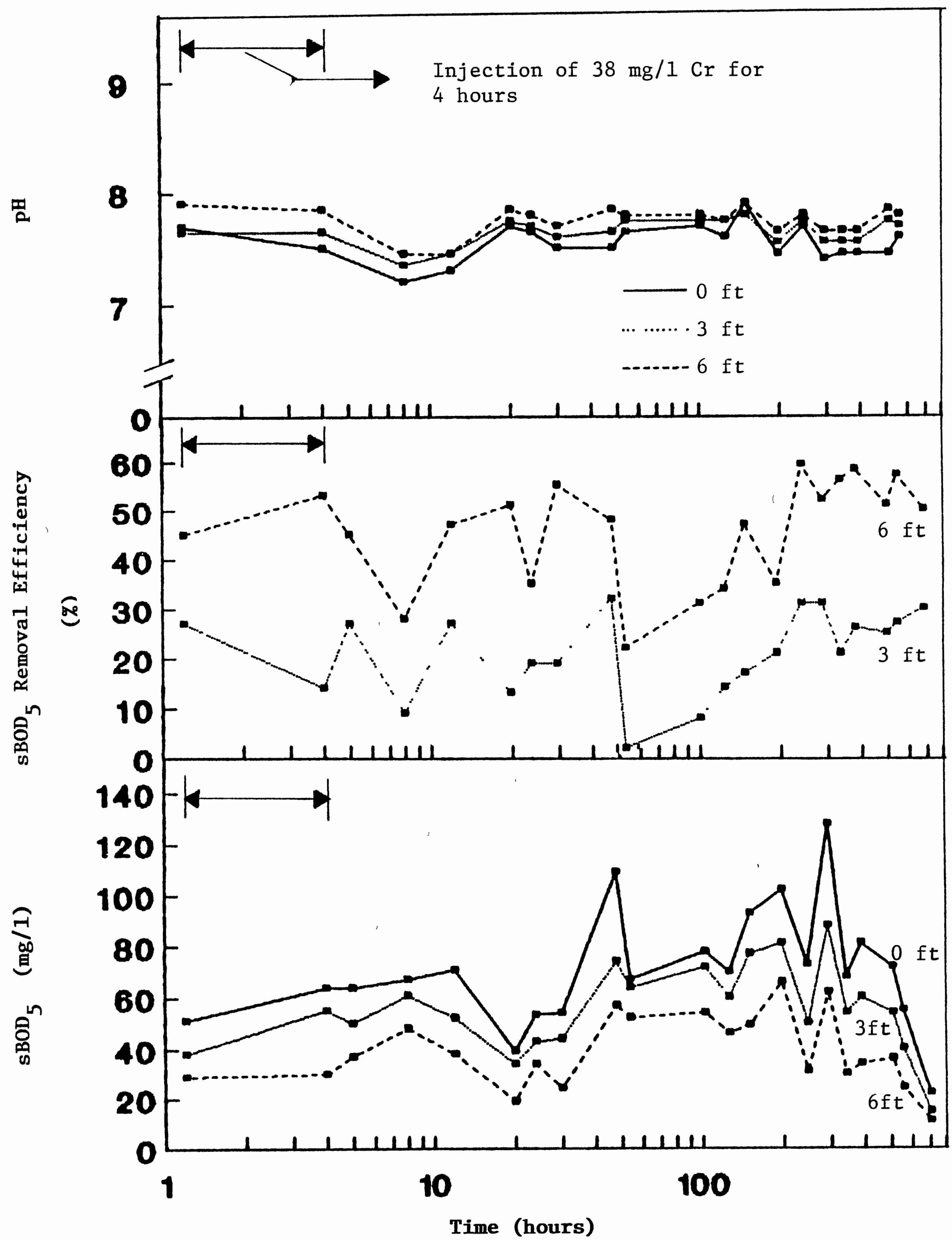

Figure 23: Effects of the 38 mg/l Cr Dose on pH, sBOD5 Removal Efficiency, and sBOD5 Concentrations at Various Tower Depths

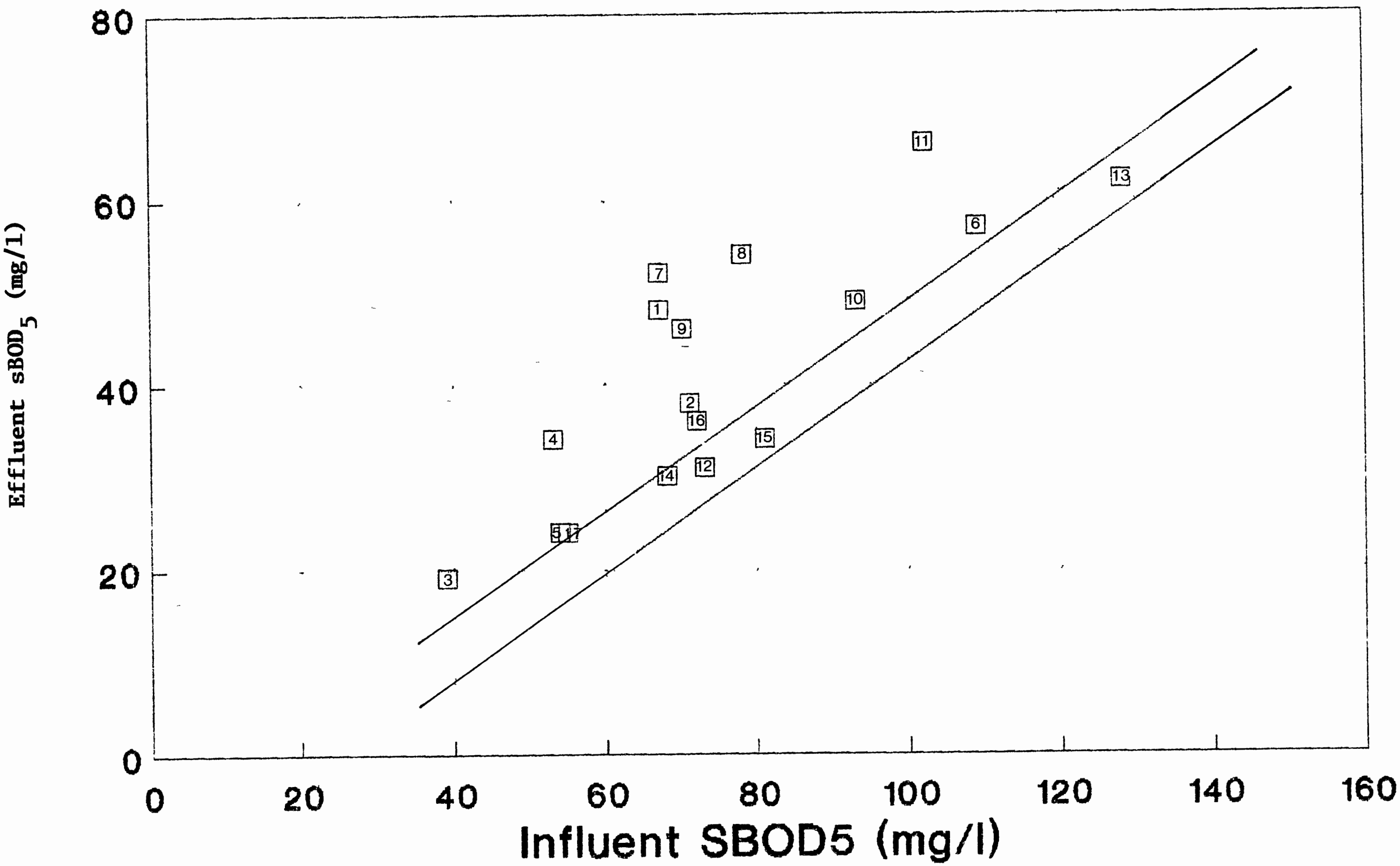

Figure 24: Hypothetical sBOD5-Response for the 38 mg/l Cr Dose
Solid Lines Represent 99 % Confidence Interval

TABLE XX

INFLUENT AND EFFLUENT $sBOD_5$ VALUES AT ELAPSED TIMES IN FIGURE 24

Metal Conc.	Number in Fig.9	Elapsed time (hours)*	Influent $sBOD_5$ (mg/l)	Effluent $sBOD_5$ (mg/l)
Cr 38 mg/l	1	4	67	48
	2	8	71	38
	3	16	39	19
	4	20	53	34
	5	26	54	24
	6	44	109	57
	7	50	67	52
	8	98	78	54
	9	122	70	46
	10	146	93	49
	11	194	102	66
	12	242	73	31
	13	290	128	62
	14	338	68	30
	15	386	81	34
	16	506	72	36
	17	554	55	24

*: Time after the injection of chromium stopped.

interval of the effluent $sBOD_5$ (vs the influent $sBOD_5$). These results indicate that the tower performance in terms of $sBOD_5$ removal returned to the pre-dosage level 242 hours after the injection stopped (Table XX).

In the inhibition screening test, $sBOD_5$ was totally inhibited by the 38 mg/l chromium concentration. However, the 38 mg/l dose fed to the tower did not severely inhibit $sBOD_5$ at the 3 ft and 6 ft depths during the injection period. In other words it did not completely inhibit the $sBOD_5$ measured on the tower. In the case of the 38 mg/l chromium concentration, the inhibition screening test is considered to be a more conservative method to measure toxicity than the tower experiment.

The recovery time was considerably longer than at the previous chromium dose (9 mg/l). The 38 mg/l slug dose of chromium had a more toxic effect on the metabolism of the microorganisms than the 9 mg/l chromium dose. The higher chromium dose is considered to have more adverse effects on the metabolic rate of microorganisms on the surface of the media than the lower chromium dose. These effects could cause a decrease in growth and reproduction of the microorganisms. Consequently, reduction of biomass would drop the performance of the biological tower.

The fate of chromium in the tower is shown in Figure 25. Table XVII also shows the concentration of soluble chromium and total chromium at each tower depth while the 38 mg/l slug dose of chromium was added to the tower. The removal efficiency of soluble and total chromium concentration through the tower was 35 and 20 percent,

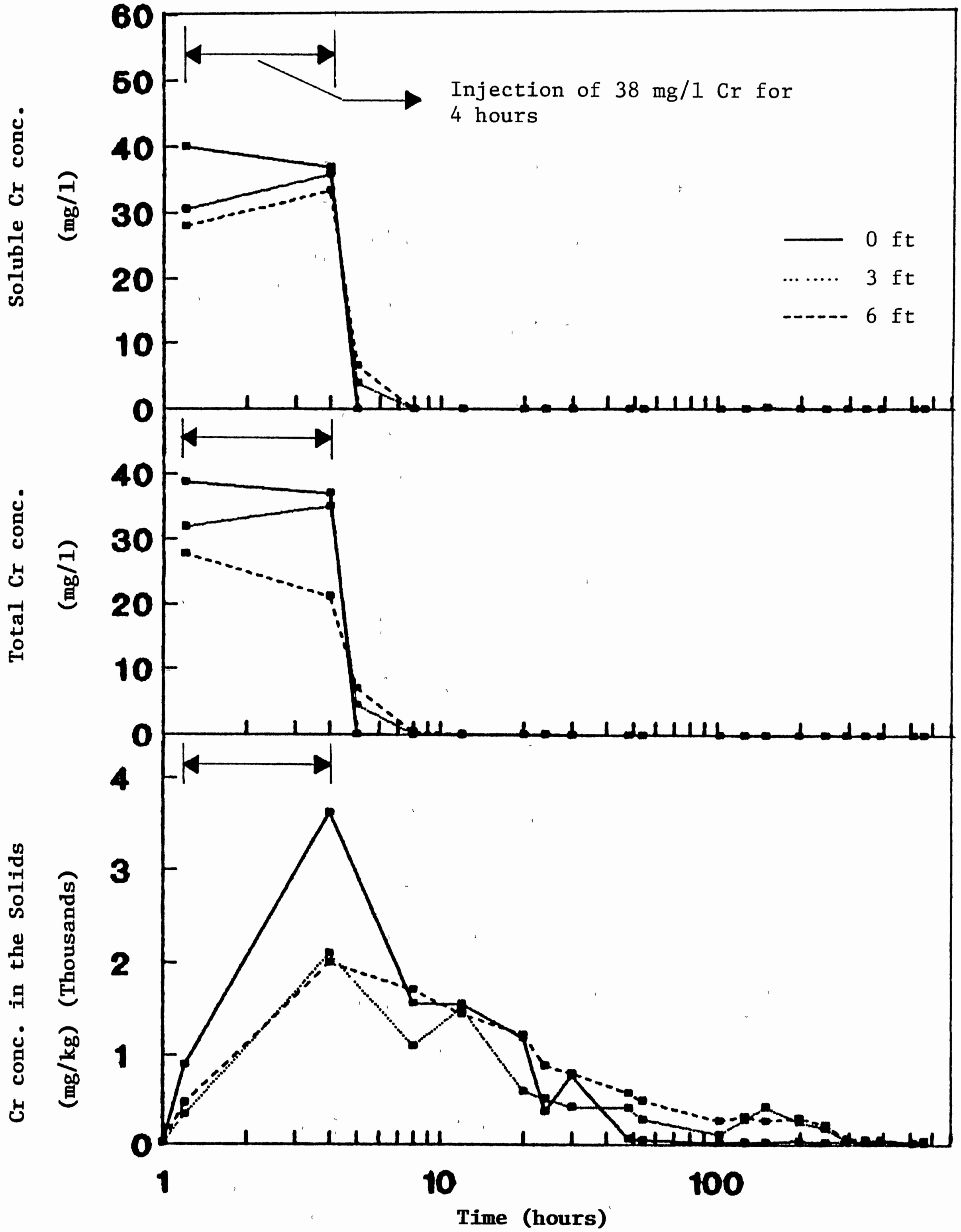

Figure 25: Cr Conc. at Various Tower Depths for the 38 mg/l Cr Dose

respectively, at the 6 ft tower depth. At the 3 ft tower depth, the removal efficiency of soluble and total chromium was 13 and 12 percent, respectively. Greater removal efficiency of soluble copper than total copper could be due to analytical error. The removal efficiency of the soluble and total chromium concentration were less than those at the 9 mg/l dosage.

One day before the start of the 38 mg/l chromium dosage, the chromium accumulated in the biofilm layer was 22±3 mg/kg (dry-weight basis) throughout the tower. Figure 25 shows the chromium concentration in the biological solids at various tower depths for the 38 mg/l chromium dose. The maximum chromium concentration accumulated in the biological solids was 2577±742 mg/kg (dry-weight basis) throughout the tower 4 hours after the start of the chromium dose. The chromium concentrations in the biological tower at other times are shown in Table XXI. The maximum tower wide average chromium concentration in the solids of 2577±742 mg/kg decreased to 39 percent (1010±288 mg/kg) 12 hours after the chromium injection stopped. The chromium concentration in the solids returned to the pre-dosage level at all tower depths 338 hours after the chromium injection stopped.

After the 38 mg/l chromium dosage, the influent chromium concentration feed to the tower was increased to 96 mg/l. The slug dose of 96 mg/l was fed to the tower for a period of 4 hours. An increase in the amount of solid detachment due to the chromium dose was not observed during this injection of chromium.

As shown in Figure 26, $sBOD_5$ at the 3 ft and 6 ft depths was completely inhibited just after the start of the 96 mg/l chromium

TABLE XXI

CHROMIUM CONCENTRATION IN THE BIOLOGICAL SOLIDS
AT THE 38 MG/L CHROMIUM DOSE

Elapsed time* (hours)	/ Cr conc. in the biological solids (mg/kg) at / 0 ft depth	3 ft depth	6 ft depth
0	3,624	2,106	2,001
4	1,566	1,099	1,707
8	1,556	1,521	1,452
16	1,198	602	1,229
20	382	521	887
50	59	286	495
122	34	280	315
194	48	255	304
242	30	189	227
338	27	25	62
506	24	18	29

*: Time after the injection of chromium stopped.

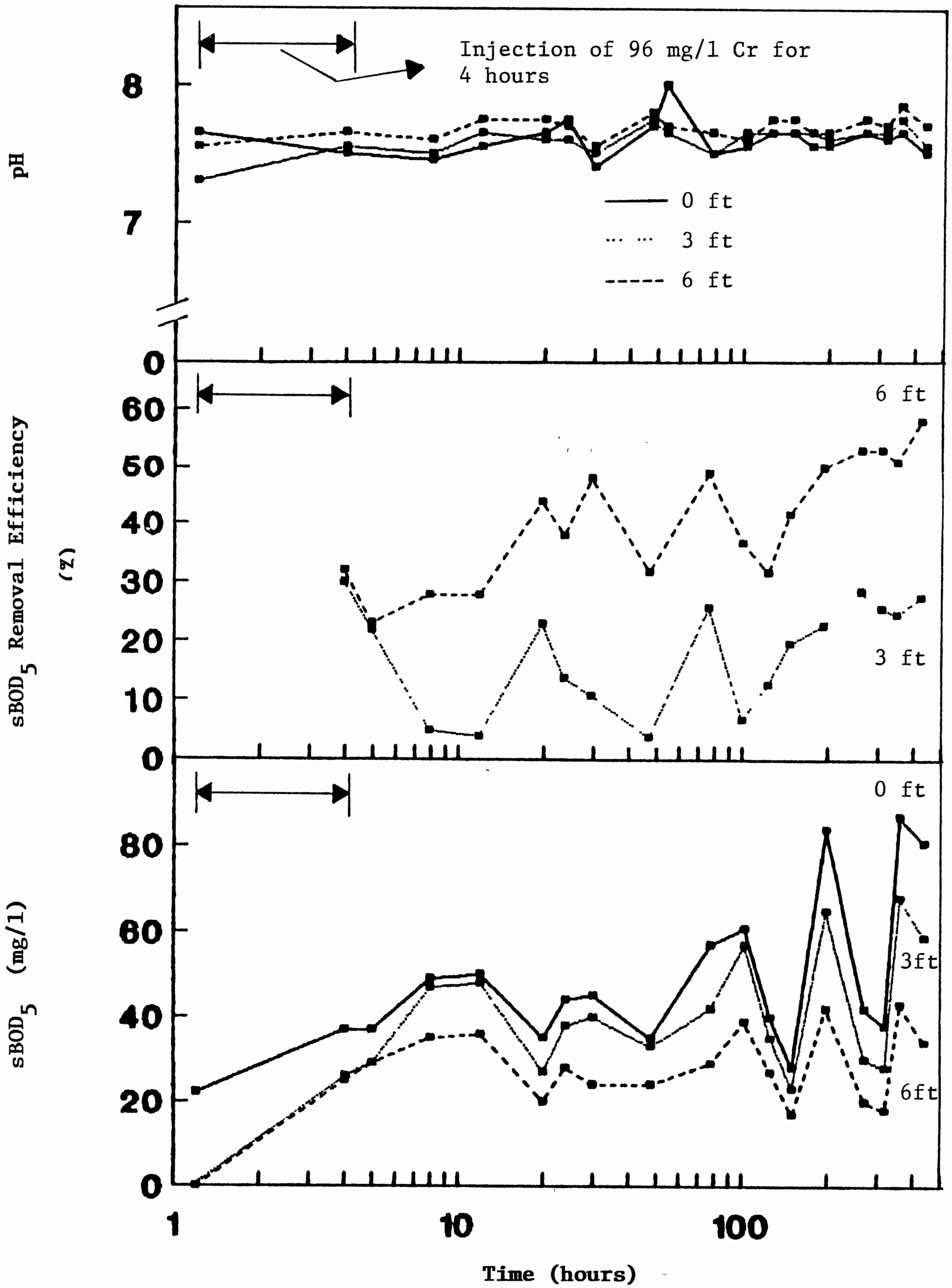

Figure 26: Effects of the 96 mg/l Cr Dose on pH, sBOD5 Removal Efficiency, and sBOD5 Concentrations at Various Tower Depths

injection. $sBOD_5$ at the 3 ft and 6 ft depths was inhibited at the same level for the first 5 hours (Fig. 26). The $sBOD_5$ values at the 3 ft and 6 ft depths did not parallel the influent $sBOD_5$ values until 194 hours after the injection stopped. Then, $sBOD_5$ at the 3 ft and 6 ft depths was considered to have reached equilibrium.

The $sBOD_5$ removal efficiency at the 6 ft tower depth showed fluctuation between 28 and 49 percent for 146 hours after the injection stopped (Fig 26). Then, the $sBOD_5$ removal efficiency at the 6 ft depth increased and reached equilibrium.

The $sBOD_5$ removal efficiency at the 3 ft tower depth had a minimum value of 4 percent 8 hours and 44 hours after the injection of chromium ceased (Fig.26). The removal efficiency at the 3 ft depth fluctuated between 4 and 29 percent for 146 hours after the injection stopped. Then, the $sBOD_5$ removal efficiency at the 3 ft depth increased and reached equilibrium (Fig. 26).

In Figure 27, point 14 is close to the range of the 99 percent confidence interval of the effluent $sBOD_5$ value (vs the influent $sBOD_5$ value). Point 15 exists within this confidence interval (Table XXII). Therefore, the tower performance was considered to be restored 362 hours after the injection stopped from these results.

During the 96 mg/l chromium dosage, the average soluble and total concentration of chromium at each depth of the tower are shown in Table XVII. The removal efficiency of both the soluble and total chromium was about 15 percent at the 6 ft tower depth. The soluble chromium removed by the top 3 ft of the tower was 2 percent. The removal efficiency of total chromium was 3 percent at the 3 ft tower depth. The removal

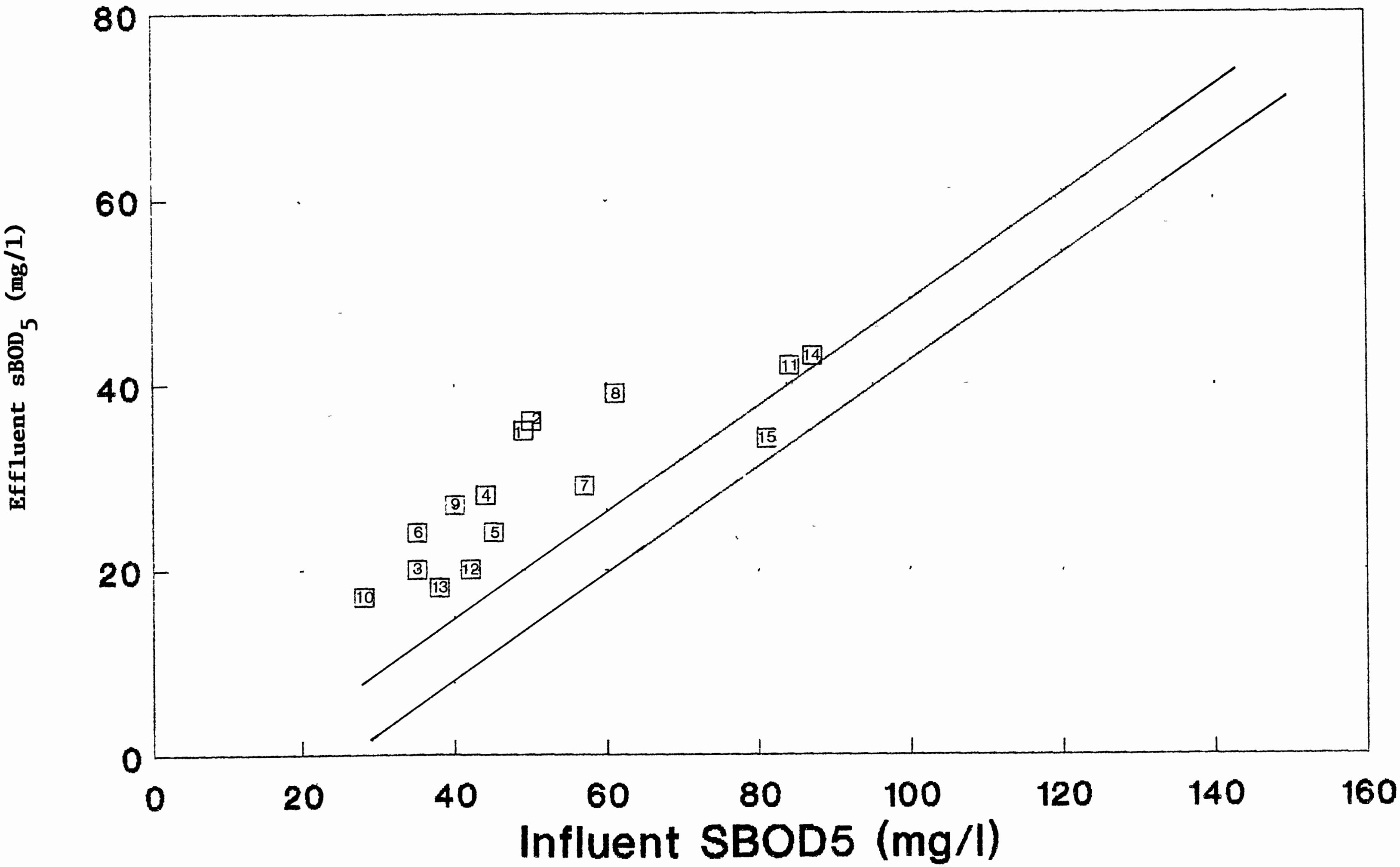

Figure 27: Hypothetical sBOD5-Response for the 96 mg/l Cr Dose
Solid Lines Represent 99 % Confidence Interval

TABLE XXII

INFLUENT AND EFFLUENT $sBOD_5$ VALUES AT ELAPSED TIMES IN FIGURE 27

Metal Conc.	Number in Fig.9	Elapsed time (hours)*	Influent $sBOD_5$ (mg/l)	Effluent $sBOD_5$ (mg/l)
Cr 96 mg/l	1	4	49	35
	2	8	50	36
	3	16	35	20
	4	20	44	28
	5	26	45	24
	6	44	35	24
	7	74	57	29
	8	98	61	39
	9	122	40	27
	10	146	28	17
	11	194	84	42
	12	266	42	20
	13	314	38	18
	14	362	87	43
	15	434	81	34

*: Time after the injection of chromium stopped.

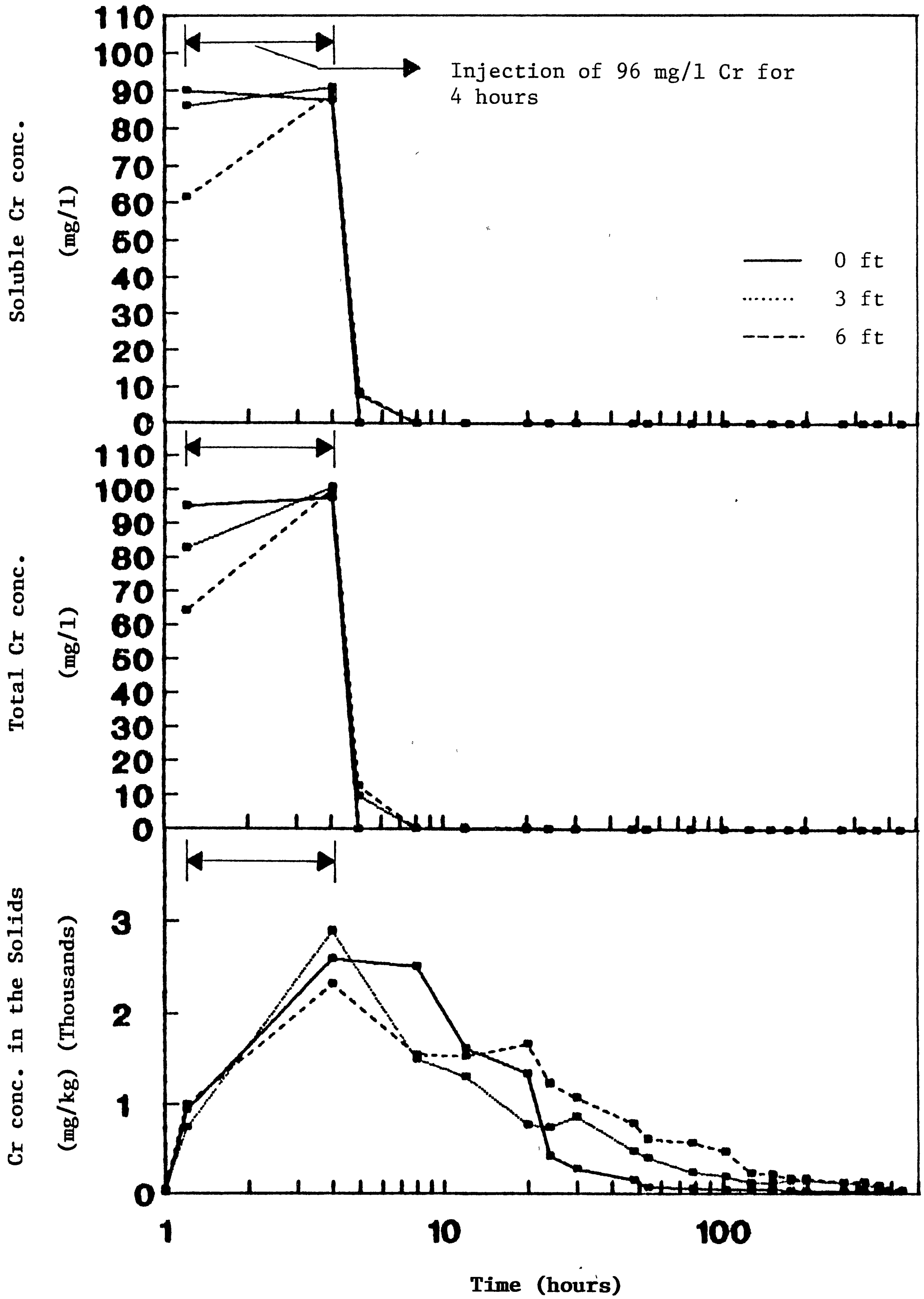

Figure 28: Cr Conc. at Various Tower Depths for the 96 mg/l Cr Dose

efficiency of chromium at the 96 mg/l dose was much lower than those experienced at the previous two chromium dosages.

Chromium concentration in the biological solids for the 96 mg/l chromium dose is shown in Figure 28. Six days before the start of the 96 mg/l chromium dosage, the chromium concentration in the biological solids was 40±15 mg/kg (dry-weight basis) throughout the tower. When the slug dose of 96 mg/l was fed, chromium was taken up in the biological slime layer up to 2,602±234 mg/kg (dry-weight basis) 4 hours after starting the chromium spiking (Fig. 28). This chromium concentration in the solids decreased to 48 percent (1259±369 mg/kg) 16 hours after the injection stopped. As shown in Table XXIII, 362 hours after the chromium injection stopped was required for the chromium concentration in the slime layer to obtain the same level as before the injection of chromium.

A summary of the tower reactions to chromium is shown in Table XXIV. At the 9 mg/l chromium dosage, the tower performance in terms of $sBOD_5$ removal returned to the original pseudo-steady state level when the biological solids contained 612±42 mg/kg (dry-weight basis) of chromium as a tower wide average. During the 38 mg/l chromium dosage, the tower wide average chromium concentration in the biological solids was 149±85 mg/kg (dry-weight basis) at the recovery time based on the tower performance. In the case of the 96 mg/l chromium dosage, the biological solids contained 66±29 mg/kg (dry-weight basis) throughout the tower, when the tower performance returned to the steady state level. The tower wide average chromium concentration in the solids decreased with increase in the recovery time in the chromium experiment

TABLE XXIII

CHROMIUM CONCENTRATION IN THE BIOLOGICAL SOLIDS AT THE 96 MG/L CHROMIUM DOSE

Elapsed time* (hours)	/ Cr conc. in the biological solids (mg/kg) at / 0 ft depth	3 ft depth	6 ft depth
0	2,591	2,894	2,320
4	2,509	1,493	1,550
8	1,619	1,310	1,525
16	1,337	774	1,667
20	428	743	1,233
44	157	477	790
122	51	122	230
194	33	147	173
266	30	128	126
314	24	107	132
358	27	75	95
434	35	25	38

*: Time after the injection of chromium stopped.

as shown in Table XXIV. This was due to time available to desorb chromium from the solids. Therefore, the relationship of the chromium concentration in the solids and the performance of the system in terms of $sBOD_5$ could not be discussed in the chromium experiment.

During the chromium feeding of three different concentrations (9, 38, and 96 mg/l), mean values of the soluble concentration in the influent containing chromium were 7, 38, and 89 mg/l. The reduction of the soluble chromium concentration was 22 percent at the 9 mg/l dose, 0 percent at the 38 mg/l dose, and 8 percent at the 96 mg/l dose. This means that chromium mainly existed in the soluble form in the municipal wastewater. The solubility of chromium in the wastewater was much higher than that of copper.

During the entire period of the chromium experiment, the pH was between 7.1 and 8.2.

TABLE XXIV

SUMMARY OF REACTIONS TO CHROMIUM IN THE BIOLOGICAL TOWER

Injection con. of Cr	Recovery time (% BOD removal)	Soluble con. (mg/l)	Total con. (mg/l)	Con. in the solids (mg/kg)
		/ at recovery time based on % BOD removal /		
9 mg/l (4 hr)[1]	26 hours[2]	0.02 (0 ft)[3]	0.02 (0 ft)	594 (0 ft)
		0.07 (3 ft)	0.12 (3 ft)	571 (3 ft)
		0.07 (6 ft)	0.25 (6 ft)	670 (6 ft)
38 mg/l (4 hr)[1]	242 hours[2]	0.01 (0 ft)	0.05 (0 ft)	30 (0 ft)
		0.02 (3 ft)	0.04 (3 ft)	189 (3 ft)
		0.02 (6 ft)	0.04 (6 ft)	227 (6 ft)
96 mg/l (4 hr)[1]	362 hours[2]	0.04 (0 ft)	0.03 (0 ft)	27 (0 ft)
		0.03 (3 ft)	0.04 (3 ft)	75 (3 ft)
		0.03 (6 ft)	0.04 (6 ft)	95 (6 ft)

1: Duration of copper injection
2: Recovery time after the injection of copper stopped
3: Depth of the biological tower

CHAPTER V

CONCLUSIONS

The following conclusions can be made from these results, based on the response of the biological tower process.

1. The tower performance in terms of $sBOD_5$ removal totally recovered within 3 days after the injection stopped at three different copper dosages (3, 56, and 47 mg/l).

2. The tower performance in terms of $sBOD_5$ removal recovered in about 2 days at the 9 mg/l chromium dose. The tower performance was restored in about 10 and 15 days at the 38 mg/l and 96 mg/l chromium doses, respectively.

3. The first (3 mg/l) and the second (56 mg/l) copper feeding caused a large amount of sloughing of inorganic solids from the filter medium. During the third (47 mg/l) copper dosage and all runs of the chromium experiment, sloughing of the solids occurred slightly.

4. Removal efficiency of soluble and total copper was 36-69 percent and 52-66 percent, respectively. In the case of chromium, the removal efficiency was 15-45 percent for soluble chromium and 15-41 percent for total chromium depending on the influent chromium concentration.

5. The metals (copper and chromium) tend to desorb quickly from the biomass after the injection stopped. In the specific conditions of

this experiment, approximately two days and one day are required to obtain a 50 percent reduction of the maximum concentrations of copper and chromium in the biomass, respectively.

CHAPTER VI

SUGGESTIONS FOR FUTURE STUDY

1. COD and TOC are little inhibited by the toxicity of heavy metals. Therefore, the effect of heavy metals in terms of COD and TOC on a biological tower should be studied.

2. The effect of heavy metals on a biological tower should be studied at the same soluble concentration and at the same feeding period in order to compare the toxicity between heavy metals.

3. A deeper biological tower (*e.g.* 12 ft or 18 ft) should yield better treatment efficiency and more sampling ports at the various tower depths than the 6 ft biological tower. Therefore, a deeper biological tower could provide more detailed information on tower performance at each depth of the tower. Analysis of the effect of heavy metals on a deeper biological tower should be carried out.

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APPENDIXES

APPENDIX A

EXPERIMENTAL DATA FOR COPPER

WASTEWATER CHARACTERISTICS FOR COPPER

COPPER (as copper sulfate)

Water Type: Raw Municipal Wastewater
Hydraulic Loading Rate: 0.9 gal/min/sq.ft

I. Development Stage

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	TOTAL BOD5 (mg/l)	TOTAL %BOD5 REMOVAL
0 ft	2	114		7.6					-	
3 ft	10:00	113	1	7.8					-	
6 ft	am	105	8	7.8					-	-
0 ft		77		7.4	844	126	122	0.97	159	
3 ft	06:00	71	8	7.6	854	106	106	1.0	153	
6 ft	pm	68	12	7.6	812	94	106	1.0	143	10
0 ft		80		7.5					200	
3 ft	midnight	72	10	7.7					186	
6 ft		68	16	7.75					180	10
0 ft	4	64		7.3					141	
3 ft	10:00	52	20	7.6					117	
6 ft	am	52	20	7.8					87	38
0 ft		93		7.65	916	148	124	0.84	171	
3 ft	06:00	83	10	7.8	872	102	86	0.84	147	
6 ft	pm	82	12	7.9	98	98	86	0.88	138	20
0 ft		-		7.55					-	
3 ft	midnight	-		7.7					-	
6 ft		-		7.75					-	-
0 ft	6	79		7.4					200	
3 ft	10:00	73	8	7.6					149	
6 ft	am	66	17	7.6					131	35
0 ft		125		7.65	994	164	120	0.73	224	
3 ft	06:00	115	8	7.6	866	106	70	0.66	194	
6 ft	pm	102	19	7.65	836	84	56	0.67	167	26
0 ft		123		7.35					225	
3 ft	midnight	109	11	7.65					171	
6 ft		98	20	7.75					162	28

WASTEWATER CHARACTERISTICS FOR COPPER (continued)

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	TOTAL BOD5 (mg/l)	TOTAL %BOD5 REMOVAL
0 ft	8	72		7.5					178	
3 ft	10:00	65	10	7.65					144	
6 ft	am	50	30	7.75					101	43
0 ft		95		7.3	960	194	160	0.82	184	
3 ft	06:00	82	14	7.5	900	128	100	0.78	174	
6 ft	pm	72	24	7.6	868	110	88	0.8	156	15
0 ft		-		7.15					-	
3 ft	midnight	-		7.25					-	
6 ft		-		7.25					-	-
0 ft	10	83		7.45					210	
3 ft	10:00	64	23	7.6					167	
6 ft	am	54	40	7.7					137	35
0 ft		120		7.35	946	170	142	0.84	238	
3 ft	06:00	98	18	7.45	868	102	78	0.76	176	
6 ft	pm	78	35	7.5	850	92	68	0.74	156	34
0 ft		123		7.35					214	
3 ft	midnight	72	41	7.45					180	
6 ft		50	60	7.65					105	51
0 ft	13	-		7.3					251	
3 ft	10:00	-		7.5					169	
6 ft	am	-		7.6					109	57
0 ft		48		7.4	944	182	160	0.88	131	
3 ft	06:00	38	21	7.55	910	150	124	0.83	133	
6 ft	pm	20	58	7.65	906	150	126	0.84	124	5
0 ft		-		7.25					-	
3 ft	midnight	-		7.5					-	
6 ft		-		7.65					-	-
0 ft	15	-		7.6					152	
3 ft	10:00	-		7.6					118	
6 ft	am	-		7.6					77	49
0 ft		72		7.1	904	178	146	0.82	159	
3 ft	06:00	41	43	7.4	884	142	122	0.86	159	
6 ft	pm	32	56	7.4	806	76	60	0.79	90	43

WASTEWATER CHARACTERISTICS FOR COPPER (continued)

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	TOTAL BOD5 (mg/l)	TOTAL %BOD5 REMOVAL
0 ft		92		7.15					174	
3 ft	midnight	60	35	7.35					159	
6 ft		40	57	7.45					105	40
0 ft	17	-		7.5					130	
3 ft	rain	-		7.65					99	
6 ft	10:00a	-		7.75					99	24
0 ft		54		7.3	846	118	96	0.81	-	
3 ft	06:00	39	28	7.35	820	80	64	0.8	-	
6 ft	pm	25	54	7.4	792	70	54	0.77	-	-
0 ft		-		-					-	
3 ft	midnight	-		-					-	
6 ft		-		-					-	-
0 ft	19	-		-					-	
3 ft	10:00	-		-					-	
6 ft	am	-		-					-	-
0 ft		44		7.4	1102	320	214	0.67	122	
3 ft	06:00	35	20	7.45	978	170	104	0.61	83	
6 ft	pm	21	52	7.45	960	176	120	0.68	90	26
0 ft		-		-					-	
3 ft	midnight	-		-					-	
6 ft		-		-					-	-

Nitrification inhibitor was added in the samples

(N.I.; nitrification inhibitor)

DEPTH	DAY ELAPSED & TIME	SBOD5 without N.I.		pH	TS	TSS	VSS	VSS/TSS	SBOD5 with N.I.	% removal
0 ft	21	33		7.35					27	
3 ft	10:00	17	48	7.55					22	19
6 ft	am			7.55						
0 ft		77		7.25	1030	196	138	0.7	77	
3 ft	06:00	62	19	7.4	908	206	170	0.83	63	18
6 ft	pm	44	43	7.45	904	226	190	0.84	46	40

WASTEWATER CHARACTERISTICS FOR COPPER (continued)

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cu/ SOL. /	TOT. (mg/l)/	IN SOLID (mg/kg)
Nitrification inhibitor was added in the samples											
SBOD5 without N.I. (N.I.; nitrification inhibitor)									SBOD5 with N.I.		% removal
0 ft		97		7.35					80		
3 ft	midnight	80	18	7.65					76		5
6 ft		63	35	7.9					65		19
0 ft	23	78		7.3							
3 ft	10:00	51	35	7.35							
6 ft	am	34	56	7.35							
0 ft		49		7.3	952	140	114	0.81			
3 ft	06:00	42	14	7.45	936	82	64	0.78			
6 ft	pm	14	71	7.55	954	126	98	0.77			
0 ft		-		6.95							
3 ft	midnight	-		7.15							
6 ft		-		7.35							
0 ft	25	60		7.35							
3 ft	10:00	36	40	7.55							
6 ft	am	25	58	7.55							
0 ft		49		7.25	880	128	100	0.78			
3 ft	06:00	30	39	7.4	776	72	50	0.69			
6 ft	pm	20	59	7.45	768	60	44	0.73			
0 ft		-		7.							
3 ft	midnight	-		7.15							
6 ft		-		7.2							
Nitrification inhibitor was added in the samples											
SBOD5 without N.I. (N.I.; nitrification inhibitor)									SBOD5 with N.I.		% removal
0 ft	27	108		7.25					79		
3 ft	10:00	64	41	7.35					59		25
6 ft	am	42	61	7.4					40		49

WASTEWATER CHARACTERISTICS FOR COPPER (continued)

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cu/ SOL. /	TOT. (mg/l)/	IN SOLID (mg/kg)
Nitrification inhibitor was added in the samples											
SBOD5 without N.I. (N.I.; nitrification inhibitor)									SBOD5 with N.I.		% removal
0 ft		103		7.1	888	148	146	0.81	90		
3 ft	06:00	68	34	7.25	810	90	122	0.82	63		30
6 ft	pm	36	65	7.35	806	76	100	0.78	35		61
0 ft		113		7.1					102		
3 ft	midnight	90	20	7.15					84		18
6 ft		54	52	7.2					53		48
0 ft	30	26		7.2							
3 ft	10:00	9	65	7.45							
6 ft	am	9	65	7.5							
0 ft		52		7.2	782	136	102	0.75			
3 ft	06:00	46	12	7.35	710	100	70	0.7			
6 ft	pm	15	71	7.2	754	190	140	0.74			
0 ft		55		7.15							
3 ft	midnight	27	51	7.3							
6 ft		18	67	7.45							
0 ft	31	-		-							
3 ft	10:00	-		-							
6 ft	am	-		-							
0 ft		47		7.2							
3 ft	06:00	31	34	7.35							
6 ft	pm	20	57	7.45							
0 ft		-		-							
3 ft	midnight	-		-							
6 ft		-		-							
0 ft	32	60		7.1							
3 ft	10:00	45	25	7.35							
6 ft	am	21	65	7.55							

WASTEWATER CHARACTERISTICS FOR COPPER (continued)

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cu/ SOL. /	TOT. (mg/l)/	IN SOLID (mg/kg)
0 ft		77		7.25	950	174	124	0.71			
3 ft	06:00	58	25	7.35	918	150	106	0.71			
6 ft	pm	25	67	7.35	880	124	94	0.76			
0 ft		116		7.							
3 ft	midnight	90	22	7.35							
6 ft		60	55	7.45							
0 ft	34	38		7.5							
3 ft	10:00	23	39	7.65							
6 ft	am	13	66	7.65							
0 ft		64		7.4	948	130	94	0.72			
3 ft	06:00	51	20	7.5	930	124	96	0.77			
6 ft	pm	25	61	7.5	846	98	74	0.76			
0 ft		-		-							
3 ft	midnight	-		-							
6 ft		-		-							
0 ft	36	50		7.7							
3 ft	rain	26	48	7.85							
6 ft	10:00a	18	64	7.85							
0 ft		64		7.65	698	142	96	0.68			
3 ft	06:00	31	52	7.75	612	68	42	0.62			
6 ft	pm	29	55	7.7	662	108	70	0.65			
0 ft		-		7.45							
3 ft	midnight	-		7.7							
6 ft		-		7.8							
0 ft	38	40		7.95	782	100	60	0.6			
3 ft	06:00	27	33	8.35	774	78	48	0.62			
6 ft	pm	15	63	8.45	734	74	50	0.68			
0 ft	40	62		8.							
3 ft	06:00	42	32	8.25							
6 ft	pm	27	56	8.45							

Glucose-Glutamic acid: 279 mg/l BOD_5

WASTEWATER CHARACTERISTICS FOR COPPER (continued)

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cu/ SOL. /	TOT. (mg/l)/	IN SOLID (mg/kg)
0 ft	42	56		7.6	780	118	60	0.69			
3 ft	06:00	32	42	7.85	780	116	88	0.76			
6 ft	pm	20	65	8.05	770	136	104	0.76			
0 ft	44	71		7.7	796	124	104	0.84			
3 ft	06:00	44	38	8.1	764	112	94	0.84			
6 ft	pm	31	57	8.25	748	42	36	0.86			
		* Glucose-Glutamic acid: 249.5 mg/l BOD_5									
0 ft	46	80		7.7	784	90	70	0.78			
3 ft	06:00	53	34	7.95	728	42	30	0.71			
6 ft	pm	33	59	8.05	716	36	26	0.81			
0 ft	48	62		7.5	730	106	68	0.64			
3 ft	06:00	30	52	7.85	770	140	92	0.66			
6 ft	pm	20	68	8.05	780	150	102	0.68			
0 ft	50	51		7.65		108	86	0.8			
3 ft	10:00	29	43	8.		122	94	0.77			
6 ft	am	18	65	8.05		92	68	0.74			
0 ft		93		7.65		96	80	0.83			
3 ft	02:00	58	38	8.05		88	72	0.82			
6 ft	pm	31	67	8.05		50	32	0.61			
0 ft		86		7.6	754	74	60	0.81			
3 ft	06:00	56	35	7.9	714	70	56	0.8			
6 ft	pm	31	64	8.05	704	76	54	0.71			
0 ft		97		7.6		88	64	0.73			
3 ft	10:00	71	27	7.9		80	54	0.68			
6 ft	pm	40	59	8.		50	28	0.56			
0 ft	51	56		7.55		50	38	0.76			
3 ft	02:00	36	36	7.9							
6 ft	am	23	60	8.05		58	42	0.72			
0 ft		38		7.55							
3 ft	06:00	25	34	8.05							
6 ft	am	14	65	8.2							

WASTEWATER CHARACTERISTICS FOR COPPER (continued)

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cu/ SOL. /	TOT. (mg/l)/	IN SOLID (mg/kg)
0 ft	52	100		7.6							
3 ft	06:00	70	30	7.9							
6 ft	pm	47	53	8.05							
0 ft	54	94		7.55	800	106	82	0.77			
3 ft	06:00	60	37	7.55	806	104	74	0.71			
6 ft	pm	36	62	7.85	726	70	52	0.74			

WASTEWATER CHARACTERISTICS FOR COPPER (continued)

II. 3 mg/l Continuous Dose of Copper for 5 days and 15 hours

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cu/ SOL. /	TOT. (mg/l)/	IN SOLID (mg/kg)
					Injection Start						
Raw	59	41		7.55							
0 ft		22		7.55	-	-	-	-			2756
3 ft	06:00	23	43	7.7	-	-	-	-			340
6 ft	am	20	52	7.9	-	-	-	-			478
Raw		62		7.55					0.05	0.09	
0 ft		60		7.55	-	1058	220	0.20	0.93	2.67	
3 ft	10:00	44	30	7.7	-	994	80	0.08	0.57	1.82	
6 ft	am	28	56	7.75	-	942	52	0.05	0.38	1.38	
Raw		104		7.55					0.08	0.15	
0 ft		74		7.5	-	134	-	-	3.3	5.18	
3 ft	02:00	58	44	7.7	-	102	-	-	1.35	2.46	
6 ft	pm	42	59	7.85	-	166	-	-	0.73	1.72	
Raw		104		7.55					0.1	0.15	
0 ft		81		7.5	902	192	156	0.81	1.44	2.14	11000
3 ft	06:00	74	29	7.75	918	228	182	0.8	0.44	2.81	7929
6 ft	pm	40	61	7.9	742	72	56	0.78	0.42	0.79	3741
Raw		101		7.35					0.07	0.09	
0 ft		80		7.35		162	130	0.8	2.35	2.88	
3 ft	10:00	34	67	7.5		112	90	0.8	0.92	1.81	
6 ft	pm	28	73	7.75		78	60	0.77	0.62	1.19	
Raw	60	25		7.55					0.09	0.11	
0 ft		24		7.6	744	76	64	0.84	1.46	2.25	14821
3 ft	06:00	21	15	7.8	712	62	48	0.77	0.77	1.5	8030
6 ft	am	6	76	7.9	662	54	34	0.63	0.36	1.27	5251
Raw		89		7.4					0.09	0.09	
0 ft		60		7.45	802	144	96	0.67	2.	2.77	14957
3 ft	06:00	38	57	7.55	716	74	50	0.68	1.05	1.68	14405
6 ft	pm	14	84	7.85	734	104	80	0.07	0.58	1.38	8605
Raw	61	114		7.5					0.06	0.09	
0 ft		82		7.4	950	158	120	0.76	2.59	3.05	14835
3 ft	06:00	52	55	7.6	780	54	24	0.44	1.32	1.81	12718
6 ft	pm	20	82	7.7	796	88	52	0.59	0.69	1.4	10044

WASTEWATER CHARACTERISTICS FOR COPPER (continued)

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS	TSS (mg/l)	VSS	VSS/TSS	/Conc. of Cu/ SOL. (mg/l)	TOT. (mg/l)	IN SOLID (mg/kg)
Raw	62	86		7.55					0.09	0.13	
0 ft		71		7.45	896	162	122	0.75	1.72	2.25	9995
3 ft	06:00	44	49	7.5	816	104	78	0.75	1.15	1.71	8723
6 ft	pm	35	59	7.7	782	78	50	0.64	0.62	1.77	6963
Raw	63	95		7.35					0.08	0.11	
0 ft		72		7.45	826	134	108	0.81	2.17	2.48	12978
3 ft	06:00	39	59	7.6	738	42	34	0.81	1.39	1.65	8502
6 ft	pm	26	73	7.7	730	44	38	0.86	0.86	1.22	9276
Copper concentration of two branches of the distributer: Right branch: Total Cu Conc. 2.46 mg/l, Dissolved Cu Conc. 2.1 mg/l; Left branch: Total Cu Conc. 2.5 mg/l, Dissolved Cu Conc. 2.24 mg/l											
Raw	64	81		7.35					0.09	0.09	
0 ft		62		7.35	856	116	90	0.76	2.8	3.27	17145
3 ft	06:00	47	42	7.55	748	54	36	0.67	1.95	2.56	15017
6 ft	pm	20	76	7.8	744	52	24	0.46	1.18	1.82	12434
Injection Stop (June 4, 6:00 am. to June 9, 9:00 pm.)											
0 ft	65	98		7.4	860	146	114	0.78	0.06	0.09	7611
3 ft	06:00	66	33	7.5	762	64	54	0.84	0.1	0.19	9033
6 ft	pm	46	53	7.7	742	44	38	0.86	0.13	0.37	9277
0 ft	67	71		7.35	782	108	88	0.81	0.07	0.11	2509
3 ft	06:00	45	37	7.55	746	94	58	0.62	0.07	0.23	2217
6 ft	pm	26	63	7.7	708	78	52	0.67	0.07	0.22	4108
0 ft	69	53		7.65	818	160	98	0.61	0.06	0.18	939
3 ft	06:00	32	40	7.75	712	64	42	0.65	0.07	0.18	1121
6 ft	pm	17	68	7.8	712	54	20	0.37	0.08	0.11	1229

WASTEWATER CHARACTERISTICS FOR COPPER (continued)

III. 56 mg/l Slug Dose of Copper for 10 hours

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cu/ SOL. /	TOT. (mg/l)/	IN SOLID (mg/kg)
						Injection Start					
Raw	75	42		7.4					0.08	0.09	
0 ft	noon	8		7.35	954	338	180	0.53	5.7	54.6	7752
3 ft		24	42	7.7	842	350	208	0.59	1.87	27.2	2608
6 ft		23	44	7.9	756	345	222	0.64	1.69	13.25	5354
Raw		49		7.45					0.09	0.1	
0 ft		5		7.45		1114	174	0.16	3.75	53.8	31568
3 ft	4:00	28	43	7.7		1028	130	0.13	2.7	36.1	32090
6 ft	pm.	29	40	7.9		1058	154	0.15	2.09	27.2	25226
Raw		83		7.4					0.05	0.11	
0 ft		27		7.45	980	290	168	0.58	5.56	61.0	32697
3 ft	8:00	35	58	7.7	836	178	98	0.55	3.47	26.8	35535
6 ft	pm.	46	45	7.85	836	160	94	0.59	2.48	16.4	24025
				Injection Stop (June 20, noon to 10 pm. for 10 hours)							
0 ft		80		7.35	732	100	74	0.74	0.08	0.09	19161
3 ft	midnight	44	46	7.5	698	88	68	0.77	0.25	1.71	17419
6 ft		41	48	7.7	858	190	142	0.75	0.8	3.72	13326
0 ft	76	38		7.7	834	214	154	0.72	0.05	0.11	13359
3 ft	8:00	28	15	7.8	750	122	92	0.75	0.09	0.97	15425
6 ft	am.	20	47	7.95	716	88	66	0.75	0.16	3.72	10060
0 ft		56		7.4	862	154	116	0.75	0.05	0.13	
3 ft	noon	34	39	7.6	752	78	58	0.74	0.08	0.41	
6 ft		19	66	7.7	746	74	52	0.7	0.15	0.87	
0 ft		80		7.25	842	132	110	0.83	0.06	0.05	6537
3 ft	6:00	47	41	7.5	742	72	62	0.86	0.06	0.25	6484
6 ft	pm.	32	60	7.6	722	58	44	0.75	0.12	0.49	7622
0 ft	77	82		7.55	1212	624	362	0.58	0.05	0.17	
3 ft	08:00	55	32	7.75	1060	280	200	0.71	0.06	0.94	
6 ft	am.	34	59	7.85	908	182	126	0.69	0.12	1.99	
0 ft		89		7.4	882	132	96	0.73	0.05	0.07	2442
3 ft	06:00	61	31	7.6	816	78	64	0.82	0.07	0.25	2906
6 ft	pm.	44	51	7.65	796	58	42	0.72	0.1	0.5	4007

WASTEWATER CHARACTERISTICS FOR COPPER (continued)

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cu/ SOL. /	TOT. (mg/l)/	IN SOLID (mg/kg)
0 ft	78	102		7.25	914	176	140	0.8	0.06	0.03	1154
3 ft	06:00	62	39	7.4	802	90	74	0.82	0.07	0.04	4372
6 ft	pm	44	57	7.6	774	80	64	0.8	0.07	0.11	3577
0 ft	79	102		7.35	812	116	88	0.76	0.08	0.1	664
3 ft	06:00	68	33	7.6	740	64	52	0.81	0.07	0.1	2085
6 ft	pm	45	56	7.7	742	54	44	0.81	0.08	0.1	2081
0 ft	80	100		7.35	746	120	88	0.73	0.08	0.05	805
3 ft	06:00	73	27	7.55	672	70	46	0.65	0.08	0.05	2382
6 ft	pm	39	61	7.8	684	70	46	0.65	0.07	0.31	2003
0 ft	82	107		7.55	746	130	92	0.71	0.09	0.06	570
3 ft	06:00	80	25	7.65	774	118	90	0.76	0.09	0.06	1138
6 ft	pm	45	58	7.7	746	110	76	0.69	0.09	0.09	579
0 ft	83	-		7.4	884	210	150	0.71	0.07	0.06	661
3 ft	06:00	-		7.55	948	242	186	0.77	0.08	0.16	783
6 ft	pm	-		7.65	786	110	74	0.67	0.09	0.11	588
0 ft	86	120		7.25	816	132	102	0.77	0.08	0.03	258
3 ft	06:00	77	36	7.45	754	64	54	0.84	0.1	0.04	454
6 ft	pm	52	63	7.5	788	84	60	0.71	0.09	0.04	375

WASTEWATER CHARACTERISTICS FOR COPPER (continued)

IV. 47 mg/l Slug Dose of Copper for 10 hours

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cu/ SOL. / (mg/l)/	TOT.	IN SOLID (mg/kg)
					Injection Start						
Raw	88	86		7.8					0.1	0.13	
0 ft		23		7.75	1184	466	290	0.62	3.23	54.75	3231
3 ft	noon	36	58	7.95	914	172	112	0.65	3.1	22.5	1662
6 ft		48	44	7.95	926	186	112	0.6	2.85	19.3	1944
Raw		73		7.4					0.09	0.11	
0 ft		19		7.45	1060	334	200	0.6	4.82	33.5	
3 ft	04:00	47	36	7.65	904	156	78	0.5	3.79	25.7	
6 ft	pm	47	36	7.75	874	136	76	0.56	3.18	20.7	
Raw		110		7.55					0.09	0.12	
0 ft		43		7.45	916	296	168	0.57	5.28	51.25	
3 ft	08:00	36	67	7.55	812	158	80	0.51	2.6	30.7	
6 ft	pm	48	56	7.7	798	138	76	0.55	2.54	20.	
					Injection Stop (July 4, noon to 10 pm. for 10 hours)						
0 ft		98		7.25	846	124	86	0.67	0.13	0.2	18707
3 ft	midnight	60	39	7.55	866	136	94	0.69	0.52	11.25	14590
6 ft		44	55	7.65	856	128	94	0.73	0.78	4.9	10615
0 ft	89	48		7.55	896	200	150	0.75	0.11	0.14	
3 ft	08:00	28	42	7.6	800	94	66	0.7	0.35	1.07	
6 ft	am	20	56	7.65	826	96	66	0.69	0.76	2.71	
0 ft		136		7.25	856	158	134	0.84	0.13	0.14	2825
3 ft	noon	-		7.45	744	72	56	0.78	0.19	0.87	8599
6 ft		47	65	7.55	794	98	74	0.76	0.29	1.43	7276
0 ft		90		7.25	786	122	90	0.74	0.11	0.12	
3 ft	06:00	54	40	7.45	768	118	88	0.75	0.15	0.98	
6 ft	pm	36	60	7.55	764	122	90	0.74	0.23	1.24	
0 ft	90	93		7.35	882	72	32	0.44	0.12	0.13	
3 ft	noon	64	31	7.45	882	190	152	0.8	0.13	0.19	
6 ft		42	55	7.55	792	208	186	0.89	0.16	0.9	
0 ft		102		7.35	914	138	104	0.75	0.11	0.1	1590
3 ft	06:00	68	34	7.5	790	80	61	0.78	0.14	0.11	3879
6 ft	pm	48	53	7.6	752	62	40	0.67	0.15	0.33	3322

WASTEWATER CHARACTERISTICS FOR COPPER

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS	TSS (mg/l)	VSS	VSS/TSS	/Conc. of Cu/ SOL. (mg/l)	TOT. (mg/l)	IN SOLID (mg/kg)
0 ft	91	138		7.15	1022	286	146	0.51	0.12	0.13	601
3 ft	06:00	100	28	7.25	860	136	92	0.68	0.13	0.13	2841
6 ft	pm	60	57	7.45	888	136	104	0.76	0.17	0.68	2512
0 ft	92	177		7.1	1040	200	150	0.75	0.12	0.1	2515
3 ft	06:00	105	41	7.4	922	106	86	0.81	0.14	0.21	1976
6 ft	pm	81	54	7.55	970	56	36	0.64	0.15	0.24	1968
0 ft	93	210		6.8	946	100	81	0.81	0.12	0.2	341
3 ft	06:00	156	26	7.	810	70	60	0.86	0.13	0.17	1441
6 ft	pm	100	52	7.2	790	56	48	0.86	0.14	0.35	1109
0 ft	95	153		7.3					0.09	0.11	633
3 ft	06:00	98	35	7.5					0.08	0.14	1868
6 ft	pm	65	58	7.7					0.12	0.11	1891
0 ft	97	-		7.3	1014	158	115	0.73	0.14	0.14	614
3 ft	06:00	-		7.5	940	96	80	0.78	0.19	0.13	2374
6 ft	pm	-	-	7.7	802	72	56	0.78	0.19	0.15	1273
0 ft	100	85		7.2	852				0.13	0.25	189
3 ft	06:00	58	32	7.5	868				0.13	0.33	21
6 ft	pm	40	53	7.55	698				0.13	0.61	159
0 ft	102	102		7.4	738	106	102	0.96	0.09	0.18	171
3 ft	06:00	60	41	7.5	738	58	50	0.86	0.08	0.18	22
6 ft	pm	36	65	7.6	658	46	40	0.87	0.1	0.2	49

APPENDIX B

EXPERIMENTAL DATA FOR CHROMIUM

WASTEWATER CHARACTERISTICS FOR CHROMIUM

CHROMIUM (as potassium dichromate)

Water Type: Raw Municipal Wastewater
Hydraulic loading rate: 1.0 gal/min/sq.ft

I. Development Stage

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cr/ SOL. TOT. / (mg/l)/	IN SOLID (mg/kg)
Hydraulic loading rate: 0.9 gal/min/sq.ft										
0 ft	8	120		7.3	918	108	80	0.74		
3 ft	6:00	90	25	7.5	862	74	60	0.81		
6 ft	pm	89	27	7.75	846	76	54	0.71		
0 ft	10	122		7.3	916	78	58	0.74		
3 ft	6:00	95	22	7.4	872	58	42	0.72		
6 ft	pm	80	35	7.6	830	50	34	0.68		
0 ft	12	124		7.25	754	78	56	0.71		
3 ft	6:00	92	26	7.4	740	66	44	0.66		
6 ft	pm	75	40	7.45	720	38	28	0.73		
0 ft	14	116		7.2	820	98	74	0.75		
3 ft	6:00	102	12	7.35	870	148	104	0.70		
6 ft	pm	83	28	7.5	850	96	70	0.72		
0 ft	15	127		7.45	794	90	74	0.82		
3 ft	6:00	97	24	7.6	776	116	90	0.77		
6 ft	pm	72	44	7.75	794	80	48	0.6		
0 ft	16	132		7.4	770	90	74	0.82		
3 ft	6:00	109	17	7.5	768	80	66	0.82		
6 ft	pm	77	41	7.8	810	136	108	0.79		
0 ft	18	74		7.4	802	122	92	0.75		
3 ft	6:00	50	33	7.5	728	64	46	0.71		
6 ft	pm	35	52	7.7	780	138	102	0.73		
0 ft	22	79	rain	7.5	758	90	66	0.73		
3 ft	6:00	58	27	7.6	696	74	56	0.75		
6 ft	pm	35	56	7.9	718	60	42	0.7		

WASTEWATER CHARACTERISTICS FOR CHROMIUM (continued)

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cr/ SOL. /	TOT. (mg/l)/	IN SOLID (mg/kg)
0 ft	24	119		7.6	960	196	132	0.67			
3 ft	6:00	90	24	7.7	1178	240	162	0.67			
6 ft	pm	68	43	7.8	1014	292	214	0.73			
0 ft	26	69		7.4	828	118	96	0.81			
3 ft	6:00	42	39	7.55	778	88	66	0.75			
6 ft	pm	27	60	7.7	776	82	62	0.75			
0 ft	29	62		7.2	798	108	86	0.82			
3 ft	6:00	38	40	7.5	746	92	76	0.82			
6 ft	pm	23	64	7.5	770	64	54	0.84			
0 ft	31	87		7.45	808	128	102	0.79			
3 ft	6:00	61	29	7.6	784	110	90	0.81			
6 ft	pm	38	56	7.75	750	132	106	0.80			
0 ft	35	97		7.35	-	170	130	0.76			
3 ft	6:00	62	36	7.55	-	244	190	0.77			
6 ft	pm	41	58	7.7	-	204	158	0.77			
0 ft	37	-		7.4	838	148	104	0.70			
3 ft	6:00	-		7.6	850	126	94	0.74			
6 ft	pm	-	-	7.9	782	124	98	0.79			
0 ft	39	158		7.35	706	148	122	0.82			
3 ft	6:00	116	27	7.5	826	88	68	0.77			
6 ft	pm	68	57	7.6	758	66	46	0.69			
0 ft	44	98		7.35	842	152	124	0.81			
3 ft	6:00	62	38	7.45	776	84	70	0.83			
6 ft	pm	37	62	7.6	744	60	46	0.76			
Increase the hydraulic loading rate: 1.0 gal/min/sq.ft											
0 ft	46	65		7.75	1146	416	324	0.77			
3 ft	6:00	43	34	7.95	948	248	184	0.74			
6 ft	pm	29	58	7.85	870	152	140	0.92			
0 ft	49	115	rain	7.65	954	136	96	0.70			
3 ft	6:00	74	36	7.7	912	100	64	0.64			
6 ft	pm	55	52	7.9	908	110	80	0.72			

WASTEWATER CHARACTERISTICS FOR CHROMIUM (continued)

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cr/ SOL. /	TOT. (mg/l)/	IN SOLID (mg/kg)
0 ft	52	106		7.5	934	140	120	0.85			
3 ft	6:00	79	26	7.65	908	128	104	0.81			
6 ft	pm	51	52	7.75	914	202	144	0.71			
0 ft	58	80		7.55	1080	312	188	0.60			
3 ft	6:00	62	22	7.65	1004	236	156	0.66			
6 ft	pm	30	63	7.75	926	176	116	0.65			
0 ft	60	75		7.35	900	172	114	0.66			
3 ft	6:00	50	33	7.5	740	160	104	0.65			
6 ft	pm	30	61	7.7	756	78	38	0.48			
0 ft	65	134		7.35	896	152	120	0.78			
3 ft	6:00	100	25	7.65	890	176	130	0.73			
6 ft	pm	65	52	7.8	874	166	120	0.72			
0 ft	72	64		7.6	878	168	138	0.82			
3 ft	noon	41	36	7.7	830	118	94	0.79			
6 ft		29	55	7.8	854	126	98	0.77			

WASTEWATER CHARACTERISTICS FOR CHROMIUM (continued)

II. 9 mg/l Slug Dose of chromium for 4 hours

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cr/ SOL. /	(mg/l)/ TOT.	IN SOLID (mg/kg)
Injection Start											
Raw	72	64		7.6	878	168	138	0.82	0.01	0.02	20
0 ft	noon	56		7.98	940	180	138	0.76	7.26	8.75	410
3 ft		39	39	8.05	844	106	78	0.73	5.48	5.75	86
6 ft		32	50	8.09	862	106	80	0.75	4.	5.13	151
Injection Stop (November 27, noon to 4:00 pm. for 4 hours)											
0 ft		125		7.2	928	134	112	0.83	0.01	0.02	3357
3 ft	4:00	80	36	7.5	852	112	92	0.82	0.09	0.39	1554
6 ft	pm	60	52	7.9	814	70	56	0.80	0.12	0.35	1206
0 ft		130		7.2	1010	178	156	0.87	0.01	0.03	2857
3 ft	8:00	94	28	7.45	844	116	92	0.79	0.05	0.22	1407
6 ft	pm	68	48	7.6	832	96	70	0.72	0.05	0.26	1070
0 ft		81		7.6	850	128	106	0.82	0.01	0.02	2640
3 ft	midnight	66	19	7.7	876	122	100	0.81	0.05	0.22	1024
6 ft		55	32	7.8	790	84	66	0.78	0.05	0.2	1100
0 ft	73	62		7.75	844	162	128	0.79	0.01	0.01	825
3 ft	8:00	39	35	7.85	788	114	84	0.73	0.06	0.22	754
6 ft	am	25	59	7.9	800	114	84	0.73	0.06	0.17	947
0 ft		139		8.5	1190	202	138	0.68	0.01	0.03	288
3 ft	noon	75	46	8.1	990	104	72	0.69	0.06	0.13	573
6 ft		53	62	8.15	960	80	56	0.7	0.07	0.13	719
0 ft		89		7.65	934	156	130	0.83	0.02	0.02	594
3 ft	6:00	65	27	7.7	914	148	122	0.82	0.07	0.12	571
6 ft	pm	43	52	7.8	918	210	178	0.84	0.07	0.25	670
0 ft	74	73		7.6	948	136	122	0.89	0.02	0.02	140
3 ft	noon	46	37	7.85	864	80	64	0.8	0.1	0.12	206
6 ft		33	55	7.9	824	66	52	0.78	0.1	0.12	534
0 ft		86		7.8	878	148	122	0.82	0.01	0.04	78
3 ft	6:00	65	25	7.85	828	112	88	0.78	0.09	0.11	275
6 ft	pm	38	56	7.85	830	144	120	0.83	0.09	0.11	525

WASTEWATER CHARACTERISTICS FOR CHROMIUM (continued)

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cr/ SOL. / (mg/l)/	TOT.	IN SOLID (mg/kg)
0 ft	75	92		7.45	904	108	88	0.81	0.03	0.04	98
3 ft	6:00	65	29	7.6	920	118	94	0.79	0.1	0.11	212
6 ft	pm	44	52	7.7	932	152	124	0.81	0.1	0.11	339
0 ft	77	151		7.35	952	174	152	0.87	0.04	0.03	50
3 ft	6:00	98	35	7.65	864	124	106	0.85	0.05	0.11	88
6 ft	pm	75	50	7.7	892	118	104	0.88	0.05	0.11	345
0 ft	78	110		7.55	848	106	92	0.86	0.03	0.02	50
3 ft	6:00	80	27	7.75	878	102	84	0.82	0.05	0.09	164
6 ft	pm	50	55	7.8	810	98	78	0.79	0.04	0.11	175
0 ft	80	76		7.6	876	106	92	0.86	0.04	0.03	34
3 ft	6:00	60	21	7.65	828	86	66	0.76	0.08	0.05	102
6 ft	pm	38	51	7.85	926	194	156	0.80	0.08	0.08	123
0 ft	82	83		7.75	858	108	88	0.81	0.04	0.04	60
3 ft	6:00	57	31	7.85	874	106	86	0.81	0.05	0.05	56
6 ft	pm	33	60	7.9	840	104	78	0.75	0.04	0.04	51
0 ft	86	71		7.55	866	120	104	0.86	0.05	0.04	22
3 ft	6:00	51	28	7.8	824	92	78	0.84	0.06	0.04	18
6 ft	pm	27	62	7.85	786	78	68	0.87	0.05	0.04	26
0 ft	87	51	Bef.In	7.7	814	144	118	0.81			
3 ft		35	31	7.8	788	104	80	0.76			
6 ft	noon	21	58	7.9	852	146	118	0.80			

WASTEWATER CHARACTERISTICS FOR CHROMIUM (continued)

III. 38 mg/l Slug Dose of Chromium for 4 hours

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cr/ SOL. /	TOT. (mg/l)/	IN SOLID (mg/kg)
Injection Start											
Raw	87	51		7.7	814	144	118	0.81	0.06	0.08	
0 ft		46		7.3	1044	154	116	0.75	38.7	40.	892
3 ft	noon	38	27	7.65	948	84	60	0.71	30.5	31.8	338
6 ft		29	45	7.9	940	86	60	0.69	27.7	28.	469
Raw		64		7.5	854	98	84	0.85	0.05	0.07	
0 ft		58		7.5	1040	140	112	0.8	36.9	37.	3624
3 ft	4:00	55	14	7.65	938	76	56	0.73	35.	35.8	2106
6 ft	pm	30	53	7.85	924	88	66	0.75	21.1	33.3	2001
Injection Stop (December 12, noon to 4:00 pm. for 4 hours)											
0 ft		64		7.5	854	98	84	0.85	0.09	0.1	
3 ft	4:00	50	27	7.85	880	118	94	0.79	4.0	4.58	
6 ft	pm	37	45	7.95	882	100	76	0.76	6.58	6.98	
0 ft		67		7.2	962	146	122	0.83	0.02	0.09	1566
3 ft	8:00	61	9	7.35	918	112	92	0.82	0.02	0.16	1099
6 ft	pm	48	28	7.45	978	190	156	0.82	0.04	0.48	1707
0 ft		71		7.3	888	102	86	0.84	0.01	0.01	1556
3 ft		52	27	7.45	850	88	66	0.75	0.01	0.11	1521
6 ft	midnight	38	47	7.45	840	66	54	0.81	0.01	0.17	1452
0 ft	88	39		7.7	908	168	136	0.80	0.01	0.1	1198
3 ft	8:00	34	13	7.75	878	158	128	0.81	0.01	0.11	602
6 ft	am	19	51	7.85	828	110	86	0.78	0.01	0.12	1229
0 ft		53		7.65	874	108	82	0.75	0.01	0.16	382
3 ft		43	19	7.7	898	126	92	0.73	0.01	0.17	521
6 ft	noon	34	35	7.8	854	104	72	0.69	0.01	0.1	887
0 ft		54		7.5	866	100	88	0.88	0.01	0.04	769
3 ft	6:00	44	19	7.6	854	88	74	0.84	0.01	0.05	424
6 ft	pm	24	55	7.7	804	66	54	0.81	0.01	0.08	805
0 ft	89	109		7.5	926	144	122	0.84	0.01	0.01	70
3 ft		74	32	7.65	876	114	96	0.84	0.01	0.02	416
6 ft	noon	57	48	7.85	816	76	64	0.84	0.01	0.03	583

WASTEWATER CHARACTERISTICS FOR CHROMIUM (continued)

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cr/ SOL. / (mg/l)/	TOT.	IN SOLID (mg/kg)
0 ft		67		7.65	1208	142	116	0.81	0.01	0.05	59
3 ft	6:00	64	2	7.75	1042	140	114	0.81	0.01	0.06	286
6 ft	pm	52	22	7.8	1272	108	88	0.81	0.02	0.05	495
0 ft	91	78		7.7	988	168	134	0.79	0.02	0.03	29
3 ft	6:00	72	8	7.75	934	126	98	0.77	0.02	0.02	117
6 ft	pm	54	31	7.8	898	108	82	0.75	0.02	0.03	269
0 ft	92	70		7.6	746	146	116	0.79	0.01	0.02	34
3 ft	6:00	60	14	7.75	742	124	90	0.72	0.02	0.03	280
6 ft	pm	46	34	7.75	724	122	86	0.70	0.02	0.04	315
0 ft	93	93		7.9	896	126	96	0.76	0.2	0.03	36
3 ft	6:00	77	17	7.8	834	114	90	0.78	0.2	0.04	425
6 ft	pm	49	47	7.9	812	96	72	0.75	0.2	0.05	275
0 ft	95	102		7.45	908	172	128	0.74	0.02	0.05	48
3 ft	6:00	81	21	7.55	812	112	70	0.62	0.02	0.04	255
6 ft	pm	66	35	7.65	812	100	66	0.66	0.01	0.05	304
0 ft	97	73		7.7	956	126	96	0.76	0.01	0.05	30
3 ft	6:00	50	31	7.75	864	88	64	0.72	0.02	0.04	189
6 ft	pm	31	59	7.8	896	108	76	0.70	0.02	0.04	227
0 ft	99	128		7.4	1074	134	116	0.86	0.02	0.02	51
3 ft	6:00	88	31	7.55	1002	110	88	0.8	0.02	0.03	59
6 ft	pm	62	52	7.65	992	138	114	0.82	0.01	0.03	75
0 ft	101	68		7.45	964	120	92	0.76	0.02	0.03	27
3 ft	6:00	54	21	7.55	920	98	74	0.75	0.01	0.04	25
6 ft	pm	30	56	7.65	938	134	102	0.76	0.02	0.05	62
0 ft	103	81		7.45	894	130	102	0.78	0.02	0.03	61
3 ft	6:00	60	26	7.55	842	90	64	0.71	0.01	0.05	39
6 ft	pm	34	58	7.65	886	100	70	0.7	0.02	0.06	49
0 ft	108	72		7.45	916	96	78	0.81	0.02	0.03	24
3 ft	(1991)	54	25	7.75	876	60	42	0.7	0.02	0.01	18
6 ft	6:00p	36	51	7.85	898	72	54	0.75	0.01	0.01	29

WASTEWATER CHARACTERISTICS FOR CHROMIUM (continued)

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cr/ SOL. / (mg/l)/	TOT.	IN SOLID (mg/kg)
0 ft	110	55		7.6	950	130	106	0.81	0.04	0.03	19
3 ft	6:00	40	27	7.7	956	124	110	0.80	0.04	0.02	52
6 ft	pm	24	57	7.8	924	110	80	0.72	0.05	0.03	48
0 ft	116	22		7.65	750	140	110	0.78			
3 ft		15	30	7.7	716	98	76	0.77			
6 ft	noon	11	50	7.85	722	136	108	0.79			

WASTEWATER CHARACTERISTICS FOR CHROMIUM (continued)

IV. 96 mg/l Slug Dose of Chromium for 4 hours

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cr/ SOL. / (mg/l)/	TOT.	IN SOLID (mg/kg)
						Injection Start					
Raw	116	22		7.65	750	140	110	0.78	0.07	0.08	
0 ft		1		7.15	1048	156	122	0.78	90.	95.	941
3 ft	noon	12	44	7.3	972	78	60	0.76	82.5	86.	737
6 ft		0		7.55	996	86	68	0.790	61.5	64.	997
Raw		37		7.5	818	112	88	0.78	0.07	0.05	
0 ft		0		7.45	964	120	92	0.76	87.52	97.5	2591
3 ft	4:00	26	30	7.55	920	98	74	0.75	91.	100.5	2894
6 ft	pm	25	32	7.65	938	134	102	0.76	89.5	100.	2320
		Injection Stop (January 10, noon to 4:00 pm. for 4 hours)									
0 ft		37		7.5	818	112	88	0.78	0.15	0.05	
3 ft	4:00	29	22	7.65	894	152	116	0.76	7.72	9.75	
6 ft	pm	29	23	7.7	934	200	152	0.76	8.4	12.8	
0 ft		49		7.45	880	128	102	0.79	0.03	0.18	2509
3 ft	8:00	47	5	7.5	898	122	92	0.75	0.06	0.19	1493
6 ft	pm	35	28	7.6	850	104	76	0.73	0.11	0.3	1550
0 ft		50		7.55	900	122	100	0.81	0.03	0.03	1619
3 ft	midnight	48	4	7.65	890	120	100	0.83	0.05	0.2	1310
6 ft		36	28	7.75	860	90	72	0.8	0.08	0.25	1525
0 ft	117	35		7.65	1324	482	248	0.51	0.03	0.08	1337
3 ft	8:00	27	23	7.6	1068	276	156	0.56	0.04	0.27	774
6 ft	am	20	44	7.7	1034	220	140	0.63	0.05	0.42	1667
0 ft		44		7.75	1022	132	110	0.83	0.02	0.04	428
3 ft	noon	38	14	7.6	976	94	74	0.78	0.05	0.13	743
6 ft		28	38	7.7	966	82	64	0.78	0.04	0.17	1233
0 ft		45		7.4	964	106	86	0.81	0.02	0.02	277
3 ft	6:00	40	11	7.5	932	100	74	0.74	0.04	0.11	866
6 ft	pm	24	48	7.55	912	78	58	0.74	0.05	0.15	1073
0 ft	118	35		7.7	1082	258	178	0.68	0.04	0.04	157
3 ft	noon	33	4	7.75	934	130	86	0.66	0.04	0.06	477
6 ft		24	32	7.8	876	72	48	0.66	0.04	0.07	790

WASTEWATER CHARACTERISTICS FOR CHROMIUM

DEPTH	DAY ELAPSED & TIME	SBOD5 (mg/l)	%BOD5 REMOVAL	pH	TS /	TSS (mg/l)	VSS /	VSS/TSS	/Conc. of Cr/ SOL. /	TOT. (mg/l)/	IN SOLID (mg/kg)
0 ft		-		8.	1158	240	134	0.55	0.04	0.03	72
3 ft	6:00	-		7.65	1006	132	72	0.54	0.04	0.08	405
6 ft	pm	-	-	7.7	930	94	56	0.59	0.04	0.09	613
0 ft	119	57		7.5	1106	216	126	0.58	0.03	0.04	66
3 ft	6:00	42	26	7.5	1024	160	100	0.62	0.03	0.11	242
6 ft	pm	29	49	7.65	986	118	76	0.64	0.04	0.07	571
0 ft	120	61		7.55	996	130	100	0.76	0.03	0.03	49
3 ft	6:00	57	7	7.65	942	96	66	0.68	0.04	0.04	192
6 ft	pm	39	37	7.6	912	84	56	0.66	0.04	0.06	471
0 ft	121	40		7.65	1116	262	172	0.65	0.04	0.04	51
3 ft	6:00	35	13	7.65	1144	326	226	0.69	0.04	0.1	122
6 ft	pm	27	32	7.75	960	146	88	0.60	0.04	0.05	230
0 ft	122	28		7.65	1104	236	142	0.60	0.05	0.04	46
3 ft	6:00	23	20	7.65	1130	268	172	0.64	0.04	0.06	127
6 ft	pm	17	42	7.75	1040	188	128	0.68	0.04	0.05	221
0 ft	123	-		7.55	974	172	94	0.54	0.04	0.05	44
3 ft	6:00	-		7.65	970	168	96	0.57	0.03	0.05	149
6 ft	pm	-	-	7.65	920	130	72	0.55	0.04	0.05	172
0 ft	124	84		7.55	960	134	94	0.70	0.03	0.03	33
3 ft	6:00	65	23	7.6	922	110	76	0.69	0.05	0.05	147
6 ft	pm	42	50	7.65	896	98	66	0.67	0.04	0.04	173
0 ft	127	42		7.65	1036	134	96	0.71	0.04	0.02	30
3 ft	6:00	30	29	7.65	954	92	62	0.67	0.03	0.04	128
6 ft	pm	20	53	7.75	950	76	42	0.55	0.03	0.03	126
0 ft	129	38		7.6	1010	138	100	0.72	0.04	0.04	24
3 ft	6:00	28	26	7.65	1010	164	120	0.73	0.03	0.05	107
6 ft	pm	18	53	7.7	942	94	62	0.65	0.04	0.05	132
0 ft	131	87		7.65	980	126	98	0.77	0.04	0.03	27
3 ft	6:00	68	25	7.75	944	84	58	0.69	0.03	0.04	75
6 ft	pm	43	51	7.85	910	68	42	0.61	0.03	0.04	95
0 ft	134	81		7.5	956	120	96	0.8	0.03	0.03	35
3 ft	6:00	59	28	7.55	964	156	120	0.76	0.04	0.04	25
6 ft	pm	34	58	7.7	920	114	82	0.71	0.04	0.04	38

VITA

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Candidate for the Degree of

Master of Science

Thesis: THE EFFECTS OF COPPER AND CHROMIUM IN TERMS OF RECOVERY TIME FOR SOLUBLE BIOLOGICAL OXYGEN DEMAND REMOVAL ON A BIOLOGICAL TOWER

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