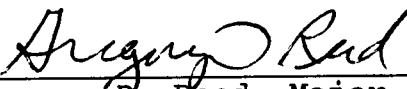
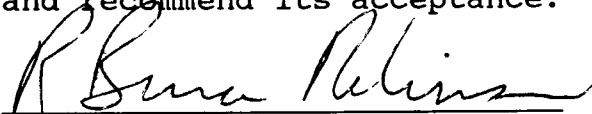


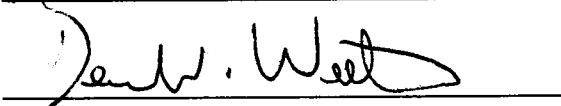
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EVALUATION OF CARBON SOURCES FOR BIODENITRIFICATION
OF CONCENTRATED NITRATE WASTEWATER
GENERATED AT THE Y-12 PLANT

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Timothy Byron Hale

August 1988

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ABSTRACT

The Y-12 West End Treatment Facility (WETF) currently treats concentrated nitrate wastewater (1-5% nitrate) generated at the Oak Ridge Y-12 plant. The facility contains 500,000 gallon tanks equipped with mixers that are used as batch suspended growth biodenitrification reactors. Acetic acid neutralized with hydrated lime (calcium acetate) is used as the carbon source for the biodenitrification process. However, partly due to the amount of lime required to neutralize the acetic acid, substantial amounts of sludge are produced that will require dewatering and disposal, possibly at a mixed waste disposal facility. Stoichiometric calculations indicate that the quantity of sludge could be reduced by 23% if a carbon source not requiring neutralization was used resulting in annual WETF storage/disposal cost savings of \$250,000 to \$1,250,000.

Denitrification data was obtained from WETF, and a laboratory study of the denitrification process was performed to determine and compare denitrification rates and sludge production of batch reactors fed with calcium acetate, methanol, and sucrose at nitrate concentrations ranging from 1% to 5%. Denitrification rates of 810 to 9000 mg/l NO_3 /day were determined for WETF Tanks fed with calcium acetate at nitrate concentrations up to 36,000 mg/l. A laboratory reactor fed with acetate had a denitrification rate of 700 mg/l NO_3 /day or

.060 $\text{NO}_3\text{-N/MLVSS/day}$; sucrose fed reactors had denitrification rates ranging from 570 to 2030 $\text{mg/l NO}_3\text{/day}$ or .039 to 0.19 $\text{NO}_3\text{-N/MLVSS/day}$. Denitrification rates and order of reaction for the concentrated nitrate wastewater were comparable with similar data found in literature for wastewater with lower concentrations of nitrates.

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CHAPTER I

INTRODUCTION

The Oak Ridge Y-12 Plant, located in Oak Ridge, Tennessee, is a United States Department of Energy (DOE) facility that produces nuclear weapon components and is operated by Martin Marietta Energy Systems, Inc. Annually, 1.5 - 2.4 million gallons (21) of concentrated nitrate wastewater (average nitrate concentrations are 30,000 mg/l) are generated primarily from the uranium purification processes, plating processes, nitrate treatment facility, and miscellaneous sources.

The wastewater is currently stored and treated in 500,000 gallon tanks at the Y-12 West End Treatment Facility (WETF). The 500,000 gallon storage tanks were retrofitted with mixers to serve as reactors for batch suspended growth biodenitrification. This process is required to reduce the nitrate levels to less than 45 mg/l of nitrates so that the wastewater, after subsequent physical/chemical treatment, may be discharged to the receiving stream, East Fork Poplar Creek, under a National Pollutant Discharge Elimination System (NPDES) permit. Acetic acid neutralized with hydrated lime (calcium acetate) serves as the carbon source for the biodenitrification process. However, due to the lime added to

neutralize the acetic acid, excessive amounts of sludge are generated in the process.

Calcium acetate was selected as the substrate for WETF based on successful denitrification rate laboratory studies and full scale treatment at the Y-12 S-3 Ponds and the 9818 biodenitrification treatment facility. However, stoichiometric calculations indicate that processes fed with calcium acetate result in excessive amounts of sludge that could be reduced by approximately 23% if alternative carbon sources were used. Considering the large amounts of WETF wastewater, substantial amounts of sludge are produced that require handling, storage, and subsequent long-term storage and/or disposal at a mixed (co-contaminated with radioactive and hazardous constituents) waste disposal facility. Such costly handling and disposal justify identifying alternative carbon sources and comparing denitrification with different carbon source feed materials in terms of bacterial acclimation time, denitrification rates, sludge production and associated cost.

The majority of biodenitrification studies have been performed using various carbon sources to support agricultural and municipal treatment processes which remove lower concentrations of nitrates. Acclimation times, denitrification rates, and observed reaction order have been analyzed and reported for denitrification at these

lower concentrations, but there is limited data available to determine if these results can be applied to denitrification of nitrate solutions with concentrations as high as 1-5% nitrates.

CHAPTER II

SCOPE

A literature study was performed to identify alternative chemicals that could be used to supply carbon to biodenitrification reactors. Data found in literature were collected for denitrification processes fed with various carbon sources that measured acclimation times, denitrification rates, and/or reaction order at nitrate nitrogen concentrations up to 1000 mg/l. Data were obtained from WETF operators who monitored and treated batch quantities of nitrate wastewater with nitrate concentrations as high as 35,000 mg/l; the WETF tanks were supplied with calcium acetate as the carbon source.

A laboratory study was performed to compare acclimation time, denitrification rates, reaction order, and sludge production of batch reactors fed with either calcium acetate, methanol, or sucrose with initial concentrations of nitrates as high as 5%. The laboratory study involved using lab scale reactors for modelling the biodenitrification process at WETF. A composite of actual wastewater that would usually be treated by the WETF was treated in the lab scale reactors. Each of three reactors, approximately 40 liters in volume and equipped with stirring mechanisms, was filled with wastewater neutralized with hydrated lime to a pH of 7 to 8. Each reactor was fed

the proper nutrients, the respective substrates, and seeded with biodenitrifying microorganisms. The pH, temperature, dissolved oxygen, and nutrient concentrations were monitored and maintained consistently between reactors. Periodic samples of each reactor were analyzed for concentrations of inorganics, nitrates, organics, total dissolved solids (TDS), mixed liquor suspended solids (MLSS), and mixed liquor volatile suspended solids (MLVSS) until denitrification reached completion.

Data collected from laboratory study were contrasted with respective data from WETF Tanks and literature values for denitrification at lower concentrations; comparisons of the acclimation time, nitrate reduction per biomass and time, order of denitrification rate, and sludge growth were performed. An economic analysis was prepared for comparing substrate feed materials based on the lab results.

CHAPTER III

LITERATURE REVIEW

Biological denitrification or bionitrification is a step in the nitrogen cycle that accomplishes the reduction by anoxic microorganisms of one or both of ionic nitrogen oxides (nitrate, NO_3^- , and nitrite, NO_2^-) to molecular nitrogen. From an environmental standpoint, the process accomplishes converting what can be an objectionable compound to a relatively innocuous end product that is not immediately available for biological growth.

Nitrites and nitrates can have the following detrimental effects.

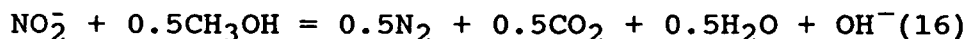
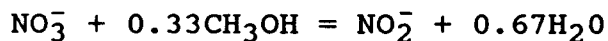
1. Eutrophication. Excessive plant growth and/or algae blooms result from high levels of nitrogen compounds in rivers, lakes, or estuaries. Results of eutrophication include deterioration in the appearance of water, odors from decomposing algae, and a lower dissolved oxygen level which can effect aquatic life.

2. Public Health. High concentrations of nitrite or nitrate in drinking water can cause methemoglobinemia, a sometimes fatal blood disorder which affects infants less than 3 months old. Nitrates can be converted to nitrites in the stomach, which, in turn, can react with hemoglobin in the blood to form methemoglobin. Methemoglobin is incapable of carrying oxygen and thus can cause

suffocation. The term "blue babies" is used to describe infants inflicted with methemoglobinemia since a symptom is a bluish tinge to the skin.

3. Water Reuse. Water may be reused for industrial purposes (e. g., source of cooling water). Nitrogen compounds can cause substantial increase in biological growth in cooling towers and distribution boxes (16).

Biodenitrification is accomplished by many common facultative bacteria in a two-step process that converts a biodegradable carbon source, nitrates, and nitrites to carbon dioxide and nitrogen as approximated by the following reactions. Methanol is used in the equations to represent a typical carbon source. The two step process is termed dissimilation or dissimilatory reduction.



Many common facultative heterotrophic bacteria such as Pseudomonas, Micrococcus, Achromobacter, Spirillum, and Bacillus are capable of performing denitrification (8). Some species are only capable of converting nitrate to nitrite. Payne, 1973 (13) lists genera of chemosynthetic bacteria capable of denitrifying (NO_3 to N_2) and genera capable of respiring nitrate to nitrite.

To maximize the rate of biodenitrification in a true dissimilatory process, anaerobic conditions must persist. Although elemental oxygen is not available, oxygen is

derived from nitrate (NO_3^-) or nitrite (NO_2^-). Therefore, biodenitrification can better be described as an anoxic process. Nitrate, NO_3^- , serves as the electron acceptor, and the organic compound serves as the electron donor. The electron transport system is identical to that used for oxidizing organic matter aerobically, except for one enzyme (6). Thus, many facultative bacteria can shift between using oxygen or nitrate/nitrogen rapidly and without difficulty.

A variety of organic compounds have been used as electron donors for full-scale and laboratory biodenitrification and are listed below.

- o organic acids (16)
 - acetic acid
 - terephthalic acid
 - glyoxylic acid
 - pyruvic acid
 - butyric acid
 - lignosulfonic acid
 - citric acid (6)
- o Alcohols
 - ethanol
 - methanol
 - N-propyl alcohol
 - N-butyl alcohol
 - tert butyl alcohol
 - iso-butyl alcohol
 - n-pentanol alcohol
- o sugars
 - sucrose
 - molasses (3)
 - glucose
 - glutamate

- o industrial wastes
 - brewery wastes (1)
 - spent sulfite liquor
 - corn silage derivative
 - yeast
 - whey
 - farm wastes (16)
- o acetone (22) and peptone (10)
- o methane (30)
- o sewage

McCarty, Beck, and Amant, 1969 (22) evaluated various carbon sources (methanol, acetic acid, ethanol, acetone, and sugar) and showed they could be effectively used for denitrification. Methanol was recommended as the most desirable primarily because of operating economics. Still higher reaction rates were achieved when neutralized acetic acid was the carbon source.

Methanol has found predominance in U. S. practice as the carbon source for biodenitrification (16). However, the Journal of Toxicology and Environmental Health (Posner 1975, (25)) advises, when practical, that safer chemicals than methanol be substituted because of health hazards due not only to ingestion but also inhalation and dermal exposure. Chronic inhalation of methanol has produced conjunctivitis, headache, gastrointestinal disturbance, vision failure, and death. Diminished vision or blindness has resulted from skin application of methanol.

Methanol has been shown to be toxic at higher concentrations to microorganisms. Bringmann and Kuhn, 1976 (18) evaluated the effect of hazardous water pollutants upon algae. The toxicity threshold of methanol for blue green algae (Microcystis aeruginosa) and green algae (Scenedesmus quadricarda) was determined to be 530 mg/l and 8000 mg/l, respectively. Further testing performed by Bringmann and Kuhn, 1980 (24) indicated Pseudomonas putida bacteria to have a toxicity threshold of 6600 mg/l of methanol and a toxicity threshold of 2850 mg/l of acetic acid neutralized with Na_2CO_3 solution.

Chou, Speece, Siddiqi, and McKeon, 1978 (17) evaluated the toxicity of petrochemicals upon anaerobic microorganisms used for anaerobic digestion. Generally, aliphatic unsubstituted alcohols were not toxic, with the exception of methanol and propanol at high concentrations. Some toxicity to methanogenic bacteria occurred at a concentration of 50 mM; toxicity increased markedly as the concentrations exceeded 60 mM.

Clark, Francis, Francke, and Strohecker, 1975 (19) evaluated the potential inhibition of high concentrations of carbon source (methanol) and nitrate upon denitrification rates. In continuous flow, stirred-bed reactors, methanol feed rate concentrations were increased to 11.6 kg/m^3 without any apparent inhibitory effects. Actual concentrations of methanol in the reactor were not

reported. Nitrate feed concentrations of greater than 6 kg NO₃/m³ appeared to inhibit denitrification rates. Denitrification rates near 10 g of NO₃/day/dm³ (10,000 mg/l/day) of reactor volume were reported when using calcium acetate as the carbon source. The effect of slowly changing the organic feed from calcium acetate to methanol was studied for an acetate acclimated reactor. It became evident the microorganisms were in a state of shock, and methanol carbon was not biologically acceptable as a carbon source to the existing biological population.

Blasczyk, Mycielski, Jaworowska, and Brzostek, 1980 (15) compared the effect of methanol, ethanol, acetic acid, and glucose with 1000 mg/l NO₃-N concentrations on the intensity of denitrification and the selection of denitrifying bacteria. Denitrification was more efficient in media with ethanol and acetic acid. Each carbon source resulted in the selection of different species of the genus Pseudomonas or Alcaligenes.

Nurse, 1978 (20) demonstrated that denitrification with methanol results in a selective enrichment for bacteria belonging to the genus Hyphomicrobium.

Table 3.2 highlights the wide range of denitrification rates achieved at development and full scale facilities using various organic compounds as substrate. Details of two of the biodenitrification studies are included.

Table 3.2. Denitrification Rates for Suspended Growth Reactors

NO ₃ -N (mg/l)	Carbon Source	Wastewater Treated	Temp. °C	NO ₃ -N Rem./ MLVSS-Day	Ref.
20-25	brewery wastes	potassium nitrate	19-24	0.15 - 0.22	(1)
20-25	methanol	potassium nitrate	19-24	0.18	(1)
	C1 to C5 acids		10	0.10 - 0.36	(2)
	molasses		16	0.036	(3)
400 - 1100*	methanol	industrial wastewater and sodium nitrate	20-30	0.15 - 0.38	(4)
10-60	methanol		20	0.12 - 0.32	(5)
120 - 500	sodium citrate	potassium nitrate	5-27	0.24 - 3.8	(6)
	methanol		16-20	0.25 - 0.30	(7)
8.0	methanol	sodium nitrate	20		(8)
65-130	sucrose nitrogen	ammonia and org.		0.009 - 0.014**	(9)
	methanol			0.055	(10)
	glucose			0.070	(10)
	peptone			0.22	(10)
20	molasses	fermentation wastewater		0.48**	(11)
1000	acetate			3.1 - 5.8	(12)

*The reactor was operated in continuous flow mode. Feed concentrations ranged from 400 to 1100, but the concentration in the reactor ranged from about 100 to 300.

**Biomass concentration was measured as mixed liquor suspended solids (MLSS).

Murphy and Dawson, 1972 (6). Batch denitrification studies were performed using potassium nitrate as the nitrogen source and sodium citrate as the carbon source. Initial concentrations of nitrate nitrogen were 500 mg/l. In all studies, it was observed that nitrate removal was characterized initially by periods of relatively slow nitrate removal followed by linear nitrate removal (zero order with respect to the nitrate concentration). It was concluded that when carbon is in excess of theoretical requirements, the reaction is independent of nitrate and carbon concentrations. See Figures 3.1 and 3.2.

Dawson and Murphy provided data that aided in explaining the wide range of reaction rates reported. Pure cultures of denitrifying bacteria indicated removal rates 10 to 50 times those previously observed in anaerobic activated sludge. These differences resulted from the varying fraction of denitrifying bacteria in sludges and the variable growth rates of the bacteria.

Stensel, Loehr, and Lawrence, 1973 (8). Results of nitrate limited batch denitrification studies indicated that nitrate removal was linear based on plots of nitrate-nitrogen concentration vs. time. A synthetic sodium nitrate solution served as the nitrate source, and methanol was the carbon source. The initial concentration of nitrate was 8.0 mg/l of nitrate nitrogen. The batch reactor was seeded with sludge from a nearby sewage

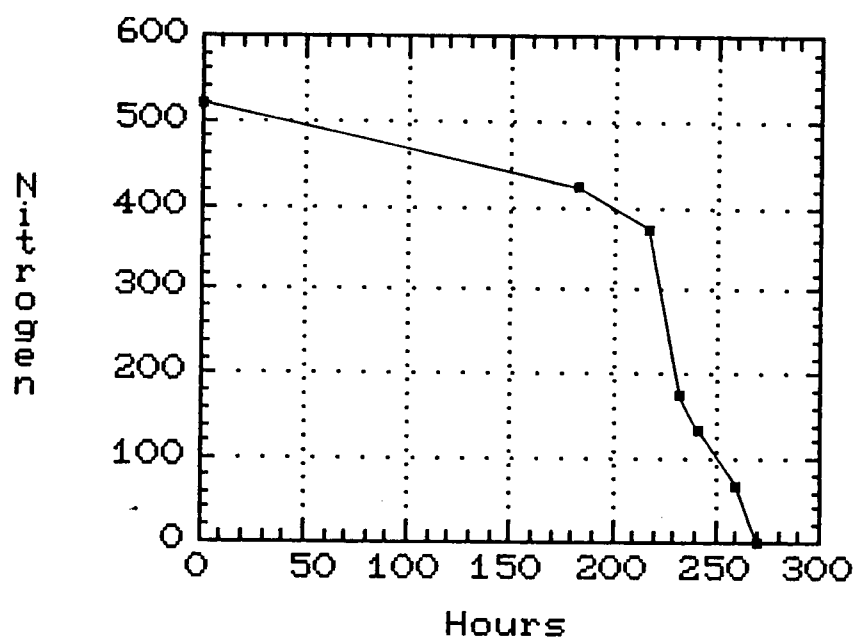


Figure 3.1. Nitrate Nitrogen vs. Time, 5°C Reaction

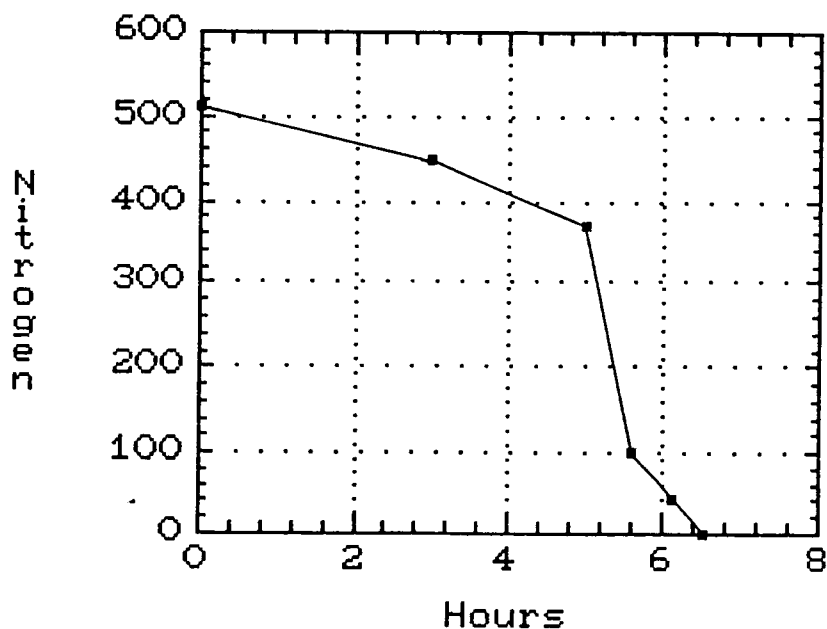


Figure 3.2. Nitrate Nitrogen vs. Time, 27°C Reaction

Adapted from Murphy, R. L. and R. N. Dawson, "The Temperature Dependency of Biological Denitrification," Water Research, 6, pp. 71-83 (1972).

treatment plant, and acclimation occurred almost immediately. Denitrification occurred at a rate of 16 mg/l of nitrate nitrogen/day, and the rate did not decrease until the nitrate concentration was near zero.

Based on review of data found in literature, it was concluded that limited information is available comparing process kinetics of batch denitrification reactors fed with alternative carbon sources at percent levels of nitrate. The detailed objectives of this study were as follows.

1. Alternative chemicals that could be used for supplying carbon to batch suspended growth reactors were identified.

2. Denitrification with alternative carbon sources added to reactors with 1-5% nitrate concentrations was compared in terms of acclimation time, denitrification rate, sludge production and associated cost.

3. Acclimation time, denitrification rates, and reaction order were determined from biodenitrifying industrial wastewater with high nitrate concentrations (1-5%) and contrasted with respective values found in literature for wastewater with nitrate nitrogen concentrations up to 1000 mg/l.

CHAPTER IV

WEST END TREATMENT FACILITY

Facility Description

The Y-12 Plant, located in Oak Ridge, Tennessee, is a United States Department of Energy (DOE) facility that produces components of nuclear weapons and is operated by Martin Marietta Energy Systems, Inc. Various production processes discharge nitrate bearing wastewaters that require treatment prior to discharge to the environment. In order to provide storage and partial treatment of these nitrate wastewaters, the storage tanks that are now part of the West End Treatment Facility (WETF) were constructed and in use by 1984. Annually, 1.5 to 2.4 million gallons of nitrate wastewater are generated at the Y-12 Plant that require treatment at the WETF. The following is a description of the primary sources of wastewater.

(1) Uranium purification processes generate acidic evaporator condensate and raffinate that contain aluminum nitrate, calcium nitrate, and extracted impurities such as magnesium, iron, nickel, molybdenum, tungsten, titanium, and zirconium.

(2) Plating shops generate spent nitric acid solutions and solutions contaminated with nitric acids. These wastewaters are also contaminated with heavy metals

such as hexavalent and trivalent chromium, copper, nickel, and zinc.

(3) A continuous flow stirred bed reactor denitrification process (Building 9818) is used for treating a portion of condensate and raffinate waste streams identified above. Because of the current mode of operation, the slurry effluent from this facility requires additional nitrate reduction and solids removal before being discharged.

(4) Mopwaters and rinsewaters used throughout Y-12 contain low concentrations of nitrates as well as other contaminants.

Nitrate concentrations in these solutions range from 100 mg/l nitrate to as high as 60% nitrate. The total amount of nitrate sent to the facility is estimated to be about 360,000 lb/yr. Waste streams contain inorganic contaminants such as Al, Ca, Cr, Cu, Fe, K, Na, Ni, P, and Si. Suspended solids concentrations range from 2 to 120,000 mg/l and dissolved solids concentrations vary from 8 to 870,000 mg/l. Alkalinities (expressed as calcium carbonate) may be present in concentrations as low as 1 mg/l and as high as 96,200. Sulfate concentrations range from less than 1 mg/l to as high as 43,000 mg/l. Other elements in small or trace amounts that have been found in some nitrate streams include As, Be, Co, La, Li, Mg, Mn, Sr, and Zn (21).

The nitrate wastewaters are mixed at WETF resulting in composited wastewater with a pH less than 2 and nitrate concentrations ranging from 2 to 5%. WETF currently consists of nine 500,000 gallon tanks; additional tanks will be constructed to provide adequate capacity for Y-12 nitrate wastewater and sludge. The 500,000 gallon storage tanks are above ground, flat-bottomed tanks that have been retrofitted with mixers to serve as reactors for batch suspended growth biodenitrification. This process is required to reduce the nitrate levels to less than 45 mg/l of nitrates so that the wastewater, after subsequent physical/chemical treatment at the WETF, may be discharged to the receiving stream, East Fork Poplar Creek, under a National Pollutant Discharge Elimination System (NPDES) permit.

Operation

Wastewater is collected in tanks at each generation point and hauled in 5,000 gallon tankers to the WETF. The majority of wastewater is acidic and is neutralized with hydrated lime before it is pumped into the process tanks. Precipitate formed from the neutralization process is not separated from the wastewater prior to addition into the tanks.

Acetic acid serves as the carbon source for the denitrification process. Acetic acid was selected as the substrate for WETF based on successful denitrification rate

laboratory studies and full scale treatment at the Y-12 S-3 Ponds and 9818 biodenitrification facility. The acetic acid is neutralized with hydrated lime to form calcium acetate before it is added to the respective process tank.

During the first two years of operation, each tank was denitrified as a batch. Denitrification did not begin until each tank was filled with wastewater, calcium acetate, and microbial seed; additional amounts of wastewater were not added until each tank had completely denitrified. Sufficient amounts of calcium acetate were added initially such that each reactor could denitrify completely, based on a carbon/nitrogen ratio of 1.1:1 to 1.3:1.

Acclimation of bacteria in the WETF batch reactor tanks has proven to be unpredictable (See Figures 4.1-4.9). Tanks F-2, F-3, F-5A, and F-6 did not acclimate such that significant denitrification of the concentrated wastewater occurred until after several months. Low operating pH, high dissolved oxygen, high nitrate and metal concentrations, cool temperatures, or a combination thereof were suspected to be inhibiting the process. To minimize the acclimation period, the contents of tanks that had denitrified were mixed with wastewater from tanks that were slow to acclimate, and denitrification began almost immediately (See Figures 4.5, 4.7, and 4.8). Still,

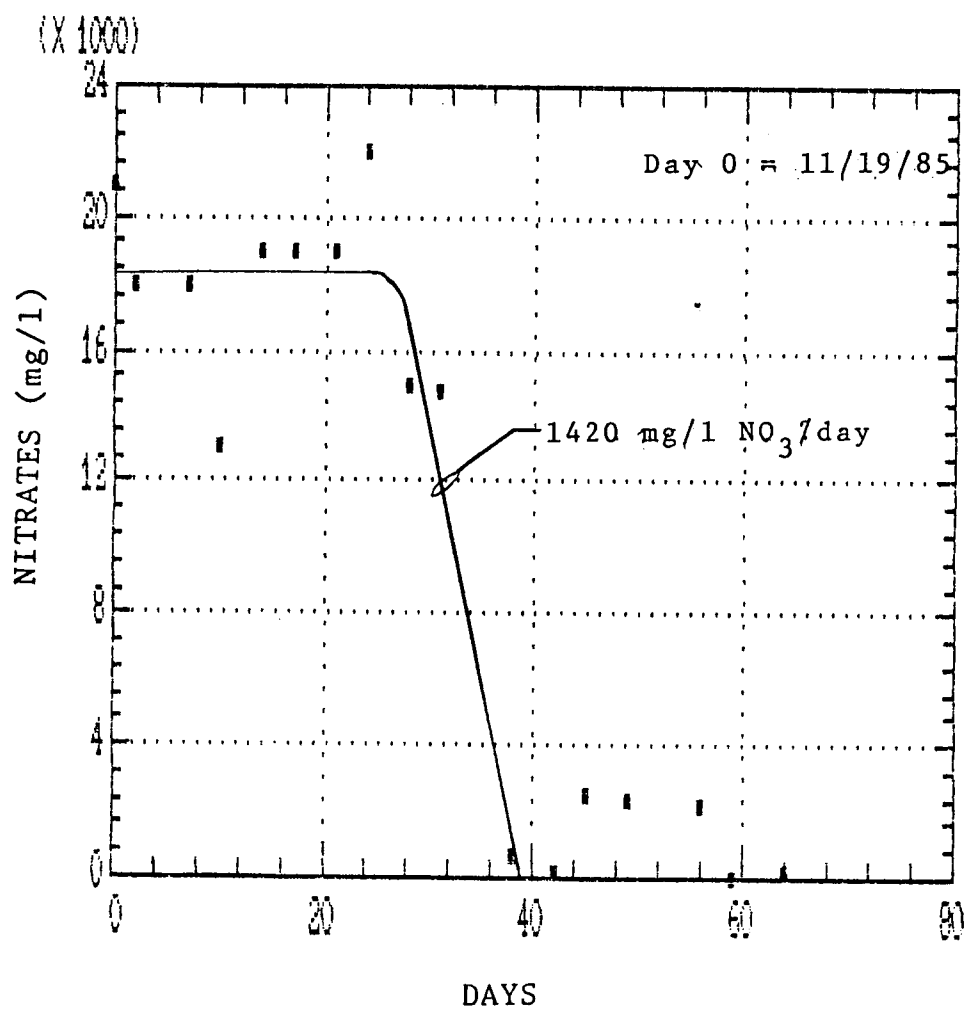


Figure 4.1. Tank F-1 - Plot of Nitrate vs. Day

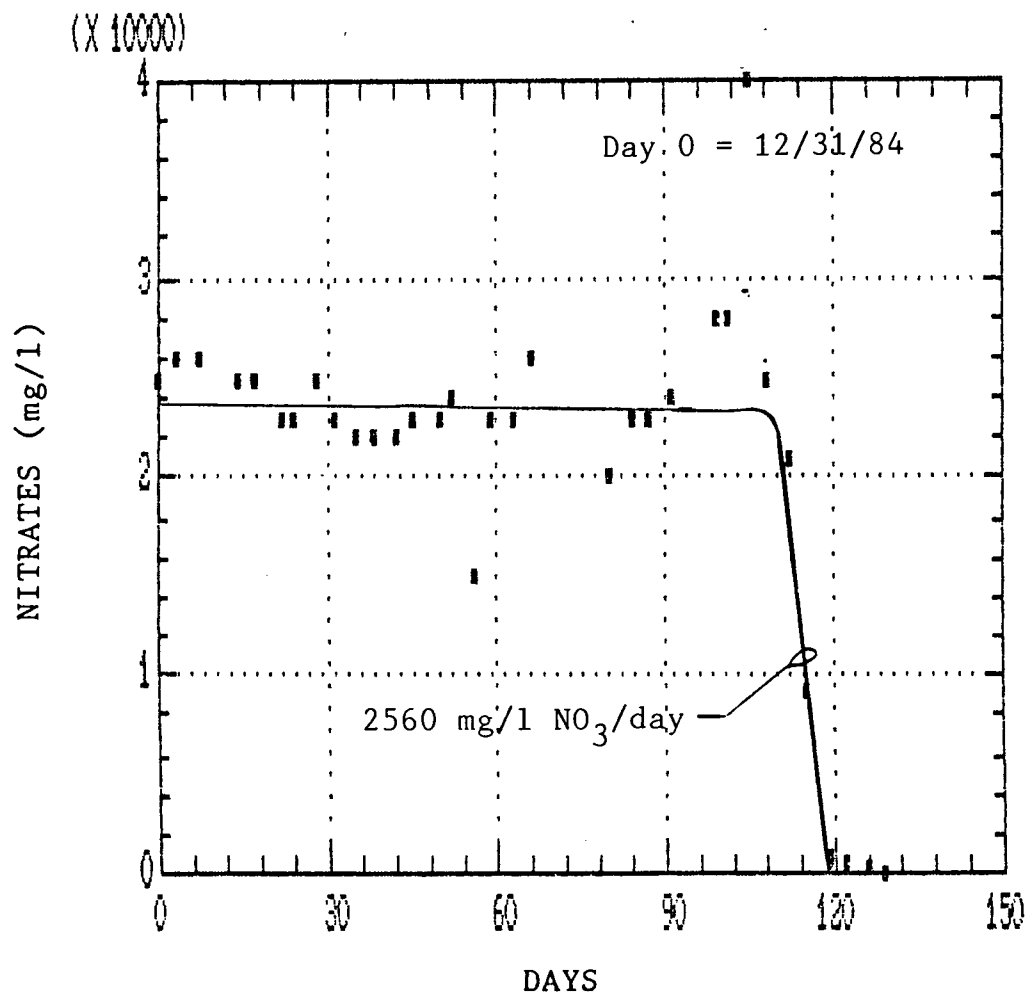


Figure 4.2. Tank F-2 - Plot of Nitrate vs. Day

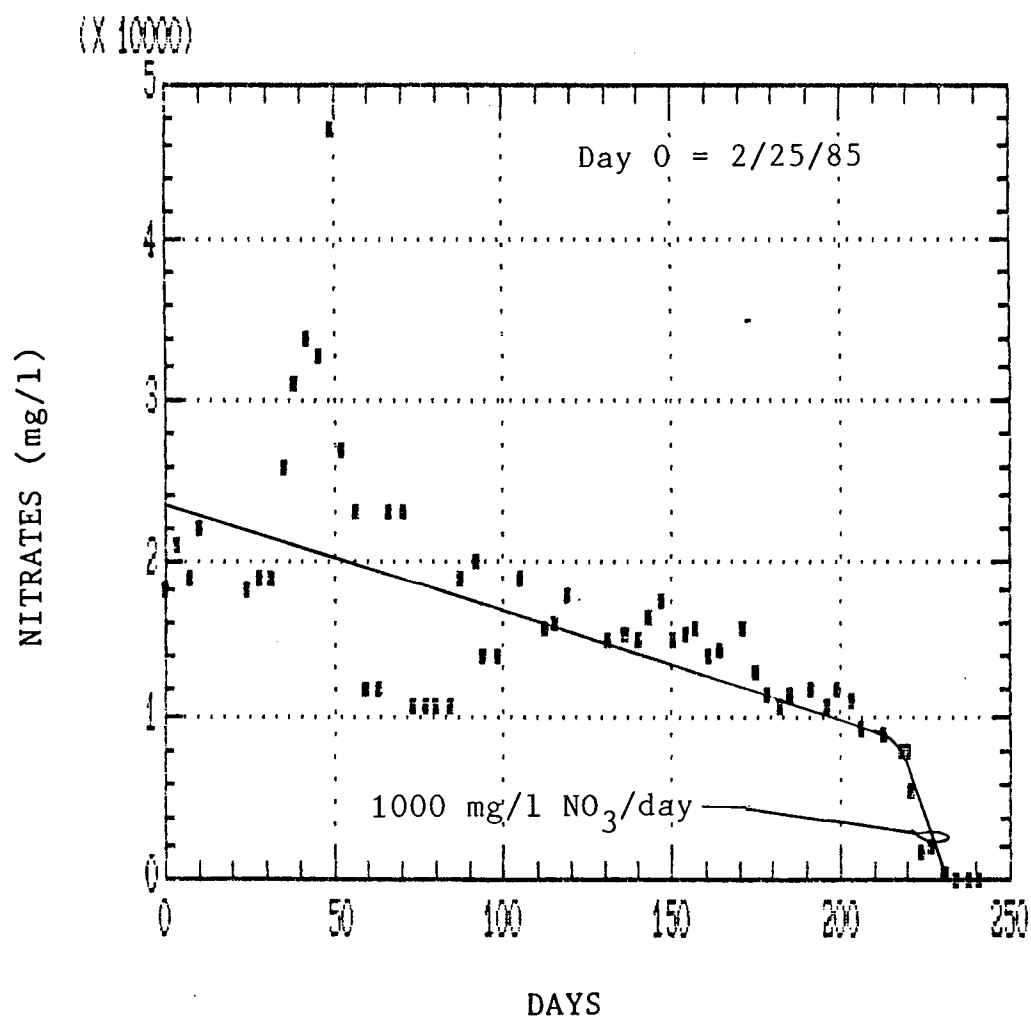


Figure 4.3. Tank F-3 - Plot of Nitrate vs. Day

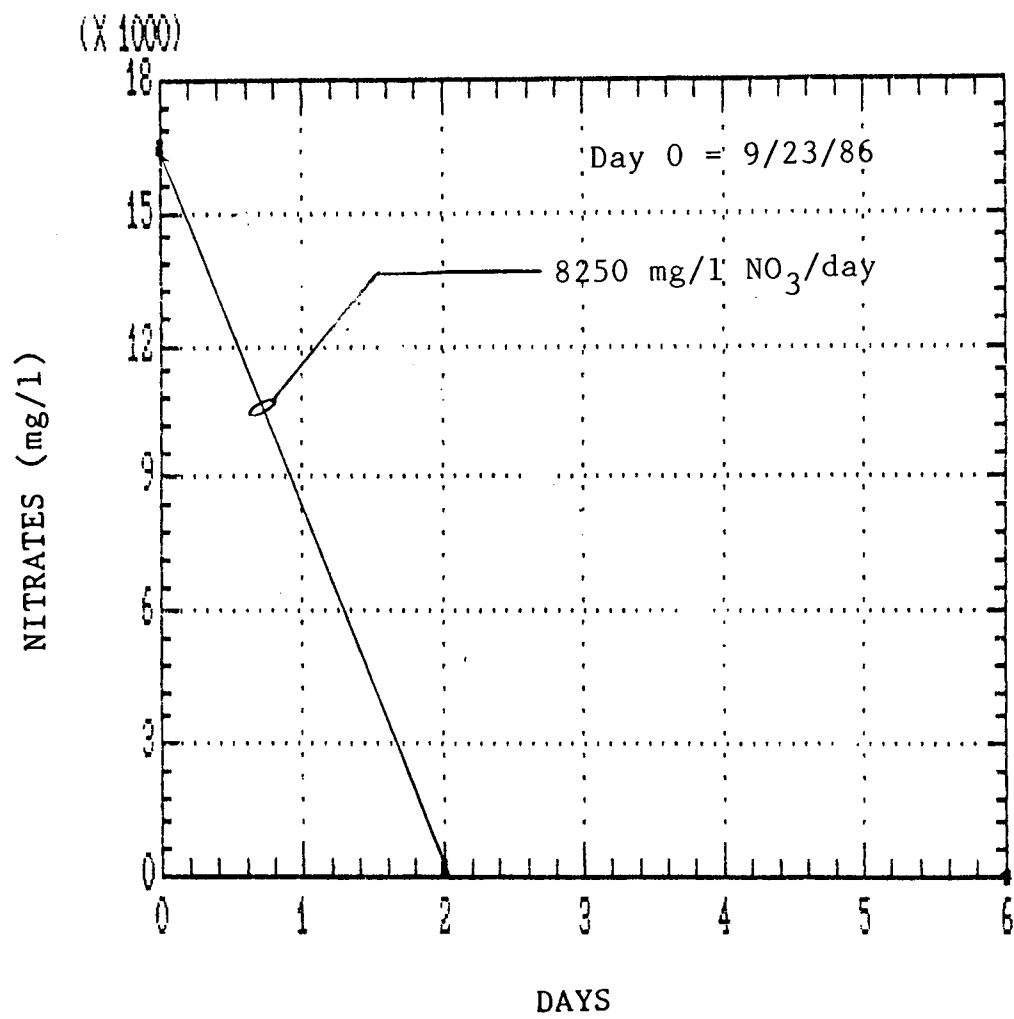


Figure 4.4 Tank F-4A - Plot of Nitrate vs. Day

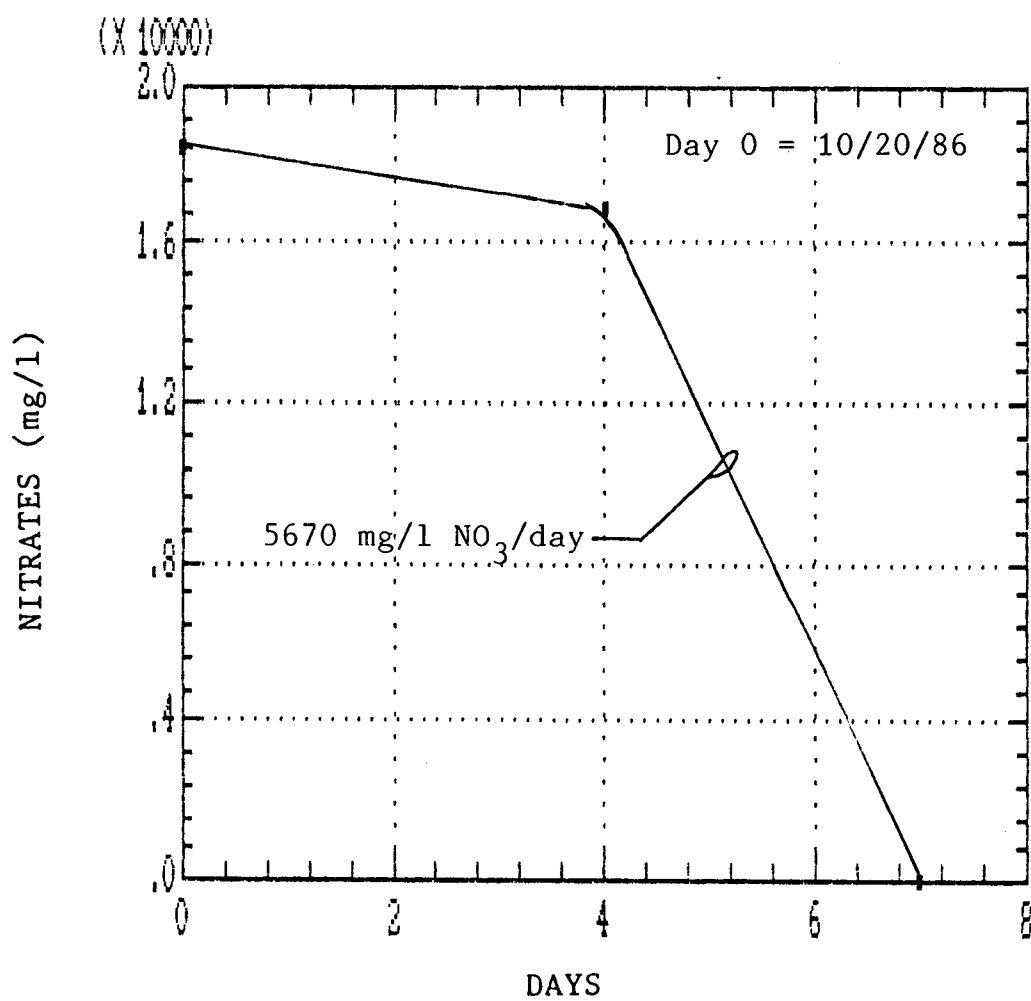


Figure 4.5. Tank F-4B - Plot of Nitrate vs. Day

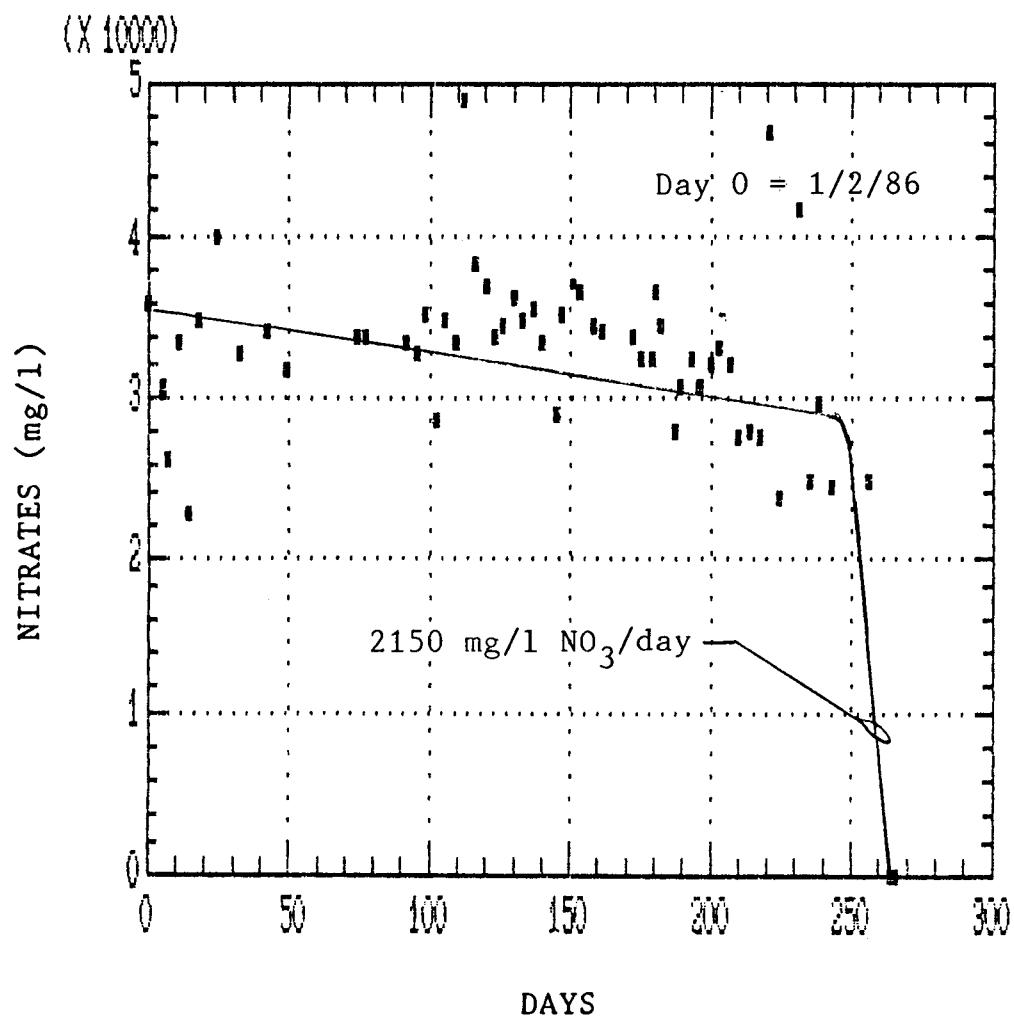


Figure 4.6. Tank F-5A - Plot of Nitrate vs. Day

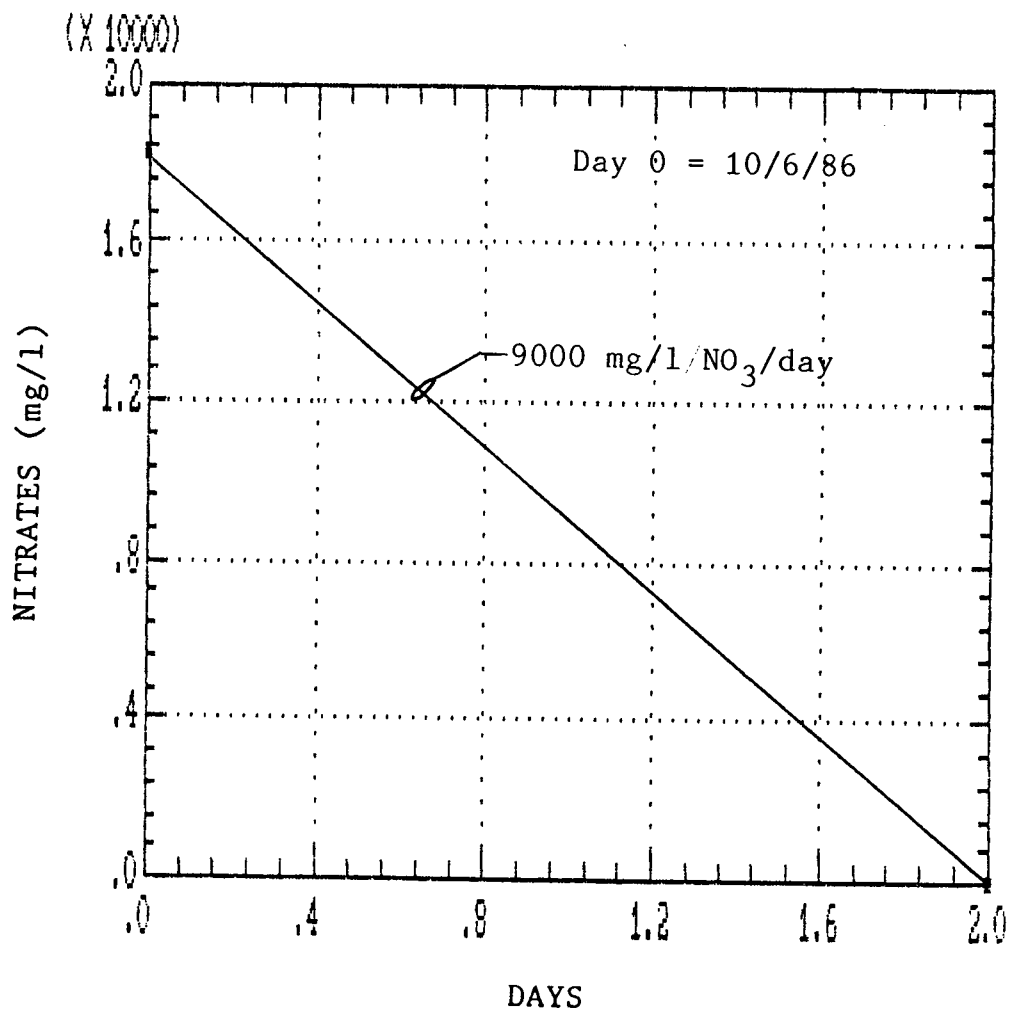


Figure 4.7. Tank F-5B - Plot of Nitrate vs. Day

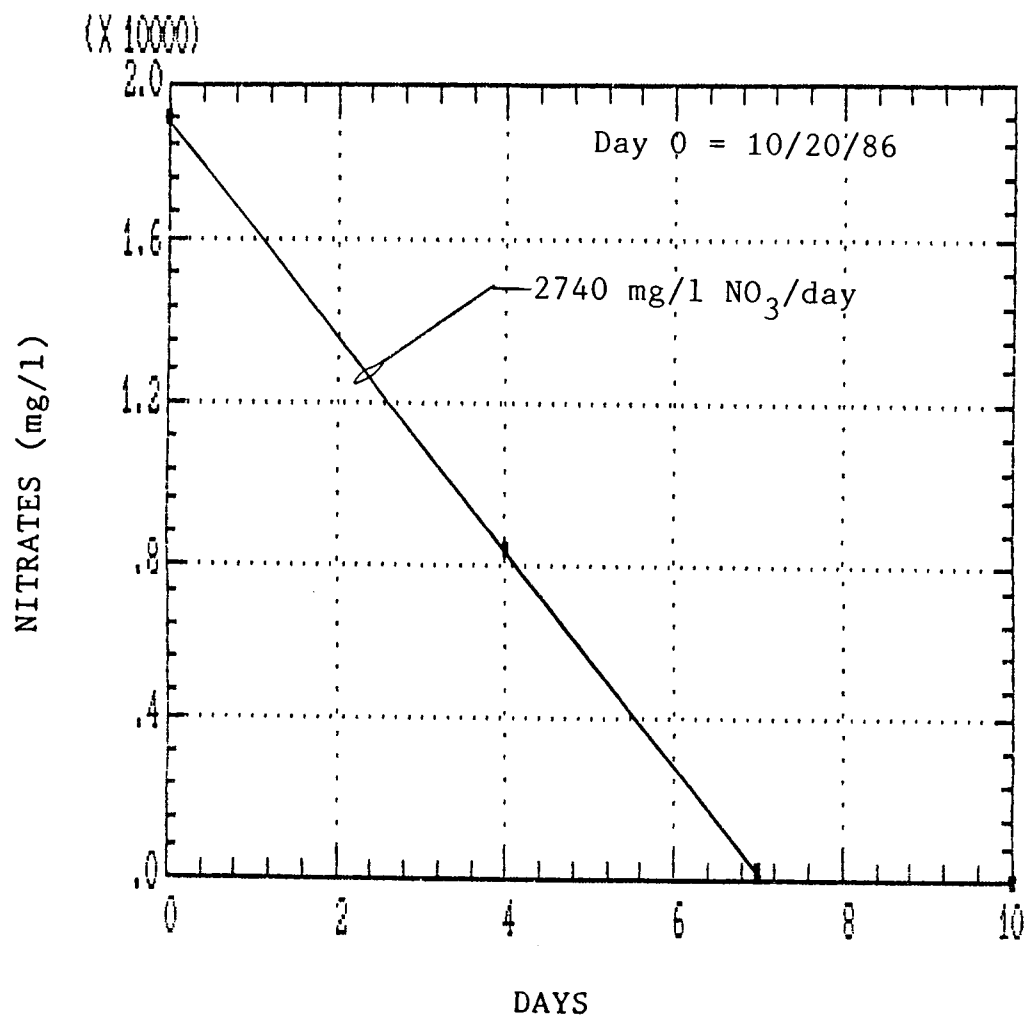


Figure 4.8. Tank F-5C - Plot of Nitrate vs. Day

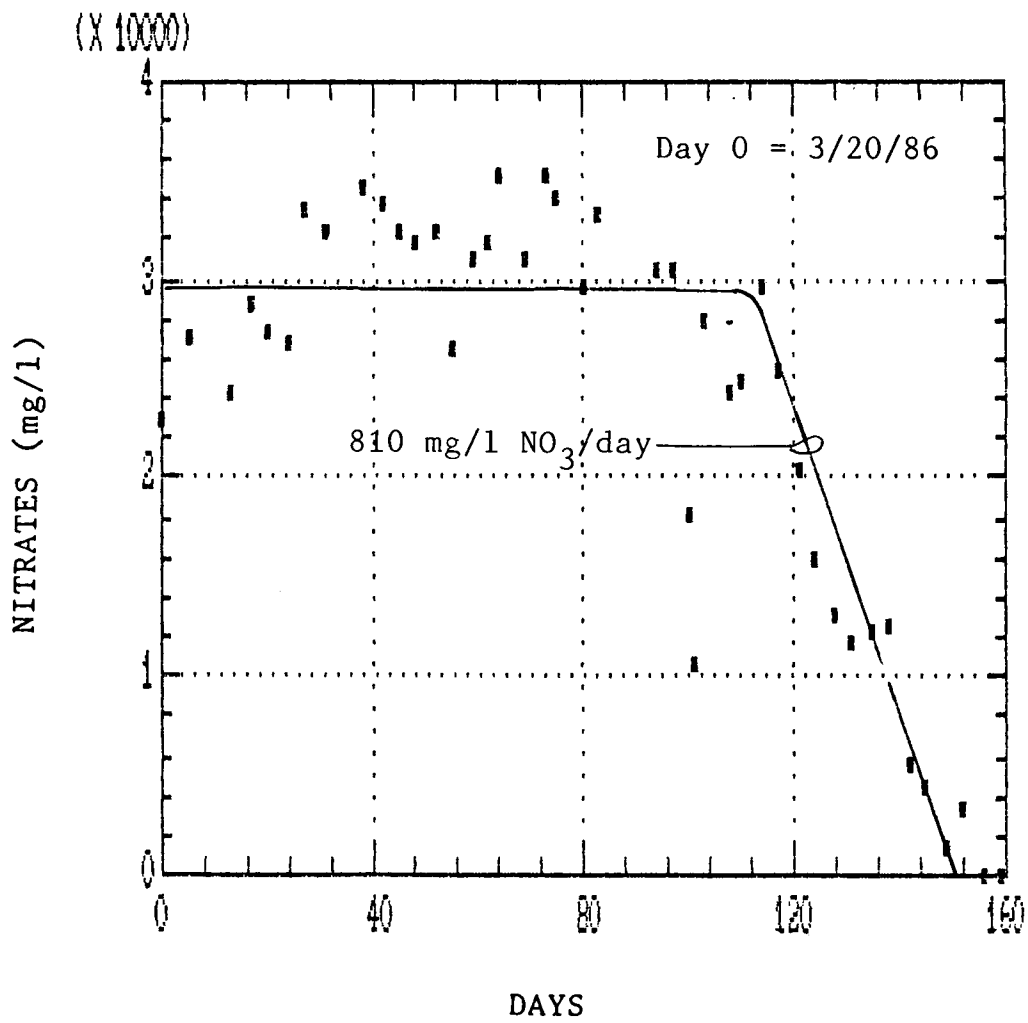


Figure 4.9. Tank F-6 - Plot of Nitrate vs. Day

problems of acclimating seed bacteria to the nitrate wastewater exist.

The pH of the reactor solutions are maintained between 6.9 to 9.0, with emphasis on maintaining the tank solution at the higher pH. The denitrification rate decreases dramatically outside of this range. The denitrification reaction causes the pH to decrease rapidly; therefore, hydrated lime is added regularly to increase the pH.

Phosphate is added periodically, primarily as triethyl phosphate, as a nutrient for biodenitrifying bacteria. Metallic nutrients are present in the wastewater.

Denitrification rates for Tanks F-1 through F-6 are shown in Figures 4.1 - 4.9. Appendix A contains analytical results for wastewater treated in Tanks F-1 through F-6.

Sludge Production

The sludge generation rate of WETF is estimated to be about 310,000 gal/yr at 20 wt% sludge or 666,000 lb/yr of solids (21). Sludge allowed to settle in the tanks after decanting supernatant has a solids content of 30% and can potentially be dewatered in an existing vacuum filter to a solids content of up to 40%. Sludge generated at WETF is a mixed waste; i.e, the sludge is a Resource Conservation and Recovery Act (RCRA) hazardous and radioactive waste. To date, there is no disposal facility in the United States that will accept a mixed waste. Therefore, the sludge will

be stored indefinitely in the 500,000 gallon tanks until an applicable disposal technology is deemed environmentally acceptable by the Department of Energy (DOE), United States Environmental Protection Agency (EPA), Tennessee Department of Health and Environment (TDHE), and Martin Marietta. Feasibility studies are being performed that consider such options as treating (e.g. fixation) the sludge so that it is no longer a RCRA hazardous waste. Such options will likely increase the volume of waste, and the waste would still be a low level radioactive waste requiring appropriate handling, storage, and disposal. Disposal of drummed low level radioactive waste at the Oak Ridge Reservation in 1987 was estimated to cost from \$50 - \$100/ft³, not including container, transportation, or packaging costs (29). Considering the amount of sludge generated and subsequent storage, treatment, and ultimate disposal options, WETF sludge represents a significant cost.

CHAPTER V

LABORATORY APPARATUS AND PROCEDURES

Laboratory Set-up

The laboratory set-up was designed to simulate full scale reactors at the WETF. Forty liter glass bottles with a geometry similar to the 500,000 gallon tanks were used as reactors. The reactors were equipped with top entering mixers to stir the reactor contents. Cloth tape was used to cover the outside of the glass bottles for safety protection and to shade the reactor solution. The reactors were located indoors and maintained at room temperature.

Except for an opening large enough for the shaft of the mixer, the mouth of the bottle was covered to minimize air entering the reactor. The mouth of the bottle had a three inch diameter opening and was large enough to periodically insert a pH probe, dissolved oxygen probe, or tubing for sampling. Samples were removed from the reactors by siphoning reactor solution with a bulb syringe through clear flexible plastic tubing. Samples were collected in 8 ounce plastic bottles that were refrigerated prior to analysis. Analytical equipment used in the laboratory were pH meters and a dissolved oxygen meter capable of measuring dissolved oxygen and temperature. The pH meters and dissolved oxygen meters were standardized prior to use. The remainder of analysis was performed by

technicians of the Y-12 Plant Laboratory, an EPA approved laboratory.

Laboratory Procedure

Procedures followed were similar to the operations performed at WETF. Wastewater that normally would be treated at WETF was composited to be characteristic of mixtures treated in the 500,000 gallon tanks. Wastewater was used from sources contributing the larger quantities to WETF. The sources were:

1. 9215 Third Mill rinsewater,
2. 9401-2 Plating Shop combined wastewaters,
3. 9212 caustic rinsewater, and
4. 9818 waste acids.

These wastewaters were composited such that mixtures contained from 1 to 5% nitrate and had a pH less than 2. Potable water and calcium nitrate were added as required to reach the desired concentrations.

The lab reactors were operated in a batch mode; no additional wastewater was added after the initial wastewater solutions were poured into the glass reactors. Hydrated lime was added into the reactors filled with wastewater until the pH of the solution was within a range of 6.9 to 9.0. The carbon sources, acetic acid, methanol, or sucrose, were then added into each respective reactor. To be consistent with the WETF mode of operation occurring at the time, carbon sources were initially added to allow

denitrification to reach completion based on the carbon utilization rate observed at WETF (1.1:1 to 1.3:1 carbon/nitrogen ratio). Hydrated lime was added to the acetic acid reactor to readjust the pH after the acetic acid was fed to the reactor. No pH adjustment was required due to the addition of methanol or sucrose. Biological seed from the 9818 bioreactor, denitrified or denitrifying West End tanks, and/or other respective lab reactors were used in this study. Phosphate, in the form of phosphoric acid, was added periodically as a microbial nutrient. Figure 5.1 represents the set-up and operation of the laboratory reactors.

The reactors were regularly monitored for:

1. pH,
2. temperature,
3. dissolved oxygen,
4. microbial population measured by growing bacteria on Easicult-TTC slides,
5. nitrate - ion chromatography analysis,
6. acetate, methanol, or sucrose - gas chromatography analysis,
7. total dissolved solids (TDS) - Standard Methods 209B (26),
8. total suspended solids (TSS) or mixed liquor suspended solids (MLSS) - Standard Methods 209C (26),
9. volatile suspended solids (VSS) or mixed liquor volatile suspended solids (MLVSS) - Standard Methods 209D (26),
10. chemical oxygen demand (COD) - Standard Methods 508 (26),
11. total organic carbon (TOC) - Standard Methods 505 (26),
12. phosphate - Ion chromatography, and
13. concentrations of metals - Inductively Coupled Plasma (ICP) analysis.

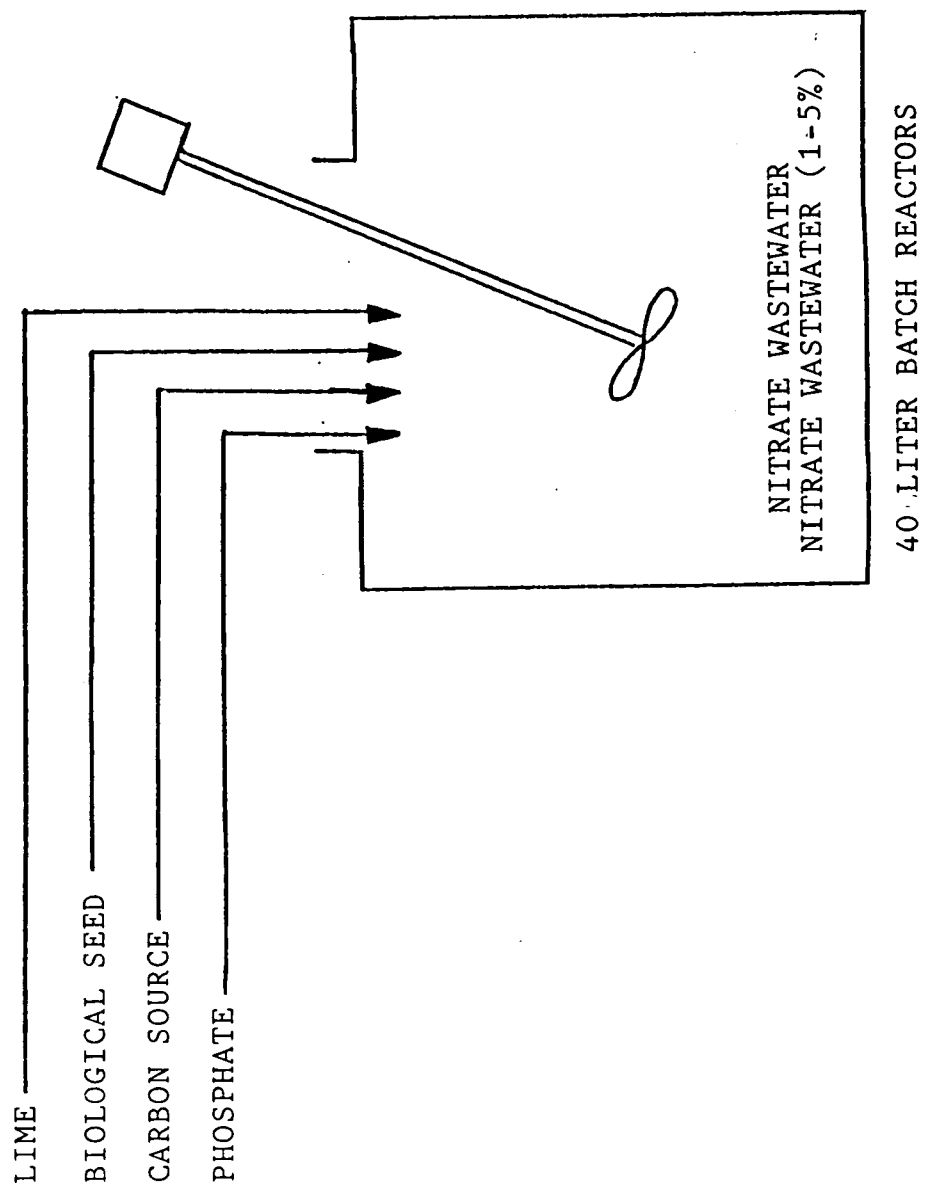


Figure 5.1. Operation of Laboratory Reactors

CHAPTER VI

DATA PRESENTATION AND OBSERVATIONS

Nine reactors operated during the course of this study are described in Table 6.1. During operation, the pH in all the reactors was adjusted by daily to weekly addition of 10 to 80 g of lime. Reactors that had significant bacterial growth or denitrification occurring required more frequent and larger additions of lime. Observations for each of the reactors are as follows.

Reactor 1 - The reactor was seeded with about 200 ml of sludge from WETF tanks and 9818 biodenitrification facility. Although there were signs of biological activity, acclimation did not occur such that significant nitrate removal occurred. Bacterial counts were high (greater than 10^7 microorganisms/ml) and the pH dropped during operation, indicating bacterial production of CO_2 . Data was collected for almost 130 days.

Reactor 2 - The reactor was seeded with about 200 ml of sludge from WETF tanks and 9818 biodenitrification facility. Bacterial acclimation to the wastewater did not occur, and little biological activity was observed. Bacterial counts were low (less than 10^5 microorganisms/ml) and the pH rarely dropped. Data was collected for almost 130 days.

Table 6.1. Summary Description of Reactors 1 - 9

Reactor ID No.	Carbon Source	Wastewater	Init. Nitrate Conc. (mg/l)
1	Acetic Acid	Composite of Y-12 wastewater	46,000
2	Methanol	Composite of Y-12 wastewater	44,000
3	Sucrose	Composite of Y-12 wastewater	45,000
4	Acetic Acid	10% Reactor 1 solution, 90% calcium nitrate solution	30,000
5	Methanol	10% Reactor 2 solution, 90% calcium nitrate solution	32,000
6	Sucrose	10% Reactor 3 solution, 90% calcium nitrate solution	28,000
7	Acetic Acid	10% composite of Y-12 waste- water, 10% WETF Sludge, and 80% calcium nitrate solution.	10,000
8A	Sucrose	10% WETF Sludge 90% calcium nitrate solution	3,000
8B	Sucrose	Calcium nitrate added to Reactor 8A.	23,000
9A	Sucrose	10% - Reactor 6 solution, 90% calcium nitrate solution	7,000
9B	Sucrose	Calcium nitrate added to Reactor 9A	22,000

Reactor 3 - The reactor was seeded with about 200 ml of sludge from WETF tanks and 9818 biodenitrification facility. Bacterial acclimation occurred in about 90 days. The denitrification rate was not observed.

Reactor 4 - The reactor was seeded with about 200 ml of sludge from WETF tanks and 9818 biodenitrification facility. Although there were signs of biological activity, acclimation did not occur such that significant nitrate removal occurred. Bacterial counts were high (greater than 10^7 microorganisms/ml) and the pH dropped during operation, indicating bacterial production of CO_2 . Data was collected for about 50 days.

Reactor 5 - The reactor was seeded with about 200 ml of sludge from WETF tanks and 9818 biodenitrification facility. Bacterial acclimation to the wastewater did not occur, and little biological activity was observed. Bacterial counts were low (less than 10^5 microorganisms/ml) and the pH rarely dropped. Data was collected for about 50 days.

Reactor 6 - The reactor was seeded with about 200 ml of sludge from WETF tanks and 9818 biodenitrification facility. Bacterial acclimation occurred almost immediately. The reactor denitrified after 50 days.

Reactor 7 - The reactor was seeded with about 4 liters of sludge from WETF tanks. Bacterial acclimation occurred

almost immediately. The reactor denitrified in about 14 days.

Reactor 8 - The reactor was initially seeded with about 4 liters of sludge from WETF tanks. The reactor was operated in two phases. During the first phase (8A) the reactor acclimated immediately and denitrified in two days. In the second phase (8A), nitrate and sucrose were added again to the reactor, and the reactor denitrified in about 24 days.

Reactor 9 - The reactor was initially seeded with about 4 liters of sludge from Reactor 6. The reactor was operated in two phases. During the first phase (9A), the reactor acclimated immediately and denitrified in four days. In the second phase (9B), nitrate and sucrose were added again to the reactor, and the reactor denitrified in about 65 days.

Denitrification rates for Reactors 1 - 9 are shown in Figures 6.1 - 6.11. Analytical results for Reactors 1 - 9 are in Appendices B and C.

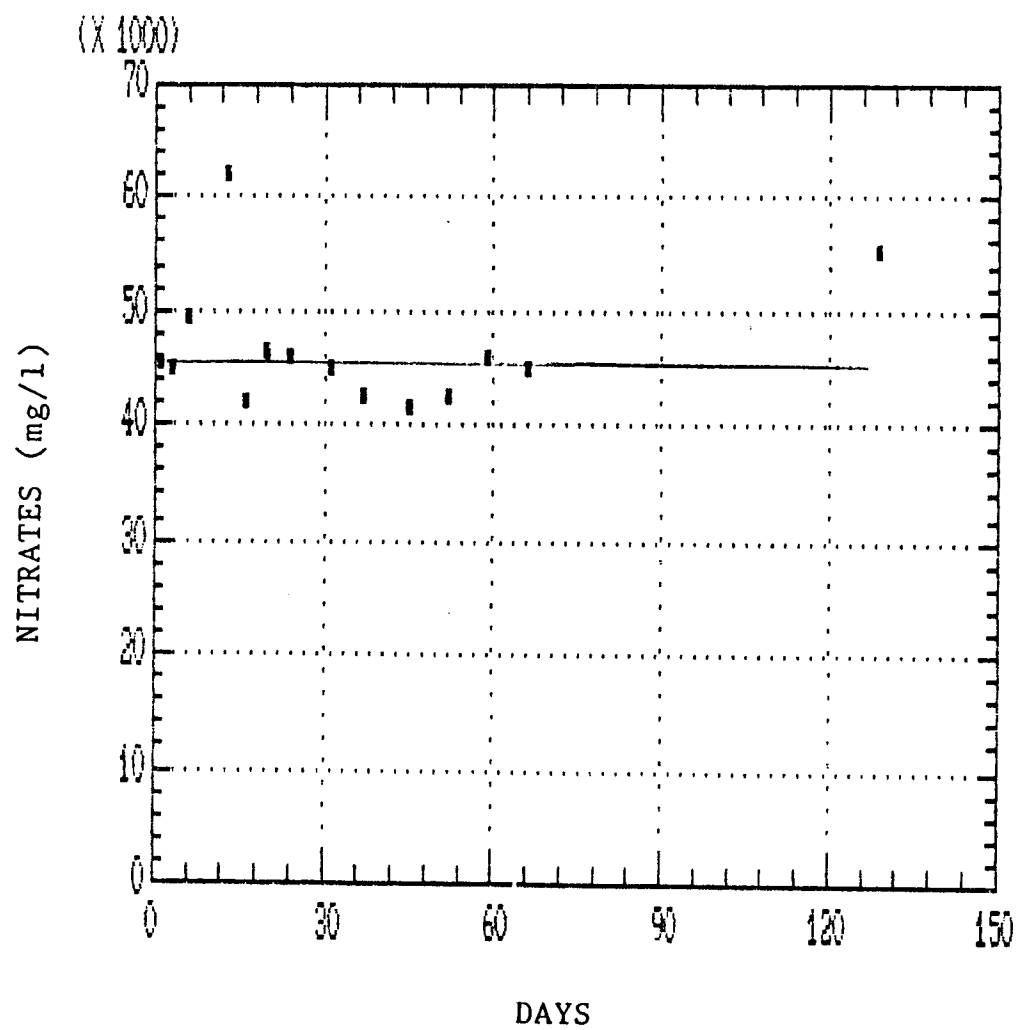


Figure 6.1. Reactor 1 - Plot of Nitrate vs. Day

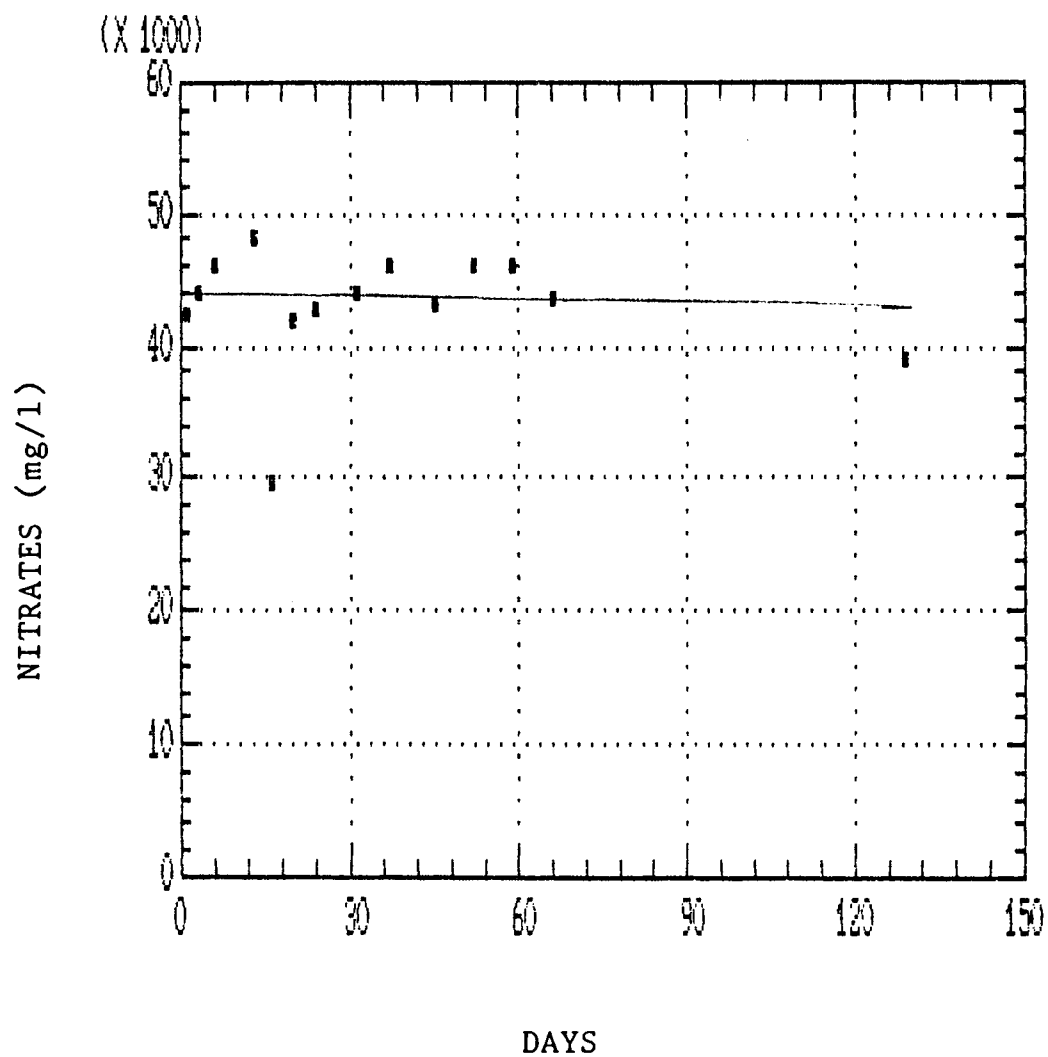
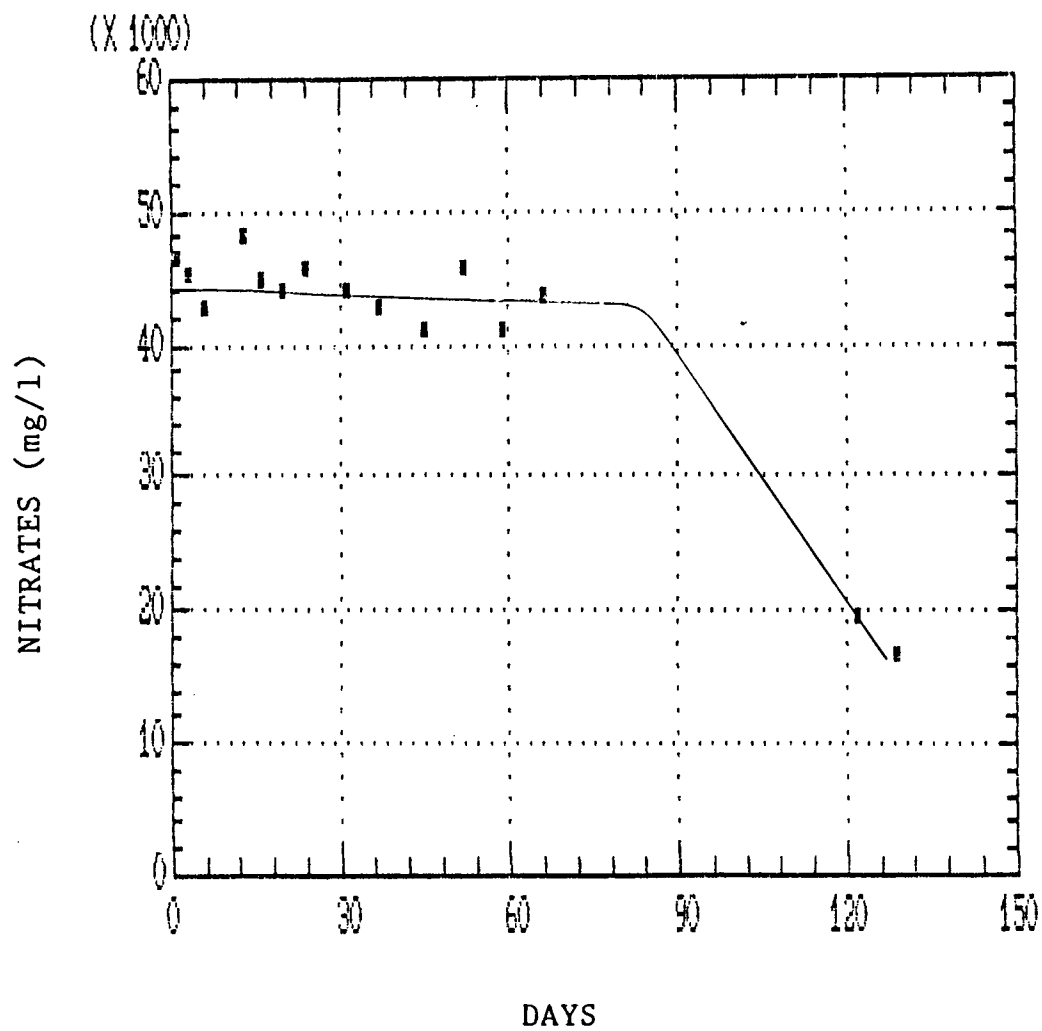


Figure 6.2. Reactor 2 - Plot of Nitrate vs. Day



Reactor 6.3. Reactor 3 - Plot of Nitrate vs. Day

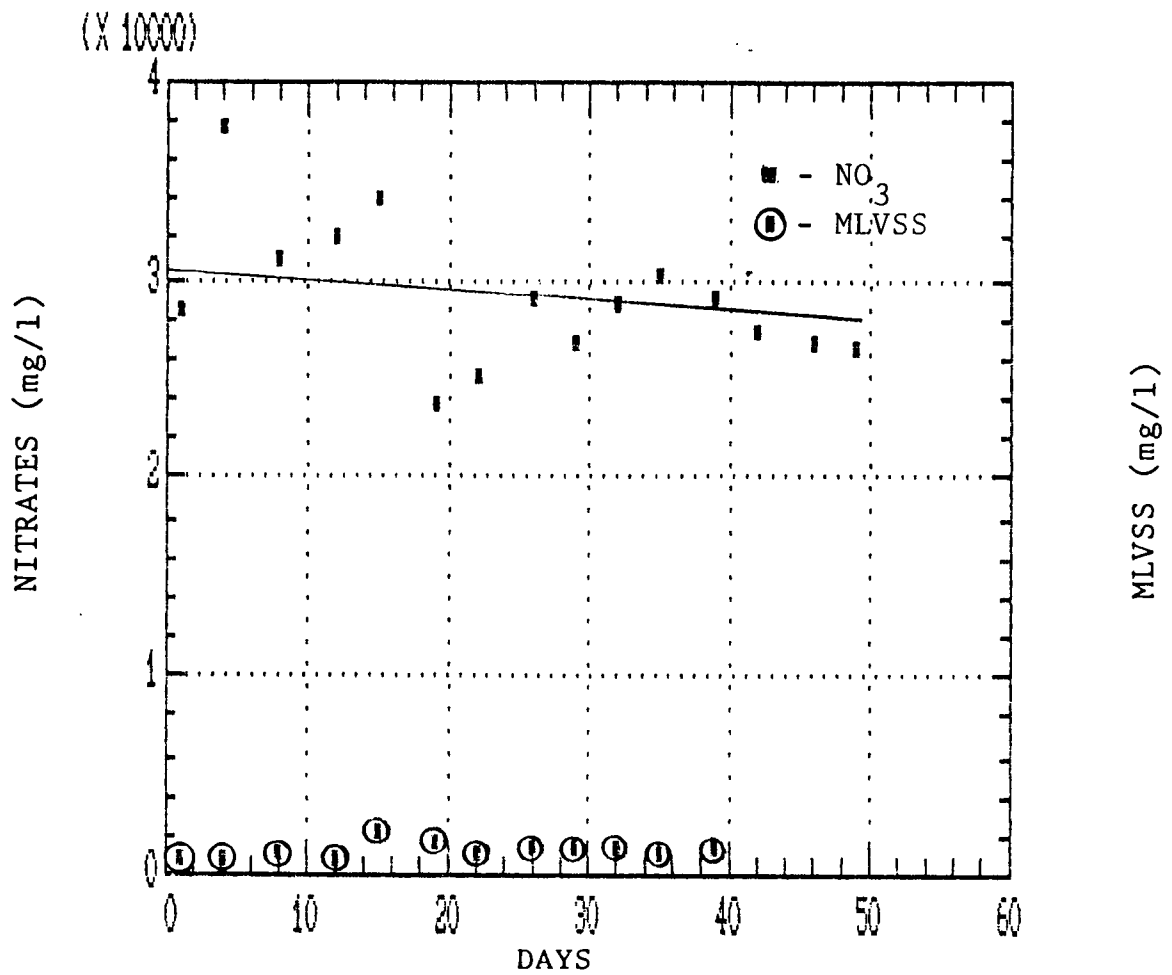


Figure 6.4. Reactor 4 - Plot of Nitrate and MLVSS vs. Day

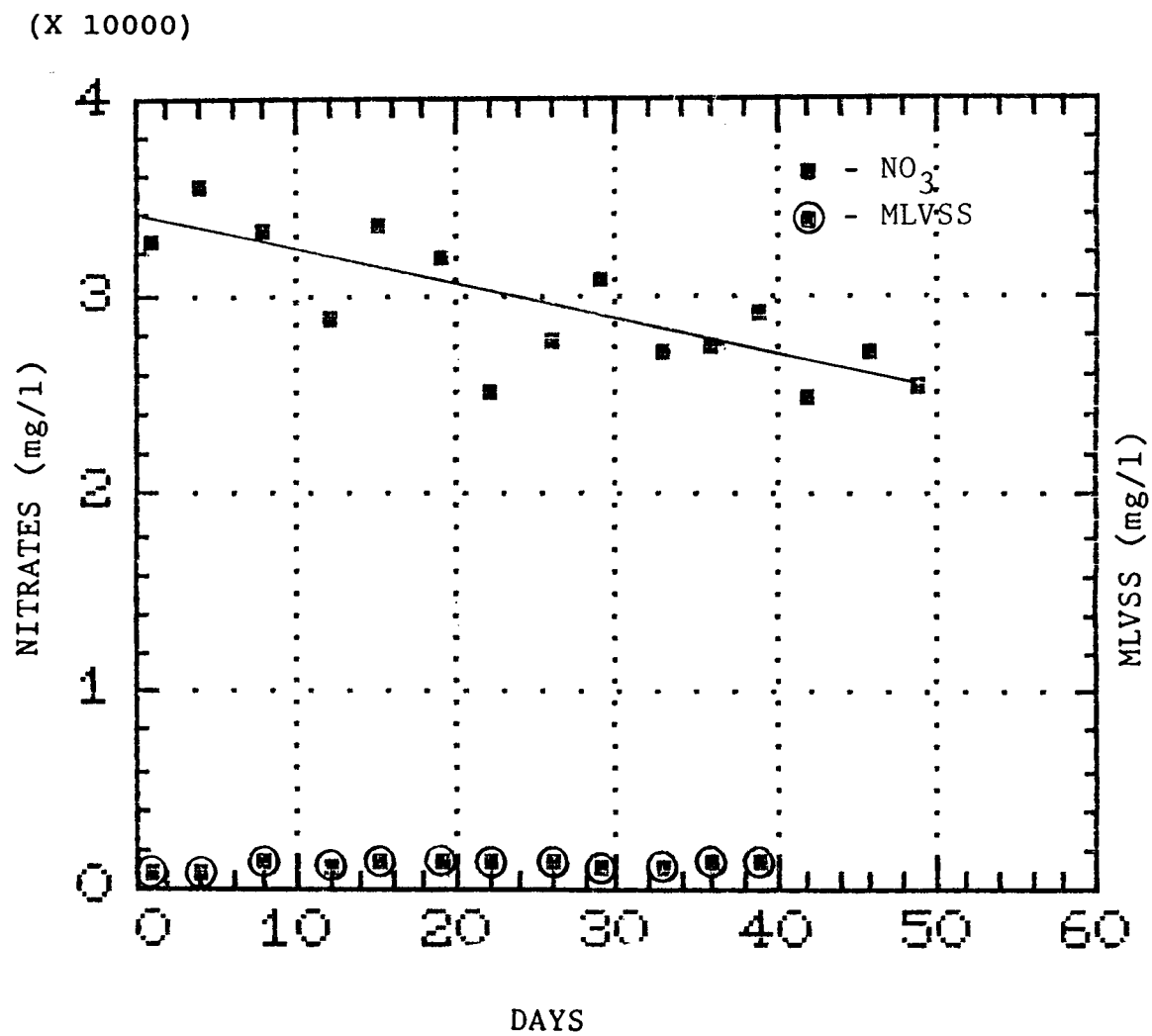


Figure 6.5. Reactor 5 - Plot of Nitrate and MLVSS vs. Day

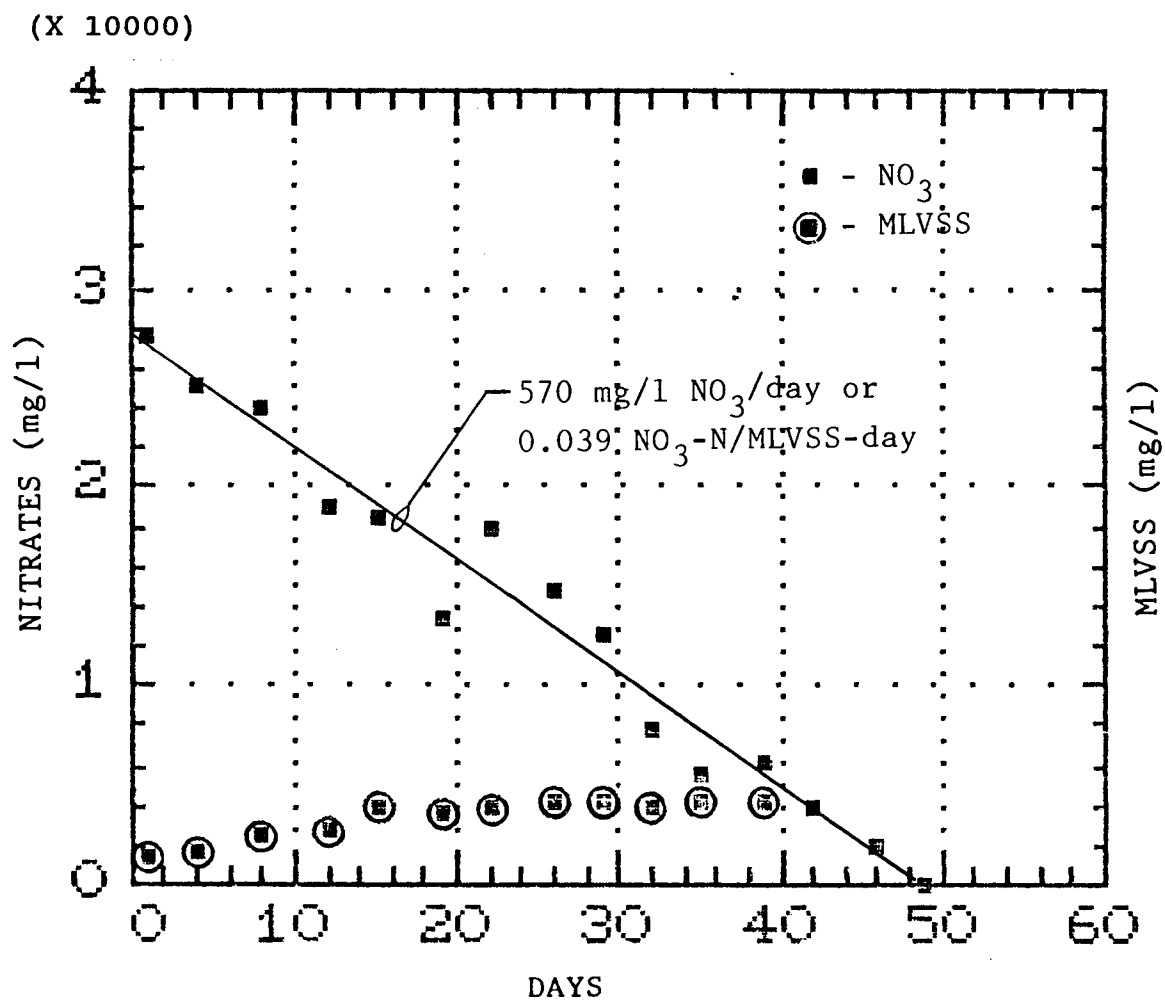


Figure 6.6. Reactor 6 - Plot of Nitrate and MLVSS vs. Day

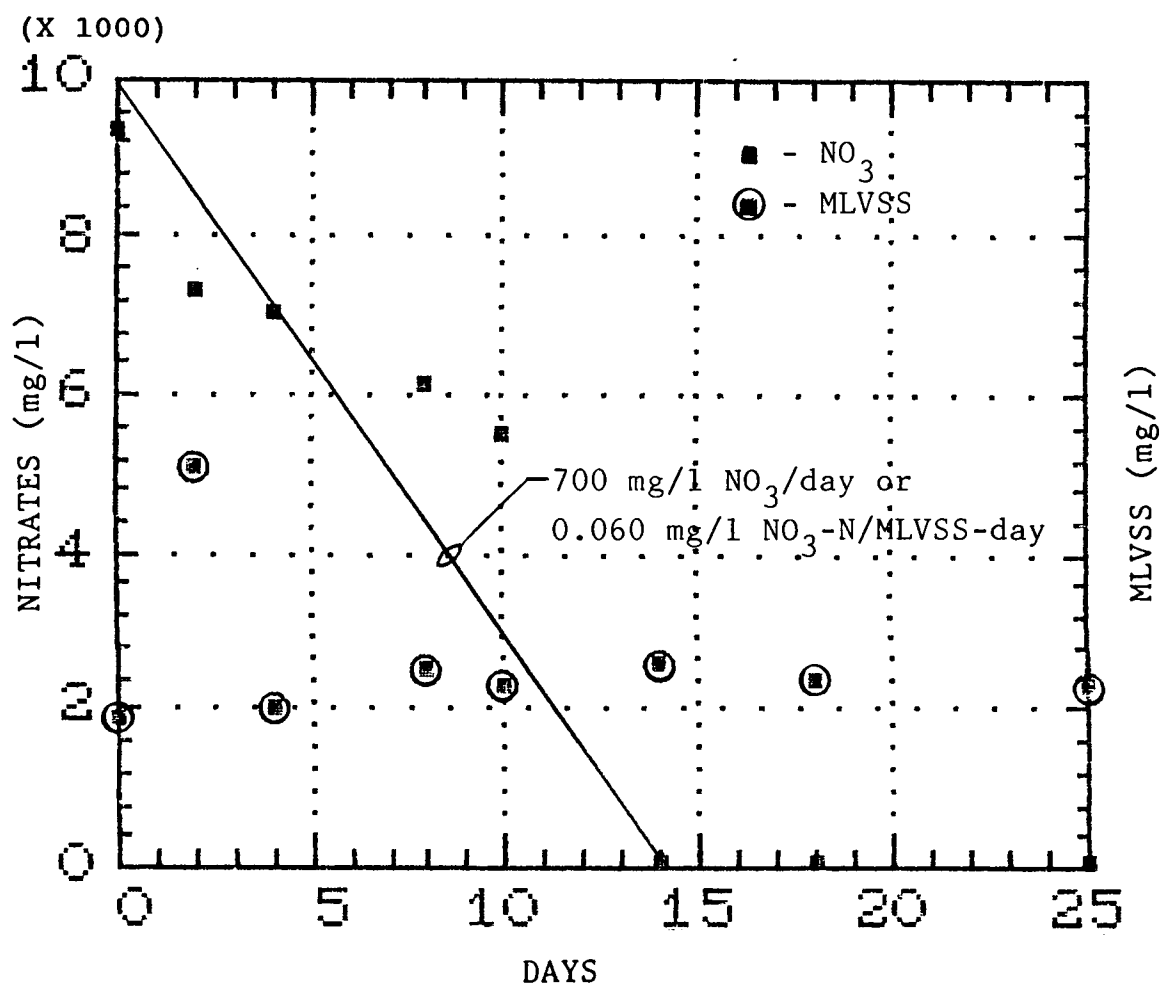


Figure 6.7. Reactor 7 - Plot of Nitrate and MLVSS vs. Day

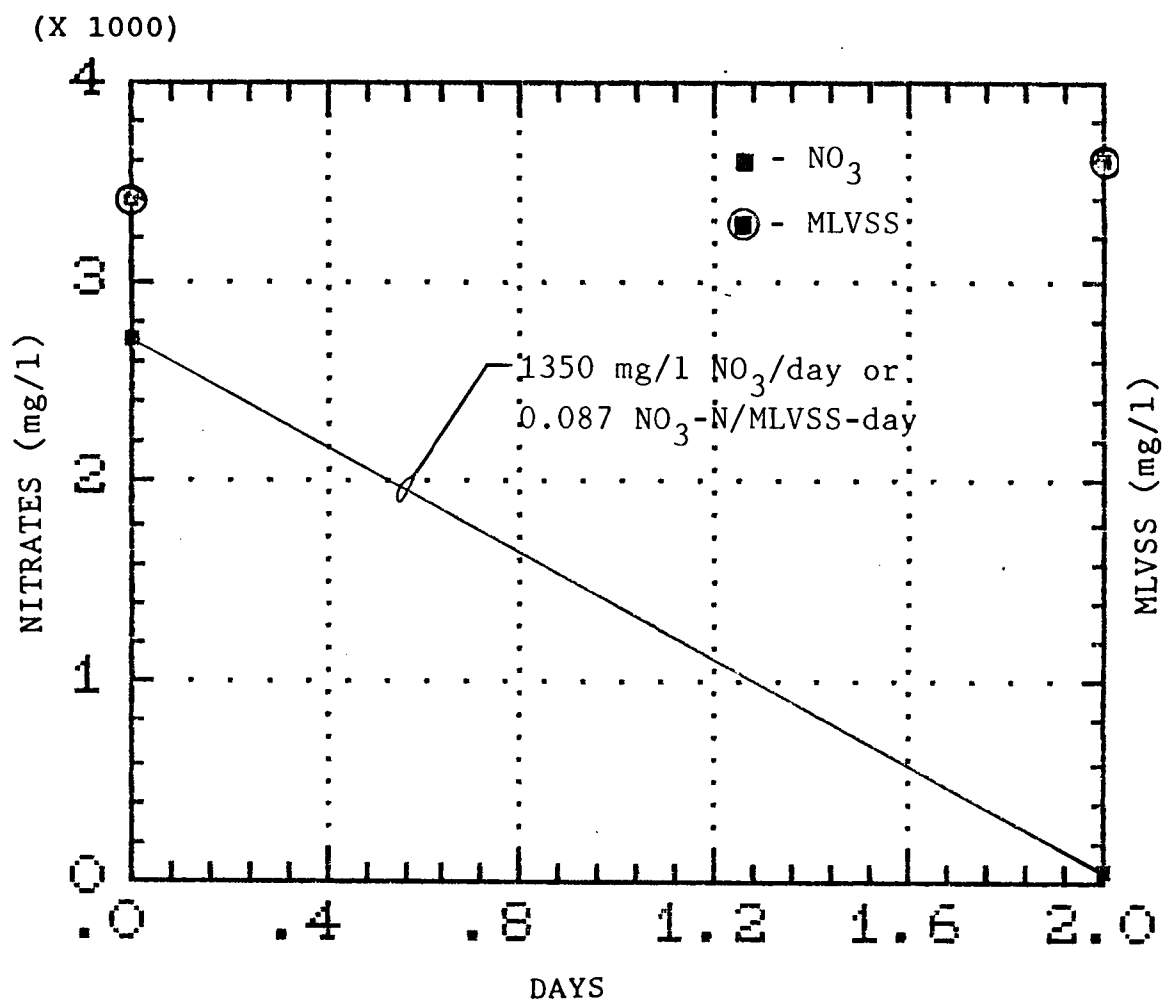


Figure 6.8. Reactor 8A - Plot of Nitrate and MLVSS vs. Day

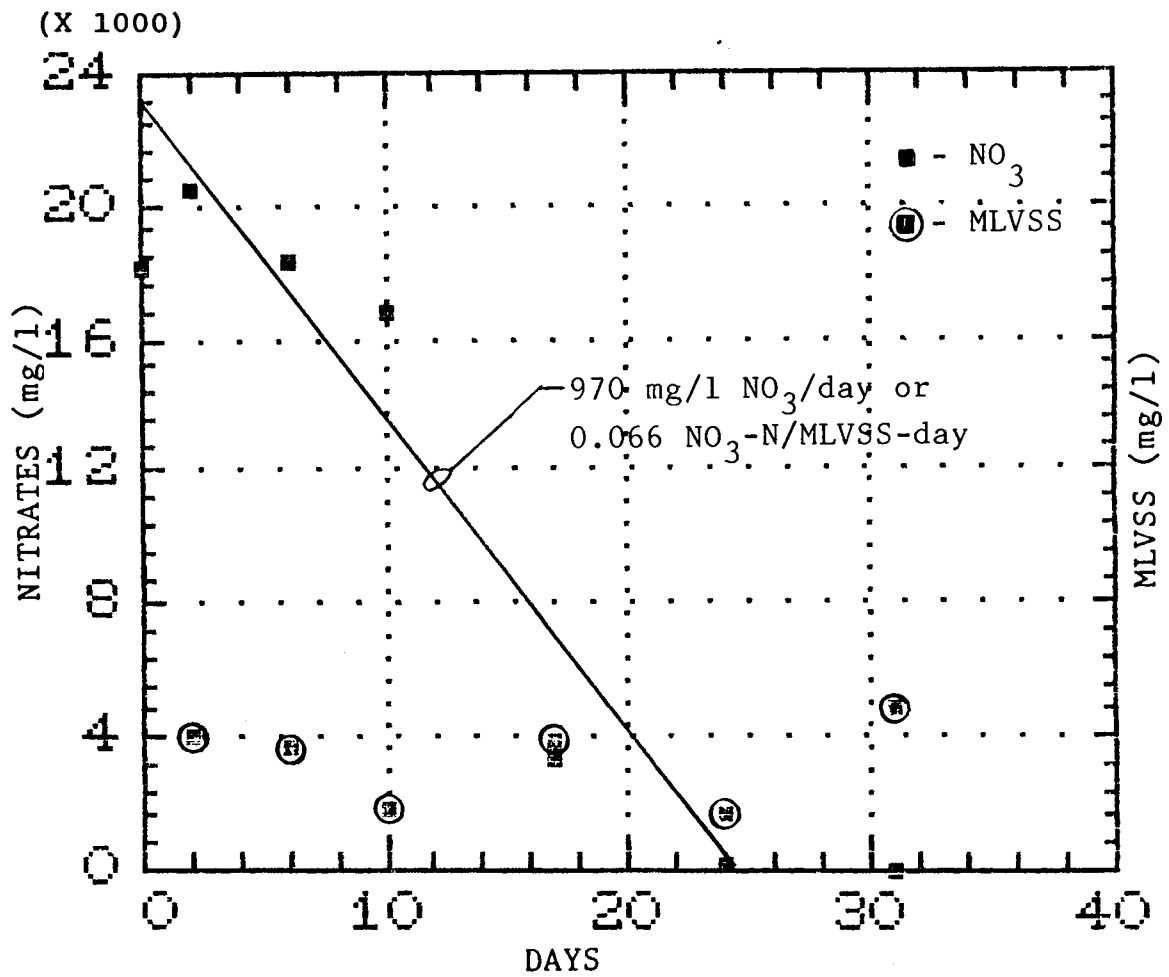


Figure 6.9. Reactor 8B - Plot of Nitrate and MLVSS vs. Day

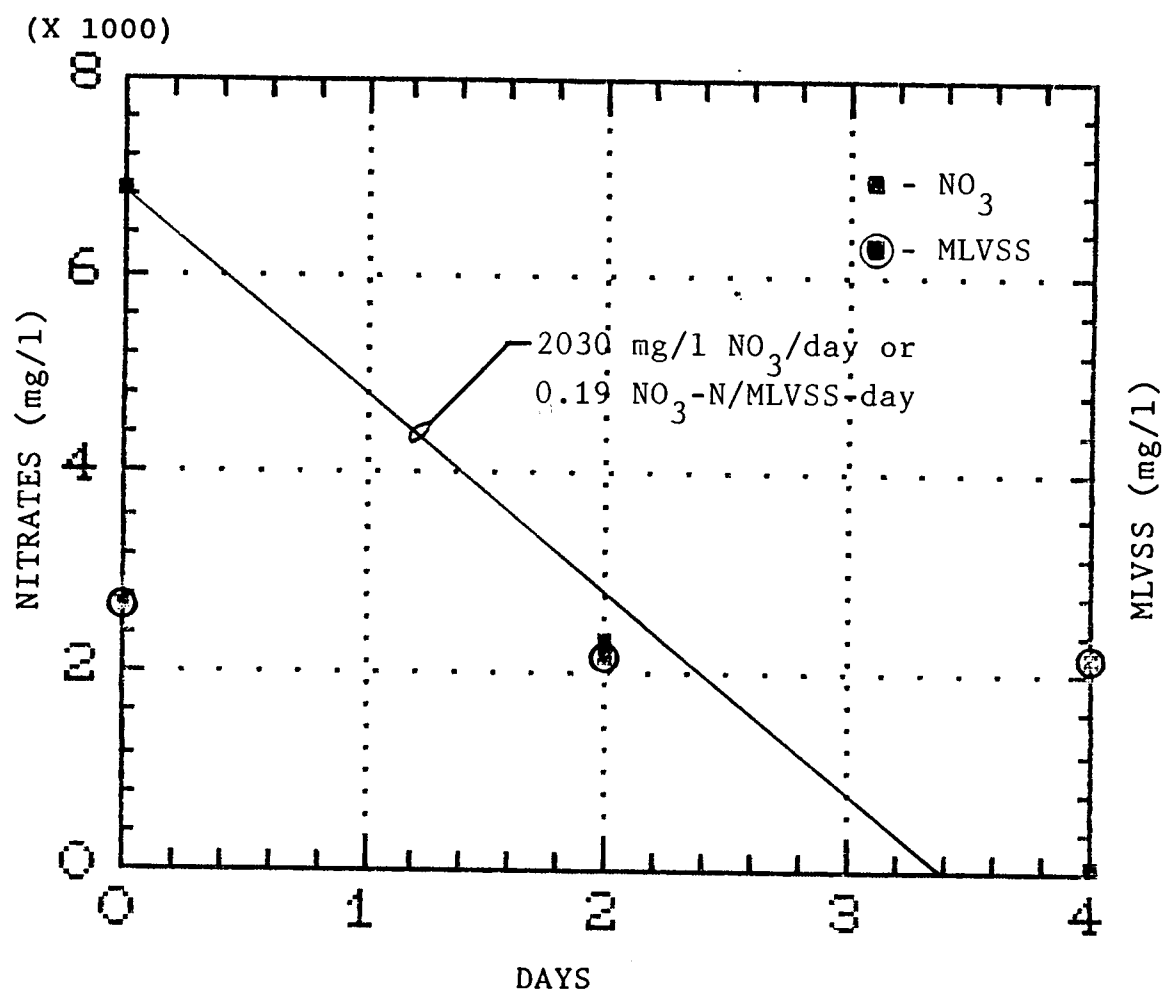


Figure 6.10. Reactor 9A - Plot of Nitrate and MLVSS vs. Day

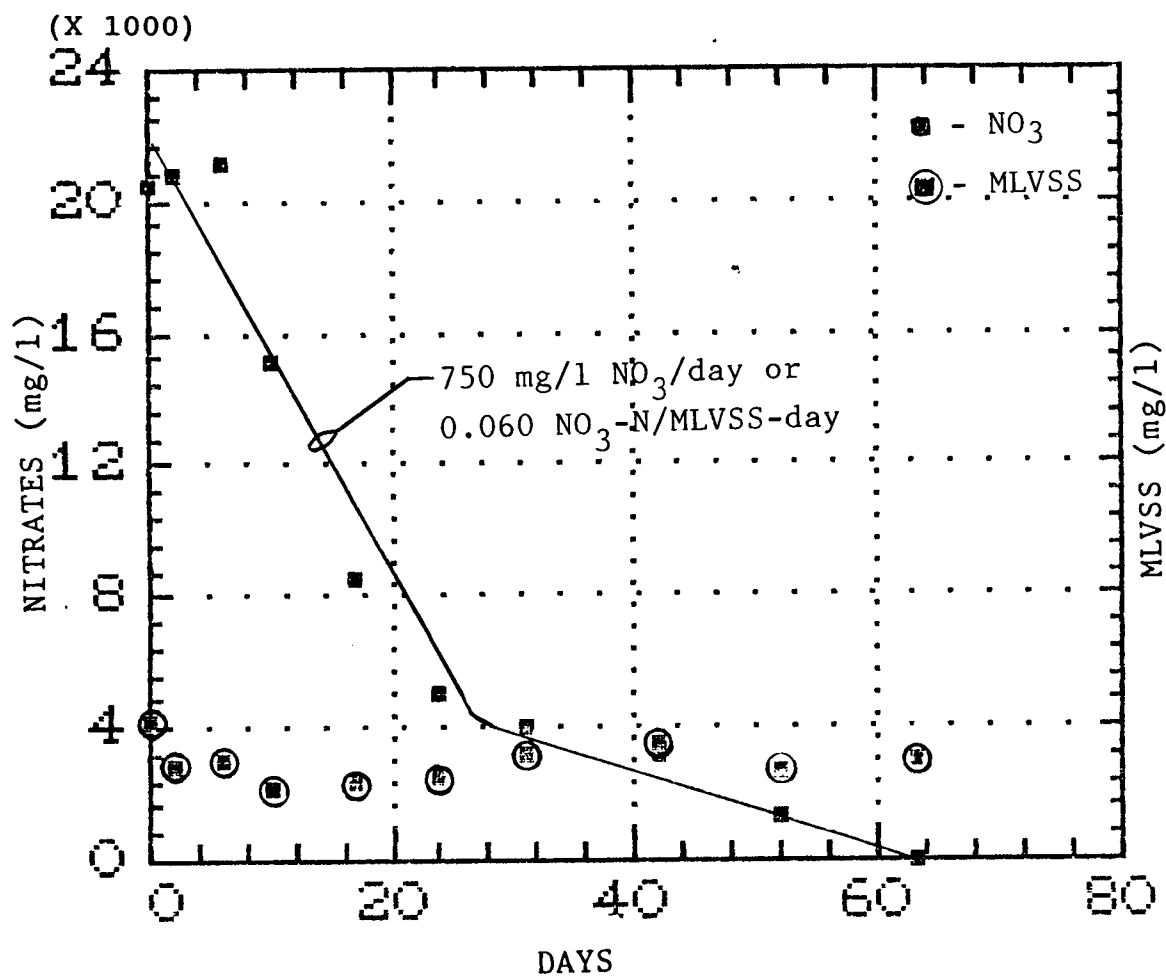


Figure 6.11. Reactor 9B - Plot of Nitrate and MLVSS vs. Day

CHAPTER VII

DISCUSSION

Acclimation

Acclimation of denitrifying organisms to WETF wastewater and laboratory reactor solutions (i.e., such that significant denitrification rates occurred) has proven to be somewhat unpredictable. Acclimation did not occur readily in WETF Tanks F-2, F-3, F-5A, and F-6A and Laboratory Reactors 1-5. Difficulties in acclimating bacteria did not occur in denitrification studies found in literature for wastewater with low concentrations of nitrates. Table 7.1 compares WETF tank and lab reactor acclimation times with those observed in literature.

There was a correlation between the carbon source and the amount of time required for the laboratory reactors to acclimate. Bacterial acclimation occurred more readily with reactors fed with sucrose than in the methanol and acetate fed reactors (See Table 7.2) despite the fact the reactors were seeded with acetate acclimated bacteria. Reactors 1 - 6 had potentially inhibitory concentrations of nitrate (30,000 - 45,000 mg/l of NO_3) and heavy metals; only the sucrose reactors acclimated to the point where significant denitrification occurred. Reactor 8 initially contained approximately 10% of acetate acclimated

Table 7.1. Comparison of Acclimation Times with Literature Values

Batch Denitrification Study	Initial Concentrations	Acclimation Time
Murphy and Dawson (6)	500 mg/l NO ₃ -N	5 hrs - 8 days
Stensel, Loehr, and Lawrence (8)	8 mg/l NO ₃ -N	Immediate
WETF Tanks		
Tank F-1 (Day 0 = 11/19/85)	18,000 mg/l NO ₃ (4000 mg/l NO ₃ -N)	28 days
Tank F-2 (Day 0 = 12/31/84)	24,000 mg/l NO ₃ (5400 mg/l NO ₃ -N)	110 days
Tank F-3 (Day 0 = 2/25/85)	24,000 mg/l NO ₃ (5400 mg/l NO ₃ -N)	220 days
Tank F-4A (Day 0 = 9/23/86)	16,500 mg/l NO ₃ (3700 mg/l NO ₃ -N)	0 days
Tank F-4B (Day 0 = 10/20/86)	18,500 mg/l NO ₃ (4100 mg/l NO ₃ -N)	4 days
Tank F-5A (Day 0 = 1/2/86)	36,000 mg/l NO ₃ (8100 mg/l NO ₃ -N)	250 days
Tank F-5B (Day 0 = 10/6/86)	18,000 mg/l NO ₃ (4000 mg/l NO ₃ -N)	0 days
Tank F-5C (Day 0 = 10/20/86)	19,000 mg/l NO ₃ (4200 mg/l NO ₃ -N)	0 days
Tank F-6 (Day 0 = 3/30/86)	30,000 mg/l NO ₃ (6800 mg/l NO ₃ -N)	110 days
Laboratory Reactors		
Reactor 1	46,000 mg/l NO ₃ (10,400 mg/l NO ₃ -N)	130+ days
Reactor 2	44,000 mg/l NO ₃ (9900 mg/l NO ₃ -N)	130+ days
Reactor 3	45,000 mg/l NO ₃ (10,100 mg/l NO ₃ -N)	90 days

Table 7.1. (Continued)

Batch Denitrification Study	Initial Concentrations	Acclimation Time
Reactor 4	30,000 mg/l NO_3 (6800 mg/l $\text{NO}_3\text{-N}$)	50+ days
Reactor 5	32,000 mg/l NO_3 (7000 mg/l $\text{NO}_3\text{-N}$)	50+ days
Reactor 6	28,000 mg/l NO_3 (6500 mg/l $\text{NO}_3\text{-N}$)	0 days
Reactor 7	10,000 mg/l NO_3 (2300 mg/l $\text{NO}_3\text{-N}$)	0 days
Reactor 8A	3000 mg/l NO_3 (680 mg/l $\text{NO}_3\text{-N}$)	0 days
Reactor 8B	23,000 mg/l NO_3 (5200 mg/l $\text{NO}_3\text{-N}$)	0 days
Reactor 9A	7000 mg/l NO_3 (1600 mg/l $\text{NO}_3\text{-N}$)	0 days
Reactor 9B	22,000 mg/l NO_3 (5000 mg/l $\text{NO}_3\text{-N}$)	0 days

Table 7.2. Comparison of Acclimation Times for Laboratory Reactors

Reactor Type	Percent of Acclimated Reactors	Range of Acclimation Times
Acetate fed (Reactors 1, 4, and 7)	33%	0 - 130+ days
Methanol fed (Reactors 2 and 5)	0%	50+ - 130+ days
Sucrose fed (Reactors 3, 6, 8A, 8B, 9A, and 9B)	100%	0 - 90 days

sludge, immediately acclimated, and began denitrifying when fed with sucrose.

None of the methanol fed reactors acclimated such that significant denitrification or bacterial growth occurred. The lack of biological activity confirms studies by Bringmann and Kuhn, 1976, 1980 (18, 24) and Chou, Speece, Siddiqi, and McKeon, 1978 (17) that high concentrations of methanol can inhibit biological activity. The lack of biological activity also agreed with observations by Clark, Francis, Franke, and Strohecker, 1975 (19) that acetate acclimated bacteria are in a "state of shock" when fed methanol. Clark et al. (19) reported no inhibitory effects when feeding high concentrations of methanol; however, the methanol was fed into a continuous flow reactor which would dilute the methanol to lower concentrations. If methanol were to be considered for feeding a batch reactor, the methanol should be bled in at a rate that would minimize methanol concentrations in the reactor.

The amount of acclimated wastewater or sludge added to or in a tank may have affected the acclimation time. Tanks 4A, 4B, 5B, and 5C and Reactors 4, 7, 8A, 8B, 9A, and 9B initially contained amounts of wastewater or sludge greater than 10%; acclimation periods for these tanks were significantly less than for the other tanks or reactors which were seeded with lesser amounts of sludge (<1%).

The following is a summary of possible reasons that

solely or in combination may have caused the excessive acclimation times observed above.

1. The concentrations of heavy metals in the reactors (See Appendix C) may be inhibiting the bacteria.

2. Low operating pH (i.e., pH of 6.8 to 8.5 instead of operating at a higher pH of 8.5 to 9.0) may be causing higher concentrations of metals to be in solution and affect acclimation of bacteria.

3. High dissolved oxygen concentrations (See Appendix A and B) may be causing the facultative bacteria to utilize oxygen as the electron acceptor instead of nitrate.

4. Data presented in Figures 4.1 - 4.9 (pp. 20 - 28) indicate that part of the acclimation time for WETF tanks occurred during the winter months, which may have slowed the growth of bacteria.

5. High nitrate concentrations as compared in Table 7.1 could be inhibiting acclimation.

6. The stressed environment due to conditions described above may be affecting the dominance of denitrifying bacteria relative to other facultative bacteria or anaerobes. Thus, acclimation may not occur until the percentage of denitrifying bacteria increases relative to other bacteria in the reactor.

7. The carbon source may be affecting the acclimation time (See Table 7.2). Studies by Blasczyk, Mycielski, Jaworowska, and Brzostek, 1980 (15) indicated that the use

of different carbon sources affected the selection of bacteria. Thus, the implications are that carbon sources could affect the dominance of denitrifying bacteria and associated acclimation time.

Denitrification Order

Figures 4.1 - 4.9 (pp. 20 - 28) and 6.1 - 6.11 (pp. 39 - 49) were plots of nitrate versus time; in general, a gradual decrease in NO_3 concentrations during the acclimation period was followed by a linear removal of nitrates with respect to time for laboratory reactors and WETF tanks. The linear removal of nitrate is indicative of a zero order reaction with respect nitrate concentrations. Such a pattern is consistent with observations made by Murphy and Dawson, 1972 (6) and Stensel, Loehr, and Lawrence, 1973 (8) at much lower nitrate concentrations. Reactor 9 (sucrose-fed) had a lower denitrification rate to occur at lower nitrate concentrations; however, the pH was not controlled or adjusted as often at the lower concentrations and likely inhibited the denitrification rate.

One of the implications of zero order denitrification is that despite excess amounts of carbon and nutrients, the active denitrifying bacterial population remains constant during the treatment phase. Log growth of bacterial populations generally has been observed in studies of biological processes supplied with excess carbon and

nutrients. Increasing MLVSS results with respect to time as shown in Figures 6.6 and 6.7 (pp. 44 and 45) indicate that bacterial growth was occurring but not necessarily in a log growth mode. It appears biological growth was dominated by species other than denitrifying bacteria.

Denitrification Rates

The sucrose laboratory reactor denitrification rate was about 1/3 of denitrification rates for the acetate fed WETF tanks; however, comparison of the denitrification rates for the sucrose fed laboratory reactors with that of acetate-fed laboratory reactors indicate that the rates were similar (See Table 7.3). A distinction in denitrification rates when comparing carbon sources may be due to the difference in the selection of denitrifying bacteria as demonstrated by Blasczyk, Mycielski, Jaworowska, and Brzostek, 1980 (15) at lower nitrate nitrogen concentrations (1000 mg/l $\text{NO}_3\text{-N}$). In their studies, denitrification was more efficient in media with ethanol and acetic acid as compared to methanol and glucose.

Maximum reaction rates observed in Tanks 1-6 approached peak rates of 10,000 mg/l/day recorded by Clark, Francis, Franke, and Strohecker, 1975 (19).

The range of denitrification rates for the laboratory reactors are similar to results from studies performed with lower concentrations of nitrates and similar carbon

Table 7.3 Denitrification Rates for WETF Tanks and Lab Reactors

<u>Tanks/ Reactors</u>	<u>Mean Denitrifi- cation Rates</u>	<u>Range of Denitrif. Rates</u>
ACETATE-FED REACTORS		
F-1 - F-6	3730 mg/l NO ₃ /day	810 - 9000 mg/l NO ₃ /day
Reactor 7	700 mg/l NO ₃ /day .060 NO ₃ -N/MLVSS/day	700 mg/l NO ₃ /day .060 NO ₃ -N/MLVSS-day
SUCROSE-FED REACTORS		
Reactor 6, 8A, 8B, 9A, and 9B	1130 mg/l NO ₃ /day .088 NO ₃ -N/MLVSS/day	570 - 2030 mg/l NO ₃ /day .039 - 0.19 NO ₃ -N /MLVSS-day

sources; these values are compared in Table 7.4. Dawson and Murphy (6) provided data that aided in explaining the wide range of reaction rates reported. In their studies, pure cultures of denitrifying bacteria indicated removal rates 10 to 50 times those previously observed in anaerobic activated sludge. These differences resulted from the varying fraction of denitrifying bacteria in sludges and the variable growth rates of the bacteria.

Sludge Production

In general, a gradual increase in the MLVSS was observed in the denitrifying reactors until the the MLVSS concentration reached about 3000 - 4000 mg/l; however, there was not a corresponding increase in the denitrification rate. It appears that a significant portion of the biomass was not actively removing nitrate, and MLVSS was not a measure of the denitrifying capacity of the biomass. A method to monitor denitrifying organisms and control the physical parameters known to affect the activity of the denitrifying subpopulation is needed to stabilize the reliability of the reactor operation.

The TSS concentrations increased during operation of each reactor due to the production of CO_2 and the addition of Ca(OH)_2 resulting in the formation of CaCO_3 . Despite agitation by the mixer, settling of the solids was observed such that the TSS concentrations reported are not

Table 7.4. Comparison of Denitrification Rates

NO ₃ -N (mg/l)	Carbon Source	Wastewater Treated	Temp. °C	NO ₃ -N Rem./ MLVSS-Day	Ref.
LABORATORY REACTORS					
2200	acetate	industrial wastewater	21-26	0.06	
680 - 6500	sucrose	industrial wastewater	25-33	0.039 - 0.19	
LITERATURE STUDIES					
20-25	brewery wastes	potassium nitrate	19-24	0.15 - 0.22	(1)
20-25	methanol	potassium nitrate	19-24	0.18	(1)
	C1 to C5 acids		10	0.10 - 0.36	(2)
	molasses		16	0.036	(3)
400 - 1100*	methanol	industrial wastewater and sodium nitrate	20-30	0.15 - 0.38	(4)
10-60	methanol		20	0.12 - 0.32	(5)
120 - 500	sodium citrate	potassium nitrate	5-27	0.24 - 3.8	(6)
	methanol		16-20	0.25 - 0.30	(7)
8.0	methanol	sodium nitrate	20		(8)
65-130	sucrose	ammonia and org.		0.009 - 0.014**	(9)
	nitrogen				
	methanol			0.055	(10)
	glucose			0.070	(10)

Table 7.4. (Continued)

NO ₃ -N (mg/l)	Carbon Source	Wastewater Treated	Temp. °C	NO ₃ -N Rem./ MLVSS-Day	Ref.
	peptone			0.22	(10)
20	molasses	fermentation wastewater		0.48**	(11)
1000	acetate			3.1 - 5.8	(12)

*The reactor was operated in continuous flow mode. Feed concentrations ranged from 400 to 1100, but the concentration in the reactor ranged from about 100 to 300.

**Biomass concentration was measured as mixed liquor suspended solids (MLSS).

representative of the total solids production in the reactors.

Economic Considerations for WETF

Little and Reed, 1986 (21) calculated that 666,000 pounds of sludge or 310,000 gal/yr at 20 wt% sludge are generated annually at WETF using calcium acetate as the carbon source. About 513,000 pounds of sludge or 238,000 gal/yr at 20 wt% sludge would be generated annually using sucrose as the carbon source. Thus, the WETF sludge production rate could be reduced by about 72,000 gal/yr at 20 wt% sludge if sucrose was used as the carbon source instead of acetate.

The WETF sludge represents a significant cost. It currently costs about \$3 - \$4/gallon to build acceptable interim sludge storage tanks (500,000 gallon capacity) at WETF (14). Although there is no acceptable disposal facility for the WETF mixed sludge, long term storage or disposal options being considered may cost \$50 - \$100/ft³ (\$6.7 - \$13.3/gal) (29).

The amount of sludge that requires storage and disposal will vary depending on the solids content of the sludge. Sludge allowed to settle in the tanks after decanting supernatant have a solids content of 30% and can potentially be dewatered in an existing vacuum filter to a solids content of up to 40%. Figure 7.1 presents cost savings expected if sucrose was used as the carbon source

WETF ANNUAL SLUDGE COSTS SAVINGS USING SUCROSE

SOLIDS CONCENTRATION	20%	30%	40%
SLUDGE REDUCTION (GAL)	72,000	41,300	26,100
STORAGE COST SAVINGS (\$/1000)	216-288	124-165	78-104
DISPOSAL COST SAVINGS (\$/1000)	481-963	276-552	174-349
TOTAL COST SAVINGS (\$/1000)	697-1251	400-717	252-453
STORAGE COSTS ARE BASED ON \$3-4/GAL TO CONSTRUCT STORAGE TANK			
DISPOSAL COSTS ARE BASED ON \$6.6-13.3/GAL			
TOTAL COSTS DO NOT INCLUDE SLUDGE HANDLING OR TREATMENT COSTS			

Figure 7.1. Potential WETF cost savings

instead of acetate for sludges generated with 20%, 30%, or 40% solids.

Based on a survey of current chemical costs, estimates of chemical costs relative to WETF are presented in Table 7.5.

Table 7.5. Organic Chemical Costs

Chemical	Cost (27, 28)	Cost/lb of Carbon	Annual Chemical Cost at WETF*
calcium acetate	\$.17/lb 70% HAc \$.03/lb lime	\$0.65	\$69,100
methanol	\$.75/gal. CH ₃ OH	\$0.30	\$31,830
sucrose	\$.18/lb sucrose	\$0.43	\$45,180

*Based on 2.4 million gallons of wastewater containing 360,000 lb/yr of nitrate treated and a 1.3:1 C/N weight ratio.

CHAPTER VIII

CONCLUSIONS

The use of sucrose as instead of calcium acetate as a carbon source for WETF can result in significant cost reduction. It is estimated that the use of sucrose will annually reduce the current sludge production rate by 26,100 gallons to 72,000 gallons, ultimately saving from \$250,000 to \$1,250,000 in storage and disposal costs. Reduction in the amount of sludge will also reduce the health, safety, and environmental liabilities associated with hazardous/radioactive wastes. Resource and Recovery Act (RCRA) regulations mandate that the generator is ultimately responsible for impacts from hazardous waste regardless of who manages the waste or how the waste is treated, stored, or disposed.

Denitrification rates of 810 to 9000 mg/l NO_3 /day were determined for WETF Tanks fed with calcium acetate at nitrate concentrations up to 36,000 mg/l NO_3 . A laboratory reactor (Reactor 7) fed with acetate had a denitrification rate of 700 mg/l NO_3 /day or .060 NO_3 -N/MLVSS/day; sucrose fed reactors had denitrification rates ranging from 570 to 2030 mg/l NO_3 /day or .039 to 0.19 NO_3 -N/MLVSS/day. Although sucrose and acetate fed laboratory reactors had similar denitrification rates, the acetate fed WETF tanks had an average denitrification rate

that was about 3 times that of the sucrose-fed laboratory reactors. The acclimation time for reactors fed with sucrose was less than for acetate fed reactors; however, the variation in acclimation times may be attributed to other parameters.

Use of methanol at WETF is not recommended due to difficulties in acclimating bacteria and the associated industrial hazards.

Reaction rates and reaction order (zero order with respect to nitrate concentration) for the high nitrate concentrations were consistent with respective values reported in literature for wastewater with lower concentrations of nitrates.

CHAPTER IX

FUTURE STUDIES

The following is a proposed list and brief description of additional study topics for WETF biodenitrification.

1. Nutrient Balance. Biological uptake rates for nitrogen and phosphorous nutrients and the impact upon denitrification rates could be determined.

2. Metal toxicity. The toxicity of various metals to biological microorganisms and corresponding denitrification rates could be evaluated.

3. pH. Previous WETF analytical data indicate denitrification rates and biological activity are negatively affected by a pH range which is not consistent with studies found in literature. The pH range and effect upon denitrification rates/biological activity and solubility of toxic metals could be evaluated. Metal solubility may be affecting biological activity.

4. Temperature. Considering the exothermic reaction of biodenitrification and daily and seasonal temperature changes, a heat balance could be performed, and its effect upon denitrification rates and biological activity could be evaluated.

5. Acclimation time. Data collected for WETF and laboratory reactors included in this report show that bacterial acclimation can take several months. Studies

could be performed that isolate the parameters suspected to cause extended acclimation times relative to biodenitrification. These parameters include heavy metals concentrations, pH, dissolved oxygen, nitrate concentrations, domination of bacterial species, and carbon source. See Section 7 for further discussion of bacterial acclimation.

6. Microbial Evaluation. The active population, genera, and species of bacteria performing biodenitrification should be determined. An operational monitoring/control strategy to produce predictable, reliable performance could be developed.

LIST OF REFERENCES

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1. Wilson, T. E., and D. Newton, "Brewery Wastes as a Carbon Source for Denitrification at Tampa, Florida," Presented at the 28th Annual Purdue Industrial Waste Conference, May, 1973.
2. Climenhage, D. C., "Biological Denitrification of Nylon Intermediates Wastewater," Presented at the 2nd Canadian Chemical Engineering Conference, September, 1972.
3. Central Contra Costa Sanitary District, Operating Report, Advanced Treatment Test Facility, January, 1974.
- ✓4. Jewell, W. J. and R. J. Cummings, "Denitrification of Concentrated Wastewaters," Presented at the Water Pollution Control Federation, Vol. 47, No. 9, September 1975.
- ✓5. Moore, S. F. and E. D. Schroeder, "The Effect of Nitrate Feed Rate on Denitrification," Water Research, 5, pp. 445-452 (1971).
- ✓6. Murphy, R. L., and R. N. Dawson, "The Temperature Dependency of Biological Denitrification," Water Research, 6, pp. 71-83 (1972).
7. Parker, D. S., F. J. Zadick, and K. E. Train, "Sludge Processing for Combined Physical-Chemical-Biological Sludges," Prepared for the EPA, Report No. R2-73-250, July 1973.
8. H. D. Stensel, R. C. Loehr, and A. W. Lawrence, "Biological Kinetics of Suspended Growth Denitrification," Water Pollution Control Federation, Vol. 45, No. 2, February 1973.
9. Silverstein, J. and E. D. Schroeder, "Performance of SBR Activated Sludge Processes with Nitrification/Denitrification," Water Pollution Control Federation, Vol. 55 (4), April 1983.
10. Paskins, A. R., G. L. Jones, and A. Wheatland, "Kinetics of Denitrification in the Activated Sludge Process," Presented at the International Conference on Advanced Treatment and Reclamation of Wastewater, 1977.

11. Nagashima, M., S. Kitamura, T. Koike, and T. Suzuki, "A Nitrification Denitrification Recycling System for Nitrogen and Phosphorus Removal from Fermentation Wastewater," Journal of Fermentation Technology, Vol. 57 (2), 1979.
- ✓12. Dodd, David J. and Derek H. Bone, "Nitrate Reduction by Denitrifying Bacteria in Single and Two Stage Continuous Flow Reactors," Water Resources, Vol. 9, 1975.
13. Payne, W. J., "Reduction of Nitrogenous Oxides by Microorganisms," Microbiological Reviews, Vol. 37, No. 4, Dec. 1973.
14. Communication with L. W. Little, Principal Engineer for WETF, Y-12 Plant, Oak Ridge, TN, March 1988.
15. Blasczyk, M., R. Mycielski, H. Jaworowska-Detuch, and K. Brzostek, "Effect of Various Sources of Organic Carbon and High Nitrite and Nitrate Concentrations on the Selection of Denitrifying Bacteria - Stationary Cultures," Acta Microbiology, Poland, Vol. 29 (4), 1980.
16. Process Design Manual for Nitrogen Control, U. S. EPA, October 1975.
17. Chou, W. Lin, R. E. Speece, R. H. Siddiqi, and K. McKeon, "The Effect of Petrochemical Structure on Methane Fermentation Technology," Progress in Water Technology, Vol. 10, No. 516, Pergamon Press, 1978.
18. Bringmann, G. and R. Kuhn, "Testing of substances for their toxicity threshold: Model Organisms Microcystis aeruginosa and Scenedesmus quadricauda, Symposium: Experimental Use of Algal Cultures in Limnology," Sandefjord, Norway, October 26-28, 1976.
19. F. E. Clark, C. W. Francis, H. L. Franke, and J. W. Strohecker, "Denitrification of Acid Wastes from Uranium Purification Processes," Oak Ridge Y-12 Plant, Report No. Y-1990, Nov. 1975.
20. Nurse, George R., "Denitrification with Methanol: Microbiology and Biochemistry," Water Research, Vol. 14, Pergamon Press, 1980.

21. Little, L. W. and G. D. Reed, "West End Treatment Facility: Sludge Reduction Alternatives," Martin Marietta Energy Systems, Y-12 Plant, Oak Ridge, TN, August 1986.
- ✓22. McCarty, P. L., Beck L., and P. St. Amant, "Biological Denitrification of Wastewaters by Addition of Organic Materials," In Proc. of the 24th Industrial Waste Conference, May 6, 7, and 8, 1969. Lafayette, Indiana: Purdue University, 1969.
23. Knowles, R., "Denitrification," Microbiological Reviews, March 1982, p. 43 - 70.
24. Bringmann, G. and R. Kuhn, "Comparison of the Toxicity Thresholds of Water Pollutants to Bacteria, Algae, and Protozoa in the Cell Multiplication Inhibition Test," Water Research, Pergamon Press, Vol. 14, 1980.
25. Posner, H. S., " Biohazards of Methanol in Proposed New Uses," Journal of Toxicology and Environmental Health, Vol.1, No. 1, September 1975.
26. Standard Methods for the Examination of Water and Wastewater, 16th Edition, Prepared and Published by the American Public Health Association, American Water Works Association, and the Water Pollution Control Federation, Washington, DC, 1985.
27. Specialty Chemical Company, Cleveland, TN.
28. Pepsi-Cola, Knoxville, TN.
29. Letter from N. W. Durfee, Oak Ridge National Laboratory, to Martin Marietta Energy Systems Engineering Division personnel, "Disposal Costs of ORNL Waste Streams", April 23, 1987.
30. Solo, F. W., Jr., H. F. Mueller, and T. E. Larson, "Denitrification of Wastewater Effluents with Methane," Water Pollution Control Federation Journal, Vol. 48, No. 7, July 1976.

APPENDICES

APPENDIX A

Analytical Results for WETF Tanks

Tank F-1 Analytical Results

Date	pH	D.O. (mg/l)	Temp. (°C)	Nitrate (mg/l)	Acetate Carbon (mg/l)	Phosphate (mg/l)
11/19/85				21000	5300	
11/21/85				18000	4600	
11/26/85				18000	6100	<5
11/29/85				13000	5200	
12/03/85				19000	6500	
12/06/85				19000	5400	7
12/10/85				19000	4700	
12/13/85				22000	4700	
12/17/85				15000	4600	<5
12/20/85				14800	4800	
12/27/85				680	<50	
12/31/85				100	<50	2
1/03/86				2550		
1/07/86				2300	<50	
1/14/86				2200	120	6
1/17/86				35	49	
1/22/86				110	150	
1/24/86				3100	<50	
1/28/86				3300	<50	<5
1/31/86				2700	<50	
2/04/86				2400	610	
2/07/86				2200	<50	
2/11/86				1700	<50	<2
2/14/86				2100	<50	
2/19/86				810	<50	2
2/21/86				2400	<50	
2/25/86				860	<50	
2/28/86				1200	<50	
3/04/86				2400	99	5
3/07/86				34	290	
3/12/86				12	160	
3/14/86				<50	280	
3/18/86				8	390	2
3/21/86				<50	430	
3/25/86				<50	440	1
3/28/86				56	120	
4/01/86				<50	480	
5/15/86	6.0	7.0	25	56400	10000	
5/19/86	6.3	6.4	23	45500	8900	
5/22/86	6.0	7.6	21	61800	9000	
5/27/86	6.4	8.6	22	50900	8000	
5/29/86	7.5	9.6	24	57800	8300	
6/02/86	6.6	6.8	24	59100	11000	
6/04/86	7.1	6.2	25	51000	9400	
6/09/86	7.1	8.0	26	58000	8100	
6/12/86	7.7	8.8	29	57000	11000	
6/23/86	7.3	7.4	28	55000	10000	
6/26/86	7.1	6.2	36	56000	9400	

Tank F-1 Analytical Results (Continued)

Date	pH	D.O. (mg/l)	Temp. (°C)	Nitrate (mg/l)	Acetate Carbon (mg/l)	Phosphate (mg/l)
6/30/86	7.4	6.8	29	53000	11000	
7/01/86	8.1	7.2	29	55200		24
7/03/86	7.8	9.6	22	49000	9400	
7/08/86	6.7	8.8	25	50900		30
7/10/86	8.5	5.8	23	52500	11000	
7/14/86	8.3	5.2	25	55800		
7/17/86	8.5	3.6	24	53300	11000	
7/21/86	8.4	3.8	25	55400	12000	42
7/24/86	8.1	4.8	26	56100	11800	
7/28/86	8.4	6.2	26	53800	10000	40
7/31/86	7.3	7.4	25	45500	10000	
8/04/86	7.2	3.8	24	38200	14000	
8/07/86	6.5	2.8	26	60400	13000	
8/11/86	6.9	2.0	22	60000		
8/14/86	7.2	3.4	26	56400	12000	
8/18/86	8.1	2.8	28	56800		
8/21/86	7.7	3.4	26		1200	
8/25/86	7.5	3.8	24	61400	4900	24
8/28/86	7.4	6.6	22	59900	17000	24
9/02/86	7.7	3.8	23	56000	9120	
9/08/86	7.6	4.6	19		8000	25
9/11/86	7.7	11.2	24			
9/15/86	7.7	6.4	21	56200	9600	
9/23/86	7.5	6.8	28	60900	10700	32
9/24/86	8.4	0.6	28			
9/25/86	7.4	4.4	31	55500	10600	
9/29/86	7.6	6.4	28	53700	13800	
9/30/86	7.4	4.6	37			
10/01/86	7.6	2.0	30			
10/02/86	7.2	3.4	48	68800	11600	
10/03/86	7.4	6.4	35			
10/06/86	6.4	3.4	30	23700	3800	50
10/07/86	7.2	3.4	28			
10/08/86	8.2	8.8	22	43900	8400	
10/10/86	8.2	8.4	21			

Tank F-2 Analytical Results

Date	Nitrate (mg/l)	Acetate Carbon (mg/l)	Phosphate (mg/l)
12/31/84	25000	6000	<1
1/03/85	26000	4400	
1/07/85	26000	3000	
1/14/85	25000	4500	<5
1/17/85	25000	5000	
1/22/85	23000	5900	
1/24/85	23000	5100	
1/28/85	25000	4400	<5
1/31/85	23000	4400	
2/04/85	22000	6300	
2/07/85	22000	4900	
2/11/85	22000	5000	<2
2/14/85	23000	4300	
2/19/85	23000	3900	<1
2/21/85	24000	4000	
2/25/85	15000	4800	
2/28/85	23000	6400	
3/04/85	23000	3500	<5
3/07/85	26000	4600	
3/12/85	27000	4300	
3/14/85	25000	5100	
3/18/85	24000	7100	3
3/21/85	20000	3900	
3/25/85	23000	3400	3
3/28/85	23000	5100	
4/01/85	24000	4600	
4/04/85		3600	
4/09/85	28000	4600	
4/11/85	28000	4100	
4/15/85	40000	5900	6
4/18/85	25000	5200	
4/22/85	21000	4300	8
4/25/85	9300	5000	
4/29/85	790	<50	
5/02/85	660	<50	
5/06/85	400	<50	
5/09/85	<50	190	

Tank F-3 Analytical Results

Date	Nitrate (mg/l)	Acetate Carbon (mg/l)	Phosphate (mg/l)
2/25/85	18000	5300	<5
2/28/85	21000	6800	
3/04/85	19000	5000	
3/07/85	22000	9400	
3/12/85	27000	9700	
3/14/85	26000	8200	
3/18/85	21000	18000	13
3/21/85	18000	8700	
3/25/85	19000	8300	13
3/28/85	19000	9800	
4/01/85	26000	10000	
4/04/85	31000	9700	
4/08/85	34000	9800	
4/11/85	33000	9400	
4/15/85	47000	11000	<5
4/18/88	27000	3800	
4/22/85	23000	5100	8
4/25/85	12000	6600	
4/29/85	12000	5400	
5/02/85	23000	7500	
5/06/85	23000	13000	
5/09/85	11000	16000	
5/13/85	11000	16000	
5/16/85	11000	9200	
5/20/85	11000	6300	<5
5/23/85	19000	9200	
5/28/85	20000	6400	
5/30/85	14000	7200	
6/03/85	14000	7400	
6/06/85	21000	8100	
6/10/85	19000	8400	
6/17/85	15790	8700	
6/20/85	15930	8600	
6/24/85	17660	9700	
7/08/85	15000	5500	
7/11/85	15500	5800	
7/13/85	15180	8900	<5
7/18/85	16545	5700	
7/22/85	17463	4300	
7/25/85	14978	7380	
7/29/85	15459	5100	<5
8/1/85	15658	6000	
8/5/85	14042	5100	
8/12/85	14433	6100	13
8/15/85	15800	5300	
8/19/85	13071	4500	
8/22/85	11574	5400	
8/26/85	10927		13

Tank F-3 Analytical Results (Continued)

Date	Nitrate (mg/l)	Acetate	Phosphate (mg/l)
		Carbon (mg/l)	
8/29/85	11574	4600	
9/04/85	11710	4600	
9/09/85	10995	5000	8
9/12/85	11778	4000	
9/16/85	11029	4600	
9/19/85	9327	4300	
9/26/85	9089	4000	
9/31/85	8170	4200	56
10/03/85	8000	5900	
10/04/85	5566	2200	
10/07/85	1804	6100	66
10/10/85	2042	1600	
10/14/85	511	1700	
10/17/85	102	90	
10/21/85	109	1000	
10/24/85	99	670	
10/28/85	100	560	93
10/31/85	106	1400	
11/04/85	104	960	
11/07/85	119	1300	
11/11/85	116	830	
11/14/85	117	960	
11/19/85	143	2400	
11/23/85	117	1800	

Tank F-4 Analytical Results

Date	pH	D.O. (mg/l)	Temp. (°C)	Nitrate (mg/l)	Acetate Carbon (mg/l)	Phosphate (mg/l)
9/23/86	6.5	1.4	26	16500	3700	67
9/24/86	8.4	0.6	28			
9/25/86	8.2	2.8	27	190	50	
9/29/86	8.4		31	50	105	
9/30/86	8.1		27			
10/01/86	6.8	1.2	26			
10/02/86	8.2		32	1550	50	
10/03/86	8.3	1.2	32			
10/06/86	8.4	1.4	22	331	50	78
10/07/86	8.5	4.2	20			
10/08/86	8.3	2.0	26	50	50	
10/10/86	8.5	0.4	29			
10/13/86	8.4		29	50	50	
10/14/86	8.5		31			
10/17/86	8.3		21			
10/20/86	6.4	0.8	20	18500	3850	
10/21/86	6.3	1.0	16			
10/23/86	6.4	4.1	31			
10/24/86	7.0	4.0	20	16900	3300	
10/27/86	9.7	0.2	23	50	50	

Tank F-5 Analytical Results

Date	pH	D.O. (mg/l)	Temp. (°C)	Nitrate (mg/l)	Acetate Carbon (mg/l)	Phosphate (mg/l)
1/02/86	8.2	6.0	13	36080	10000	
1/07/86	7.9	10.8	10	30700	16000	
1/09/86	8.1	4.2	9	26210	10000	
1/13/86	7.7	9.4	10	33700		
1/16/86	7.9	8.8	12	22800	6700	
1/20/86	8.0	10.8	12	35000	9900	
1/26/86	7.9	5.0	8	40000	12000	26
2/03/86	8.1	3.0	8	32800	10600	
2/13/86	8.1	5.2	13	34400	10000	
2/20/86	7.3	5.3	16	31800	9100	
3/10/86	7.5	8.0	16		9100	
3/13/86	7.5	8.0	16		8100	
3/17/86	7.3	8.8	16	34000	9200	
3/20/86	7.9	9.4	12	34000	9600	
3/25/86	7.4	7.0	17			
4/03/86	7.8	7.4	20	33400	11000	
4/07/86	7.2	8.8	21	33000	9700	
4/10/86	7.9	10.2	18	35400	10000	
4/14/86	7.2	7.6	21	28500	9900	
4/17/86	7.6	9.2	20	34900	3600	
4/21/86	8.2	7.2	19	33400	5600	
4/24/86	7.5	9.0	20	48900	8400	
4/28/86	7.9	7.0	20	38400	8800	
5/02/86	7.8	7.4	18	37000	8900	
5/05/86	7.6	6.6	20	33800	9500	
5/08/86	7.8	8.6	21	34700	9000	
5/12/86	7.7	6.4	23	36400	9200	
5/15/86	7.8	7.6	21	35100	8700	
5/19/86	7.4	5.8	23	35500	10000	
5/22/86	7.6	8.0	22	33700	9500	
5/27/86	7.6	4.6	26	29100	8700	
5/29/86	7.9	7.4	22	35400	7500	
6/02/86	7.9	8.8	22	37200	9400	
6/04/86	8.3	9.2	23	36600	9900	
6/09/86	8.3	9.4	27	34700	8700	
6/12/86	8.1	7.2	28	34400	10000	
6/23/86	8.0	6.2	28	33900	9800	85
6/26/86	7.7	7.4	28	32400	7200	
6/30/86	7.7	8.0	30	32400	8900	
7/01/86	7.4	7.8	29	36800		
7/03/86	7.5	5.0	29	34600	9600	78
7/08/86	7.1	6.8	29	27900	6200	77
7/10/86	8.0	5.8	27	30700	9400	
7/14/86	7.7	7.0	29	32600	9200	
7/17/86	7.7	5.8	28	30600	8100	
7/21/86	7.7	5.2	28	32000		74
7/24/86	7.3	3.2	30	33200	9300	
7/28/86	7.8	4.8	30	32000	7600	75

Tank F-5 Analytical Results (Continued)

Date	pH	D.O. (mg/l)	Temp. (°C)	Nitrate (mg/l)	Acetate Carbon (mg/l)	Phosphate (mg/l)
7/31/86	7.6	2.4	31	27500	8300	
8/04/86	7.4	2.8	28	28100	8500	
8/07/86	6.8	3.2	29	27500	9900	
8/11/86	6.9	2.6	29	26700	4800	78
8/14/86	7.2	3.4	28	23900	1900	
8/21/86	7.3	1.2	28	41900	7800	
8/25/86	6.9	2.0	27	24900	4100	76
8/28/86	8.3	4.0	23	29600	11000	
9/02/86	8.1	3.8	23	24300	6900	
9/08/86	7.9	1.0	22		1500	
9/11/86	7.8	0.4	23	24500	8260	
9/15/86	6.8	6.8	23	24700	5400	
9/23/86	8.1		38	50	1000	78
9/24/86	8.4	0.6	28			
9/25/86	8.7	2.8	29	54	670	
9/29/86	9.1		35	50	500	
9/30/86	9.1	2.8	32			
10/01/86	8.2	0.6	33			
10/02/86	8.4	0.4	33	1300	670	
10/03/86	9.1	1.2	33			
10/06/86	6.3	1.0	25	18300	2650	54
10/07/86	6.4	2.6	27			
10/08/86	8.3	1.4	32	50	50	
10/10/86	8.8	2.6	32			
10/13/86	9.0	0.6	30	50	50	
10/14/86	9.0	1.0	28			
10/15/86	9.0	2.8	20			
10/16/86	8.4	3.2	21	50	85	
10/17/86	8.8	7.8	21			
10/20/86	6.4	2.2	19	19200	2860	
10/21/86	6.8	2.8	22			
10/23/86	7.1	2.4	26			
10/24/86	9.3	2.6	20	8400	1530	
10/27/86	8.5	1.8	23	217	566	
10/28/86	8.8		18			
10/29/86	9.2	1.4	22			
10/30/86	9.1	3.0	29	50	50	

Tank F-6 Analytical Results

Date	pH	D.O. (mg/l)	Temp. (°C)	Nitrate (mg/l)	Acetate Carbon (mg/l)	Phosphate (mg/l)
3/20/86	8.9	3.0	12	23000	5700	
3/25/86	8.4	7.0	17	27100	5500	
4/03/86	8.5	3.6	19	24400	9000	
4/07/86	8.0	5.2	20	28800	5100	
4/10/86	8.2	5.6	18	27300	6500	
4/14/86	7.9	4.8	21	26700	7900	
4/17/86	7.9	8.2	18	33400	3400	
4/21/86	8.2	4.4	17	32500	4000	
4/28/86	8.0	3.6	18	34600	7900	
5/02/86	7.8	6.6	21	33900	7000	
5/05/86	7.8	5.8	20	32400	7600	
5/12/86	7.9	6.6	22	31900	6800	
5/15/86	7.8	4.8	22	32400	7200	
5/19/86	7.8	3.6	24	26300	7300	
5/22/86	7.6	6.4	22	31800	7700	
5/27/86	7.6	4.0	26	35100	7200	
5/29/86	7.8	6.4	25	31000	6600	
6/02/86	7.7	6.0	23	35300	8200	
6/04/86	8.6	6.2	23	34000	8500	
6/09/86	8.5	7.6	27	29700	6700	
6/12/86	8.3	7.6	29	33200	7700	
6/23/86	7.8	6.6	26	30500	7000	
6/26/86	7.9	6.4	27	30500	6200	
6/30/86	6.6	5.8	29	18200	4400	
7/01/86	7.0	7.2	28	10700		58
7/03/86	7.3	5.6	28	28000	6500	
7/08/86	7.6	8.2	28	24200	6700	76
7/10/86	7.8	2.4	27	25000	7200	
7/14/86	7.8	6.8	27	29700	7000	
7/17/86	7.2	5.6	28	25300	5900	
7/21/86	6.5	2.0	31	20400	4400	107
7/24/86	6.3	2.6	31	16000	4400	
7/28/86	6.7	6.2	31	13100	3200	71
7/31/86	6.9	1.8	31	11600	2000	
8/04/86	6.9	2.8	25	12200	3100	
8/07/86		2.8	27	12600	4500	
8/11/86	7.3	2.2	28	5600	600	80
8/14/86	7.4	1.8	30	4500	8000	
8/18/86	8.1	2.8	34	1400	660	
8/21/86	8.7	0.1	33	3390	180	
8/25/86	8.8	0.8	28	50	50	87
8/28/86	8.6	1.4	28	50	50	

APPENDIX B

Laboratory Reactor Analytical Results

Reactor 1 Analytical Results

Day	pH	D.O. (mg/l)	Temp. (°C)	Nitrate (mg/l)	TOC (mg/l)	COD (mg/l)	Acetate Carbon (mg/l)	Phosphate (mg/l)	TDS (mg/l)	TSS (mg/l)	VSS (mg/l)
0	7.4										
1	7.7			45700	15000	13000	11000	17	83000	35000	16000
2	7.9	7.2	28								
3	7.7	5.5	29	45000	15000	32000	10000	18	82000	35000	19000
6	7.7	6.1	30	49400	14000	35000	10000	15	87000	42000	20000
7	7.7	5.8	30								
8	7.7	5.6	30								
9	7.3	6.0	30								
10	8.2	5.5	30								
13	8.1	5.5	32	62000	14000	36000		11	87000	40000	20000
14	7.9	5.6	31								
15	7.8	5.6	31								
16	7.9	5.5	32	41900	15000	32000	9700	5	100000	22000	7300
17	7.8	5.9	32								
20	8.0	5.1	32	46500	15000	35000	11000	10	110000	18000	4900
21	8.2	5.0	21								
22	8.4	5.0	32								
23	8.4	4.3	32								
24	8.3	3.3	33	46200	14000	35000	9900	12	102000	24000	3200
27	8.3	0.3	33								
28	8.4	0.4	34								
29	8.4	0.3	33								
30	8.2	0.3	32								
31	8.4	0.1	33	45200	14000	36000		11	94000	40000	18000
34	8.4	0.2	33								
35	8.5	0.2	33								
37	7.9	1.0	30	42600				62			
40	8.4	0.2	33								
42	8.4	0.2	34								
44	8.3	0.3	33								
45	8.6	0.2	32	41600	13000	34000			95000	34000	14000
48	8.3	0.2	31								
49	8.4	0.2	30								
50	8.4	0.2	31								
51	8.3	0.4	31								
52	7.9	0.4	32	42600	14000	35000	12000	66	85000	37000	15000
54	8.4	0.3	33								
55	8.3	0.4	34								
57	8.2	0.3	34								
59	7.7	0.3	32	45900	14000	32000	11000	60	79000	38000	16000
62	7.9	0.2	32								
63	8.0	0.1	33								
64	8.1	0.2	34								
66	8.1	0.2	30	45100					91000	39000	16000
69	8.5	0.2	31								
71	8.2	0.2	32								
73	7.9	6.3	30								
129				55100			12850				

Reactor 2 Analytical Results

Day	pH	D.O. (mg/l)	Temp. (°C)	Nitrate (mg/l)	TOC (mg/l)	COD (mg/l)	Methyl Alcohol (mg/l)	Phosphate (mg/l)	TDS (mg/l)	TSS (mg/l)	VSS (mg/l)
0	7.4										
1	7.6		28	42500	6700	52000	39000	16	63000	20000	8300
2	7.7	7.4	29								
3	7.5	6.0	30	44100	1100	42000	35000	16	60000	24000	12000
6	7.5	6.3	30	45900	13000	45000	35000	13	56000	21000	9000
7	7.6	6.2	31								
8	7.6	5.8	30								
9	7.1	6.0	30								
10	8.2	6.1	30								
13	7.9	6.6	32	48000	13000	49000	40000	10	56000	21000	9000
14	7.8	5.9	31								
15	7.7	5.8	31								
16	7.9	5.9	32	29600	13000	47000		8	57000	14000	4400
17	7.8	6.0	32								
20	8.1	5.7	32	41800	13000	47000	31000	5	61000	14000	4000
21	8.2	5.5	33								
22	8.3	5.8	32								
23	8.3	5.6	33								
24	8.2	5.2	34	42600	12000	47000	31000	11	63000	17000	2500
27	8.3	5.6	34								
28	8.4	5.2	34								
29	8.4	5.2	34								
30	8.3	5.5	33								
31	8.5	5.4	33	44100	13000	48000	33000	10	52000	28000	12000
34	8.4	5.5	33								
35	8.5	5.8	33								
37	8.5	6.2	30	46000			34000	58			
40	8.4	5.7	33								
42	8.5	4.4	34								
44	8.4	5.0	33								
45	8.6	5.4	32	43200	13000	37000			58000	26000	11000
48	8.5	6.0	31								
49	8.7	5.8	30								
50	8.6	5.4	31								
51	8.7	5.4	31								
52	8.2	5.4	32	46100	13000	39000	28000	61	61000	27000	9900
54	8.5	5.4	34								
55	8.5	5.5	35								
57	8.6	5.3	34								
59	8.1	5.4	32	45900	11000	42000		55	60000	28000	12000
62	8.2	5.3	32								
63	8.0	5.6	33								
64	7.9	5.6	33								
66	8.0	5.9	31	43600					62000	31000	13000
69	8.6	5.6	31								
71	8.3	5.4	32								
73	8.2	6.0	30								
129				38900			28600				

Reactor 3 Analytical Results

Day	pH	D.O. (mg/l)	Temp. (°C)	Nitrate (mg/l)	TOC (mg/l)	COD (mg/l)	Sucrose (mg/l)	Phosphate (mg/l)	TDS (mg/l)	TSS (mg/l)	VSS (mg/l)
0	8.0										
1	8.2		28	46800	17000	24000	28500	16	72000	29000	15000
2	8.8	7.1	29								
3	8.6	6.0	30	45400	19000	43000	30500	17	71000	35000	16000
6	8.6	6.3	30	42700	16000	21000	31000	14	72000	30000	16000
7	8.7	6.3	30								
8	8.7	6.2	30								
9	8.1	6.3	30								
10	8.4	6.4	29								
13	8.4	6.4	32	48000	15000	36000	35000		72000	28000	15000
14	8.2	5.7	31								
15	7.9	2.2	31								
16	7.9	4.3	32	44700	16000	33000	29500	0	77000	17000	5600
17	7.7	2.5	32								
20	7.0	0.6	32	43900	15000	33000	22600	0	83000	15000	4300
21	8.5	2.0	33								
22	8.3	3.1	32								
23	8.5	2.4	32								
24	7.6	1.1	33	45600	15000	33000	28600	1	82000	17000	4100
27	8.3	1.7	33								
28	8.5	0.5	34								
29	8.5	1.8	33								
30	8.2	2.5	32								
31	8.5	0.8	33	44100	16000	26000	31800	2	78000	18000	6400
34	8.1	2.8	33								
35	8.6	1.3	33								
37	8.1	0.2	30	42800			15300	11			
40	8.4	2.6	33								
42	8.3	2.5	34								
44	7.2	0.1	33								
45	9.0	0.1	32	41200	15000	31000	15200		78000	33000	16000
48	8.4	3.0	31								
49	7.8	0.1	30								
50	8.0	0.2	31								
51	8.2	0.2	32								
52	7.2	0.1	32	45800	15000	34000	28800	80	60000	34000	16000
54	8.6	2.2	33								
55	8.1	3.0	34								
57	8.2	3.1	34								
59	7.0	0.2	31	41100	16000	30000		61	66000	38000	17000
62	6.7	0.1	32								
63	8.3	0.1	33								
64	7.7	0.6	33								
66	7.9	1.1	30	43400					65000	44000	21000
69	8.0	2.8	30								
71	7.2	0.1	32								
73	6.9	0.1	30								
122				19600			10				
129				16700							

Reactor 4 Analytical Results

Day	pH	D.O. (mg/l)	Temp. (°C)	Nitrate (mg/l)	TOC (mg/l)	COD (mg/l)	Acetate Carbon (mg/l)	Phosphate (mg/l)	TDS (mg/l)	TSS (mg/l)	VSS (mg/l)
1	8.2	6.1	29	28600	8200	13000	9300	10	72000	5300	900
4	9.4	6.0	30	37800	9300	24000	11200	10	71000	5100	820
5	9.3	6.3	31								
6	6.9	4.5	32								
7	8.7	5.1	31								
8	9.0	5.4	31	31100	9400	26000	10700	12	75000	5400	1200
11	9.7	6.1	32								
12	8.8	5.9	31	32100	8900	39000	9380	9	78000	5500	870
13	9.3	5.9	29								
14	8.6	6.2	29								
15	9.1	6.3	29	34000	9400	37000	9430	11	73000	6900	2100
17	8.2	5.9	29								
18	8.4	6.2	27								
19	9.2	6.3	27	23700	9300	25000	9660	9	68000	7500	1800
20	7.2	0.4	28								
21	7.6	0.3	29								
22	7.6	0.4	28	25200	8900	26000	10200	10	68000	6400	1200
25	7.2	0.2	27								
26	7.6	0.2	26	29200	9800	27000	8850	10	63000	6800	1400
27	7.1	0.2	26								
28	7.3	0.2	25								
29	7.4	0.2	25	26800	9300	24000	9480	10	62000	6900	1300
30	7.0										
31	7.3	0.2	25								
32	7.6	0.2	25	28700	9500	24000	9670	10	60000	8500	1500
33	7.1	0.5	25								
34	8.3	1.4	26								
35	7.7	0.2	27	30100	9800	23000	8740	10	57000	7200	1200
37	7.1										
39	7.2	0.2	25	29000	9700	22000		10	63000	7600	1400
40	8.2										
41	7.5	0.2	26								
42	7.1	0.2	26	27500	9000	23000					
44	7.1										
46	7.1	0.2	27	26800	8900						
49	7.2	0.2	27	26500							
52	6.8	0.2	27								

Reactor 5 Analytical Results

Day	pH	D.O. (mg/l)	Temp. (°C)	Nitrate (mg/l)	TOC (mg/l)	COD (mg/l)	Methyl Alcohol (mg/l)	Phosphate (mg/l)	TDS (mg/l)	TSS (mg/l)	VSS (mg/l)
1	8.2	6.0	29	32800	9200	33000	26000	9	44000	4200	850
4	8.5	6.2	30	35600	9300	21000	28000	10	40000	4300	950
5	8.3	6.5	31								
6	8.1	6.1	32								
7	7.9	5.9	32								
8	8.0	5.5	32	33300	10000	35000	32000	10	47000	4700	1500
11	7.5	5.2	32								
12	7.7	5.3	32	28800	9600	39000	27600	10	58000	6100	1200
13	7.4	5.6	30								
14	7.4	5.3	29								
15	7.6	5.7	29	33500	9600	45000	25400	9	49000	4700	1400
17	6.6	1.8	29								
18	9.2	6.5	27								
19	7.6	6.5	28	31800	9400	35000	26800	8	39000	6700	1400
20	8.4	6.5	28								
21	8.5	6.6	29								
22	7.8	6.5	28	25200	9000	38000	83300	9	40000	6300	1400
25	8.4	6.4	27								
26	7.5	6.0	26	27600	9500	36000	57300	10	35000	6100	1500
27	8.4	6.4	26								
28	8.2	6.2	25								
29	7.3	6.6	25	30600	9200	35000	25500	11	35000	5900	1200
31	8.2										
32	8.3	6.8	25								
33	7.3	6.7	25	27200	9200	36000	30000	8	35000	6200	1000
34	8.3	7.1	25								
35	8.3	6.7	26								
36	7.5	6.7	27	27400	9800	34000	30000	9	37000	6000	1400
37	8.1										
39	7.5	6.7	25	29100	9400	34000	26500	8	42000	6700	1400
40	8.4										
41	8.1	6.8	26								
42	8.3	6.6	26	24800	9100	37000	30000				
44	8.1										
46	8.0	6.5	27	27200			27300				
49	7.8	6.2	27	25300							

Reactor 6 Analytical Results

Day	pH	D.O. (mg/l)	Temp. (°C)	Nitrate (mg/l)	TOC (mg/l)	COD (mg/l)	Sucrose (mg/l)	Phosphate (mg/l)	TDS (mg/l)	TSS (mg/l)	VSS (mg/l)
1	8.1	0.2	29	27700	8600	21000	7300	16	54000	7800	1400
4	6.9	0.2	30	25200	7900	36000	10	20	51000	9200	1600
5	6.5	0.3	31								
6	6.7	0.2	33								
7	6.4	0.2	32								
8	9.4	0.2	32	24100	7100	20000	10	18	47000	17000	2400
11	6.1	0.2	32								
12	6.2	0.2	32	18900	6800	19000	10	36	53000	20000	2800
13	6.3	0.2	30								
14	6.8	0.2	30								
15	6.4	0.2	30	18400	6800	14000	10	20	37000	25000	3800
17	7.1	0.1	29								
18	7.0	0.2	27								
19	6.9	0.2	28	13500	5600	2400	10	23	42000	26000	3500
20	6.7	0.2	28								
21	9.2	0.2	28								
22	8.2	0.2	28	18000	4800	17000	10	17	40000	28000	3800
25	6.9	0.2	27								
26	7.3	0.2	27	14900	13000	33000	5600	20	43000	29000	4100
27	6.7	0.2	26								
28	6.8	0.2	25								
29	7.2	0.2	25	12500	12000	33000	10	23	40000	35000	4200
31	6.6	0.2	25								
32	6.9	0.2	25	7800	11000	34000	10	24	32000	42000	3900
33	8.7	0.4	25								
34	6.9	0.2	25								
35	7.0	0.2	27	5600	12000	32000	10	20	32000	45000	4200
37	7.6	0.2									
39	7.1	0.2	26	6100	11000	38000	10	30	30000	43000	4300
41	7.0	0.2	26								
42	6.7	0.2	26	4050	9900	31000	10				
44	6.6										
46	6.8	0.2	27	1900			10				
49	7.2	0.2	27	50							
52	6.9	0.2	26								

Reactor 7 Analytical Results

Day	pH	D.O. (mg/l)	Temp. (°C)	Nitrate (mg/l)	TOC (mg/l)	COD (mg/l)	Acetate Carbon (mg/l)	Phosphate (mg/l)	TDS (mg/l)	TSS (mg/l)	VSS (mg/l)
0	7.2			9340	2600	6100	3080	12	24000	14000	1900
1	7.0	0.4	25								
2	6.8	6.8	25	7340	3200	7600	1200	5	16000	29000	6100
4	8.7	6.2	25	7040	2700	8200	1200	5	21000	15000	2000
7	6.8	0.3	25								
8	7.0			6140	2300	7600	3000	5	13000	17000	2500
10	7.0	0.3	21	5500	1800	8200	80	5	17000	17000	2300
11	7.1	0.4	25								
14	7.6	0.2	25	50	970	6000	2100	5	12000	22000	2600
18	8.3	0.2	26	50	260	1600	320	5	24000	26000	2400
25	9.1	2.6	25	50	140	980	50	5	3600	26000	2300

Reactor 8 Analytical Results

Day	pH	D.O. (mg/l)	Temp. (°C)	Nitrate (mg/l)	TOC (mg/l)	COD (mg/l)	Sucrose (mg/l)	Phosphate (mg/l)	TDS (mg/l)	TSS (mg/l)	VSS (mg/l)
0	8.5			50	1600	4600	10000	24	8700	63000	7900
1	8.8	0.2	25								
2	8.5	0.4	25	2710	1700	8200	63000	9	11000	24000	3400
4	9.0	0.4	26	50	920	3500	0	18	4500	24000	3600
7	8.1	0.3	25								
8	6.5			18100			31000	5			
10	6.9	0.4	21	20400	380	2800	11	5	32000	34000	4000
11	6.7	0.2	25								
14	7.0	1.0	26	18300	193	1500	27000	5	27000	36000	3700
18	7.6	2.5	26	16700	270	3400	35000	5	26000	23000	1800
25	7.3	1.0	26	3270	1600	12000	0	5	16000	45000	3800
32	7.5	0.3	26	200	1200	9400	1830	5	11000	35000	1600
39	8.1			50	1000	400	2730	26	3700	48000	4900

Reactor 9 Analytical Results

Day	pH	D.O. (mg/l)	Temp. (°C)	Nitrate (mg/l)	TOC (mg/l)	COD (mg/l)	Sucrose (mg/l)	Phosphate (mg/l)	TDS (mg/l)	TSS (mg/l)	VSS (mg/l)
0	6.8			6900	2700	7300	3000	8	15000	7500	2700
1	6.8	0.4	26								
2	7.1	0.4	26	2340	2800	9100	10	8	8400	8600	2200
4	7.3	0.2	26	50	1600	5900	10	7	2800	11000	2200
7	6.8	0.2	25								
8	9.1			20400	1400	5200	10	5	34000	19000	4200
10	8.7	5.8	21	20800	1400	4800	10	5	35000	16000	2800
11	8.0	0.8	25								
14	7.0	0.2	26	21200	980	6000	9000	5	33000	19000	3000
18	7.6	1.5	25	16100	28	2500	3000	5	26000	21000	2100
25	7.1	0.3	26	8540	2000	14000	0	5	25000	23000	2300
32	7.3	0.2	25	5050	2000	14000	611	5	20000	26000	2500
39	6.8			4060	1300	9400	2700	5	19000	25000	3200
50	7.1			3200	2300	9400	103	5	18000	25000	3600
60	7.1			1300	1100	9700	0	5	14000	20000	2700
71	7.8			50	1400	3000	0	5	1700	29000	3100

APPENDIX C

Laboratory Reactor Inorganic Analysis Results

Reactor 1 Inorganic Analysis Results

Element	Day 59 Results	Day 66 Results	Day 73 Results
Aluminum	<1.5	<1.5	<1.5
Arsenic	<3	<3	<3
Boron	2.6	2.6	3.1
Barium	8.0	8.0	8.3
Beryllium	<0.01	<0.01	<0.01
Calcium	23000	24000	25000
Cadmium	<0.010	<0.10	<0.10
Cesium	<1.5	<1.5	<1.5
Cobalt	0.14	0.16	0.16
Chromium	0.11	<0.10	<0.10
Copper	5.8	5.9	5.4
Gallium	<2	<2	<2
Iron	<0.3	<0.3	<0.3
Lanthanum	<0.3	<0.3	<0.3
Lead	<1	<1	<1
Lithium	23	23	26
Magnesium	230	140	260
Manganese	0.53	<0.03	0.80
Molybdenum	0.55	0.57	0.49
Niobium	1.1	1.0	1.0
Nickel	<0.2	<0.2	<0.2
Phosphorus	26	27	27
Potassium	220	220	250
Scandium	<0.03	<0.03	<0.03
Silicon	<1	<1	2
Silver	<0.02	<0.02	<0.2
Sodium	3600	3600	3800
Strontium	10	11	12
Thorium	<1	<1	<1
Titanium	<0.05	<0.05	<0.05
Vanadium	<0.2	<0.2	<0.2
Yttrium	<0.03	<0.03	<0.03
Zinc	<0.10	<0.10	<0.10
Zirconium	<0.10	<0.10	<0.10

Samples were filtered before analysis.

Reactor 2 Inorganic Analysis Results

Element	Day 59 Results	Day 66 Results	Day 73 Results
Aluminum	<1.5	2.4	0.2
Arsenic	<3	<3	<3
Boron	1.9	2.0	2.2
Barium	7.8	7.8	8.0
Beryllium	<0.01	<0.01	<0.01
Calcium	12000	12000	12000
Cadmium	<0.10	<0.10	<0.10
Cesium	<1.5	<1.5	<1.5
Cobalt	0.11	0.11	0.12
Chromium	<0.10	<0.10	<0.11
Copper	5.6	5.6	5.7
Gallium	<2	<2	<2
Iron	<0.3	<0.3	<0.3
Lanthanum	<0.3	<0.3	<0.3
Lead	<1	<1	<1
Lithium	12	12	13
Magnesium	120	120	150
Manganese	0.14	0.14	<0.03
Molybdenum	<0.40	<0.40	<0.40
Niobium	0.6	0.5	0.5
Nickel	<0.2	<0.2	<0.2
Phosphorus	26	26	26
Potassium	220	220	240
Scandium	<0.03	<0.03	<0.03
Silicon	<1	<1	<1
Silver	<0.2	<0.2	<0.2
Sodium	3600	3400	3700
Strontium	5.6	5.6	6.2
Thorium	<1	<1	<1
Titanium	<0.05	<0.05	<0.05
Vanadium	<0.2	<0.2	<0.2
Yttrium	<0.03	<0.03	<0.03
Zinc	<0.10	<0.10	<0.10
Zirconium	<0.10	<0.10	<0.10

Samples were filtered before analysis.

Reactor 3 Inorganic Analysis Results

Element	Day 59 Results	Day 66 Results	Day 73 Results
Aluminum		7.6	200
Arsenic	<3	<3	<3
Boron	3.4	3.8	4.0
Barium	7.0	6.9	6.2
Beryllium	<0.01	<0.01	<0.01
Calcium	12000	12000	13000
Cadmium	<0.10	0.13	<0.10
Cesium	<1.5	<1.5	<1.5
Cobalt	<0.10	<0.10	<0.10
Chromium	<0.10	0.68	0.11
Copper	0.57	0.75	0.50
Gallium	<2	<2	<2
Iron	0.5	7.5	0.9
Lanthanum	<0.3	<0.3	<0.3
Lead	<1	<1	<1
Lithium	11	12	12
Magnesium	88	74	110
Manganese	1.1	0.86	1.4
Molybdenum	<0.40	0.53	<0.40
Niobium	0.2	0.6	0.4
Nickel	0.2	0.6	0.4
Phosphorus	35	39	35
Potassium	230	220	240
Scandium	<0.03	<0.03	<0.03
Silicon	3	10	9
Silver	<0.2	<0.2	<0.2
Sodium	3600	3600	3700
Strontium	6.8	7.1	7.8
Thorium	<1	<1	<1
Titanium	<0.05	0.16	<0.05
Vanadium	<0.2	<0.2	<0.2
Yttrium	<0.03	<0.03	<0.03
Zinc	<0.10	0.45	<0.10
Zirconium	2.7	5.0	3.4

Samples were filtered before analysis.

Reactor 4 Inorganic Analysis Results

Element	Day 1 Results	Day 4 Results	Day 8 Results	Day 12 Results	Day 15 Results
Aluminum	<1.5	<1.5	<1.5	<1.5	<1.5
Arsenic	<3	<3	<3	<3	<3
Boron	0.4	0.5	0.4	<0.2	<0.2
Barium	1.1	1.2	1.2	1.1	1.2
Beryllium	<0.01	<0.01	<0.01	<0.01	<0.01
Calcium	18000	18000	17000	15000	17000
Cadmium	<0.1	<0.1	<0.10	<0.10	<0.10
Cesium	<1.5	<1.5	<1.5	<1.5	<1.5
Cobalt	<0.10	<0.10	<0.10	<0.10	<0.10
Chromium	<0.10	<0.10	<0.10	<0.10	<0.10
Copper	0.57	0.15	0.53	0.59	0.53
Gallium	<2	<2	<2	<2	<2
Iron	<0.3	<0.3	<0.3	<0.3	<0.3
Lanthanum	<0.3	<0.3	<0.3	<0.3	<0.3
Lead	<1	<1	<1	<1	<1
Lithium	4.2	4.2	3.8	3.5	3.7
Magnesium	40	39	28	19	18
Manganese	0.5	0.59	<0.03	<0.03	<0.03
Molybdenum	<0.40	<0.40	<0.40	<0.40	<0.40
Niobium	<0.2	1.0	0.8	0.7	0.8
Nickel	<0.2	<0.2	<0.2	<0.2	<0.2
Phosphorus	2	3	2	2	2
Potassium	29	23	29	25	34
Scandium	<0.03	<0.03	<0.03	<0.03	<0.03
Silicon	<1	9	<1	<1	<1
Silver	<0.2	<0.2	<0.2	<0.2	<0.2
Sodium	390	390	390	330	360
Strontium	7.0	7.2	7.0	6.4	6.9
Thorium	<1	<1	<1	<1	<1
Titanium	<0.05	<0.05	<0.05	<0.05	<0.05
Vanadium	<0.2	<0.2	<0.2	<0.2	<0.2
Yttrium	<0.03	<0.03	<0.03	<0.03	<0.03
Zinc	0.13	0.14	<0.10	<0.10	<0.10
Zirconium	<0.10	<0.10	<0.10	<0.10	<0.10

Samples were filtered before analysis.

Reactor 4 Inorganic Analysis Results (Continued)

Element	Day 19 Results	Day 22 Results	Day 29 Results	Day 35 Results	Day 42 Results
Aluminum	2.0	<1.5	<1.5	<1.5	<1.5
Arsenic	<3	<3	<3	<3	<3
Boron	0.2	0.3	0.4	<0.2	0.4
Barium	1.3	1.3	1.5	1.4	1.4
Beryllium	<0.01	<0.01	<0.01	<0.01	<0.01
Calcium	17000	18000	18000	18000	17000
Cadmium	<0.1	<0.1	<0.10	<0.10	<0.10
Cesium	<1.5	<1.5	<1.5	<1.5	<1.5
Cobalt	<0.10	<0.10	<0.10	<0.10	<0.10
Chromium	<0.10	<0.10	<0.10	<0.10	<0.10
Copper	0.55	0.40	0.10	0.28	0.13
Gallium	<2	<2	<2	<2	<2
Iron	<0.3	<0.3	<0.3	<0.3	<0.3
Lanthanum	<0.3	<0.3	<0.3	<0.3	<0.3
Lead	<1	<1	<1	<1	<1
Lithium	3.6	3.9	4.2	4.2	4.2
Magnesium	16	25	28	26	26
Manganese	<0.03	0.03	0.34	0.44	0.44
Molybdenum	<0.40	<0.40	<0.40	<0.40	<0.40
Niobium	0.9	0.8	0.8	0.7	0.8
Nickel	<0.2	<0.2	<0.2	<0.2	<0.2
Phosphorus	2	3	3	3	3
Potassium	28	27	28	32	33
Scandium	<0.03	<0.03	<0.03	<0.03	<0.03
Silicon	<1	<1	3	2	3
Silver	<0.2	<0.2	<0.2	<0.2	<0.2
Sodium	350	380	430	400	410
Strontium	6.7	7.1	7.5	7.3	7.4
Thorium	<1	<1	<1	<1	<1
Titanium	<0.05	<0.05	<0.05	<0.05	<0.05
Vanadium	<0.2	<0.2	<0.2	<0.2	<0.2
Yttrium	<0.03	<0.03	<0.03	<0.03	<0.03
Zinc	0.13	0.14	<0.10	<0.10	0.15
Zirconium	<0.10	<0.10	<0.10	<0.10	<0.10

Samples were filtered before analysis.

Reactor 4 Inorganic Analysis Results (Continued)

Element	Day 49 Results
Aluminum	<1.5
Arsenic	<3
Boron	0.3
Barium	1.5
Beryllium	<0.01
Calcium	18000
Cadmium	<0.1
Cesium	<1.5
Cobalt	<0.10
Chromium	<0.10
Copper	0.13
Gallium	<2
Iron	<0.3
Lanthanum	<0.3
Lead	<1
Lithium	4.5
Magnesium	25
Manganese	0.21
Molybdenum	<0.40
Niobium	0.9
Nickel	<0.2
Phosphorus	3
Potassium	24
Scandium	<0.03
Silicon	3
Silver	<0.2
Sodium	410
Strontium	7.9
Thorium	<1
Titanium	<0.05
Vanadium	<0.2
Yttrium	<0.03
Zinc	<0.10
Zirconium	<0.10

Samples were filtered before analysis.

Reactor 5 Inorganic Analysis Results

Element	Day 1 Results	Day 4 Results	Day 8 Results	Day 12 Results	Day 15 Results
Aluminum	<1.5	<1.5	<1.5	<1.5	<1.5
Arsenic	<3	<3	<3	<3	<3
Boron	0.4	0.4	0.4	<0.2	<0.2
Barium	0.71	0.72	0.68	0.70	0.74
Beryllium	<0.01	<0.01	<0.01	<0.01	<0.01
Calcium	8700	7700	8200	8100	8000
Cadmium	<0.10	<0.10	<0.10	<0.10	<0.10
Cesium	<1.5	<1.5	<1.5	<1.5	<1.5
Cobalt	<0.10	<0.10	<0.10	<0.10	<0.10
Chromium	<0.10	<0.10	<0.10	<0.10	<0.10
Copper	0.44	0.50	0.53	0.42	0.40
Gallium	<2	<2	<2	<2	<2
Iron	<0.3	<0.3	<0.3	<0.3	<0.3
Lanthanum	<0.3	<0.3	<0.3	<0.3	<0.3
Lead	<1	<1	<1	<1	<1
Lithium	2.4	2.1	2.3	2.4	2.5
Magnesium	37	33	36	41	42
Manganese	<0.03	<0.03	<0.03	<0.03	<0.03
Molybdenum	<0.40	<0.40	<0.40	<0.40	<0.40
Niobium	0.5	0.3	0.4	0.3	0.4
Nickel	<0.2	<0.2	<0.2	<0.2	<0.2
Phosphorus	3	2	2	2	2
Potassium	22	17	24	28	25
Scandium	<0.03	<0.03	<0.03	<0.03	<0.03
Silicon	<1	<1	<1	<1	<1
Silver	<0.2	<0.2	<0.2	<0.2	<0.2
Sodium	380	330	360	350	360
Strontium	3.3	3.0	3.2	3.2	3.2
Thorium	<1	<1	<1	<1	<1
Titanium	<0.05	<0.05	<0.05	<0.05	<0.05
Vanadium	<0.2	<0.2	<0.2	<0.2	<0.2
Yttrium	<0.03	<0.03	<0.03	<0.03	<0.03
Zinc	<0.10	<0.10	<0.10	<0.10	<0.10
Zirconium	<0.10	<0.10	<0.10	<0.10	<0.10

Samples were filtered before analysis.

Reactor 5 Inorganic Analysis Results (Continued)

Element	Day 19 Results	Day 22 Results	Day 29 Results	Day 35 Results	Day 42 Results
Aluminum	1.7	1.6	<1.5	<1.5	<1.5
Arsenic	<3	<3	<3	<3	<3
Boron	<0.2	0.2	0.3	<0.2	0.2
Barium	0.88	1.0	1.2	1.1	1.1
Beryllium	0.02	<0.01	<0.01	<0.01	<0.01
Calcium	8100	8400	8700	8400	8500
Cadmium	<0.10	<0.10	<0.10	<0.10	<0.10
Cesium	<1.5	<1.5	<1.5	<1.5	<1.5
Cobalt	<0.10	<0.10	<0.10	<0.10	<0.10
Chromium	<0.10	<0.10	<0.10	<0.10	<0.10
Copper	0.37	0.36	0.52	0.55	0.53
Gallium	<2	<2	<2	<2	<2
Iron	<0.3	<0.3	<0.3	<0.3	<0.3
Lanthanum	<0.3	<0.3	<0.3	<0.3	<0.3
Lead	<1	<1	<1	<1	<1
Lithium	2.4	2.7	2.8	2.9	2.8
Magnesium	6.4	9.5	20	29	32
Manganese	<0.03	0.03	<0.03	<0.03	<0.03
Molybdenum	<0.40	<0.40	<0.40	<0.40	<0.40
Niobium	0.4	0.4	0.3	<0.3	0.4
Nickel	<0.2	<0.2	<0.2	<0.2	<0.2
Phosphorus	2	2	3	3	3
Potassium	22	24	30	30	31
Scandium	<0.03	<0.03	<0.03	<0.03	<0.03
Silicon	<1	<1	<1	<1	<1
Silver	<0.2	<0.2	<0.2	<0.2	<0.2
Sodium	350	370	420	400	400
Strontium	3.2	3.4	3.6	3.4	3.4
Thorium	<1	<1	<1	<1	<1
Titanium	<0.05	<0.05	<0.05	<0.05	<0.05
Vanadium	<0.2	<0.2	<0.2	<0.2	<0.2
Yttrium	<0.03	<0.03	<0.03	<0.03	<0.03
Zinc	<0.10	<0.10	<0.10	<0.10	<0.10
Zirconium	<0.10	<0.10	<0.10	<0.10	<0.10

Samples were filtered before analysis.

Reactor 5 Inorganic Analysis Results (Continued)

Element	Day 49 Results
Aluminum	<1.5
Arsenic	<3
Boron	<0.2
Barium	1.5
Beryllium	0.02
Calcium	8900
Cadmium	<0.10
Cesium	<1.5
Cobalt	<0.10
Chromium	<0.10
Copper	0.43
Gallium	<2
Iron	<0.3
Lanthanum	<0.3
Lead	<1
Lithium	2.8
Magnesium	37
Manganese	<0.03
Molybdenum	<0.40
Niobium	0.4
Nickel	<0.2
Phosphorus	2
Potassium	25
Scandium	<0.03
Silicon	<1
Silver	<0.2
Sodium	400
Strontium	3.6
Thorium	<1
Titanium	<0.05
Vanadium	<0.2
Yttrium	<0.03
Zinc	0.14
Zirconium	<0.10

Samples were filtered before analysis.

Reactor 6 Inorganic Analysis Results

Element	Day 1 Results	Day 4 Results	Day 8 Results	Day 12 Results	Day 15 Results
Aluminum	<1.5	<1.5	33	<1.5	<1.5
Arsenic	<3	<3	<3	<3	<3
Boron	0.6	0.6	0.4	0.3	0.2
Barium	0.36	0.30	0.40	0.19	0.19
Beryllium	<0.01	<0.01	<0.01	<0.01	<0.01
Calcium	8500	8500	7000	7200	7200
Cadmium	<0.10	<0.10	<0.10	<0.10	<0.10
Cesium	<1.5	<1.5	<1.5	<1.5	<1.5
Cobalt	<0.10	<0.10	<0.10	<0.10	<0.10
Chromium	<0.10	<0.10	<0.10	<0.10	<0.10
Copper	0.11	0.20	0.33	0.28	0.27
Gallium	<2	<2	<2	<2	<2
Iron	<0.3	<0.3	5.5	<0.3	<0.3
Lanthanum	<0.3	<0.3	<0.3	<0.3	<0.3
Lead	<1	<1	<1	<1	<1
Lithium	1.8	2.1	1.5	1.8	1.8
Magnesium	37	36	33	48	54
Manganese	0.08	0.05	<0.03	0.44	0.51
Molybdenum	<0.40	<0.40	<0.40	<0.40	<0.40
Niobium	0.5	0.5	0.4	0.3	<0.3
Nickel	<0.2	<0.2	<0.2	0.2	0.2
Phosphorus	8	7	5	8	6
Potassium	15	12	25	21	15
Scandium	<0.03	<0.03	<0.03	<0.03	<0.03
Silicon	6	10	5	18	16
Silver	<0.2	<0.2	<0.2	<0.2	<0.2
Sodium	380	380	360	360	350
Strontium	3.1	3.2	3.4	3.6	3.8
Thorium	<1	<1	<1	<1	<1
Titanium	<0.05	<0.05	0.7	0.5	0.5
Vanadium	<0.2	<0.2	<0.2	<0.2	<0.2
Yttrium	<0.03	<0.03	<0.03	<0.03	<0.03
Zinc	<0.10	0.12	<0.10	<0.10	<0.10
Zirconium	0.10	<0.10	1.0	0.24	0.44

Samples were filtered before analysis.

Reactor 6 Inorganic Analysis Results (Continued)

Element	Day 19 Results	Day 22 Results	Day 29 Results	Day 35 Results	Day 42 Results
Aluminum	5.8	15	7.1	22	28
Arsenic	<3	<3	<3	<3	<3
Boron	0.6	0.6	0.6	0.6	0.6
Barium	0.22	0.26	0.20	0.15	0.17
Beryllium	<0.01	<0.01	<0.01	<0.01	<0.01
Calcium	7900	8100	7300	6900	7100
Cadmium	<0.10	<0.10	<0.10	<0.10	<0.10
Cesium	<1.5	<1.5	<1.5	<1.5	<1.5
Cobalt	<0.10	<0.10	<0.10	<0.10	<0.10
Chromium	<0.10	0.11	<0.10	0.12	0.13
Copper	0.13	0.07	0.53	0.57	0.60
Gallium	<2	<2	<2	<2	<2
Iron	1.8	7.5	1.9	6.4	8.3
Lanthanum	<0.3	<0.3	<0.3	<0.3	<0.3
Lead	<1	<1	<1	<1	<1
Lithium	1.9	1.9	1.6	1.5	1.5
Magnesium	61	65	79	91	100
Manganese	0.32	0.55	0.36	0.41	0.48
Molybdenum	<0.40	<0.40	<0.40	<0.40	<0.40
Niobium	0.5	0.4	<0.3	<0.3	<0.3
Nickel	0.3	0.2	0.2	0.2	0.3
Phosphorus	6	5	6	6	6
Potassium	14	19	16	31	34
Scandium	<0.03	<0.03	<0.03	<0.03	<0.03
Silicon	12	7	16	19	18
Silver	<0.2	<0.2	<0.2	<0.2	<0.2
Sodium	370	380	390	370	370
Strontium	4.3	4.5	4.9	5.1	5.5
Thorium	<1	<1	<1	<1	<1
Titanium	0.19	0.21	0.49	0.59	0.76
Vanadium	<0.2	<0.2	<0.2	<0.2	<0.2
Yttrium	<0.03	<0.03	<0.03	<0.03	<0.03
Zinc	<0.10	<0.10	<0.10	<0.10	<0.10
Zirconium	0.93	1.1	1.1	1.2	1.3

Samples were filtered before analysis.

Reactor 7 Inorganic Analysis Results

<u>Element</u>	<u>Day 0 Results</u>
Aluminum	<1.5
Arsenic	<3
Boron	0.9
Barium	1.2
Beryllium	<0.01
Calcium	3700
Cadmium	<0.10
Cesium	<1.5
Cobalt	<0.10
Chromium	<0.10
Copper	0.88
Gallium	<2
Iron	<0.3
Lanthanum	<0.3
Lead	<1
Lithium	3.0
Magnesium	27
Manganese	<0.03
Molybdenum	<0.40
Niobium	0.5
Nickel	<0.2
Phosphorus	2
Potassium	59
Scandium	<0.03
Silicon	1
Silver	<0.2
Sodium	1800
Strontium	2.4
Thorium	<1
Titanium	<0.05
Vanadium	<0.2
Yttrium	<0.03
Zinc	0.12
Zirconium	<0.10

Samples were filtered before analysis.

Reactor 8 Inorganic Analysis Results

<u>Element</u>	<u>Day 0 Results</u>
Aluminum	<1.5
Arsenic	<3
Boron	1.1
Barium	0.01
Beryllium	<0.01
Calcium	8
Cadmium	<0.10
Cesium	<1.5
Cobalt	<0.10
Chromium	<0.10
Copper	0.50
Gallium	<2
Iron	<0.3
Lanthanum	<0.3
Lead	<1
Lithium	1.5
Magnesium	28
Manganese	<0.03
Molybdenum	0.40
Niobium	<0.3
Nickel	0.4
Phosphorus	5
Potassium	46
Scandium	<0.03
Silicon	1
Silver	<0.2
Sodium	1400
Strontium	0.08
Thorium	<1
Titanium	0.11
Vanadium	<0.2
Yttrium	<0.03
Zinc	0.11
Zirconium	0.13

Samples were filtered before analysis.

Reactor 9 Inorganic Analysis Results

<u>Element</u>	<u>Day 0 Results</u>
Aluminum	<1.5
Arsenic	<3
Boron	0.7
Barium	0.36
Beryllium	<0.01
Calcium	2400
Cadmium	<0.10
Cesium	<1.5
Cobalt	<0.10
Chromium	<0.10
Copper	0.13
Gallium	<2
Iron	0.3
Lanthanum	<0.3
Lead	<1
Lithium	5.5
Magnesium	81
Manganese	<0.03
Molybdenum	<0.40
Niobium	<0.3
Nickel	<0.2
Phosphorus	<1
Potassium	25
Scandium	<0.03
Silicon	6
Silver	<0.2
Sodium	530
Strontium	2.1
Thorium	<1
Titanium	<0.05
Vanadium	<0.2
Yttrium	<0.03
Zinc	0.12
Zirconium	0.13

Samples were filtered before analysis.

VITA

Timothy Byron Hale was born in Oak Ridge, Tennessee on April 30, 1958. He lived in Clinton, Tennessee and attended Clinton/Anderson County public schools until graduation from Clinton High School in June 1976. The following September he entered Tennessee Technological University, Cookeville, Tennessee, and in June 1980 received a Bachelor of Science Degree in Civil Engineering.

In June 1980, Timothy began full time employment with the Process Engineering Division of Union Carbide Corporation, Nuclear Division*, in Oak Ridge, Tennessee. Work activities included coordination of design of three industrial wastewater treatment facilities at the Y-12 Plant and RCRA Facility Investigation (RFI) plans in support of the Oak Ridge Gaseous Diffusion Plant Remedial Action Project. He is presently an employee of Martin Marietta Energy Systems, Inc.

While working with Union Carbide Corporation and Martin Marietta, Timothy pursued graduate studies at The University of Tennessee in the Evening School Program beginning January 1981. Requirements for a Master of Science Degree in Environmental Engineering were completed in August 1988. He obtained registration as a Professional Engineer in the State of Tennessee in 1985.

*DOE Contract was renegotiated in April 1984 and awarded to Martin Marietta Energy Systems, Inc.