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Recirculating sand filter design and operating criteria for removal of nitrogen from domestic septic tank effluent

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To the Graduate Council:

I am submitting herewith a dissertation written by Efrain Enrique Ruiz entitled "Recirculating sand filter design and operating criteria for removal of nitrogen from domestic septic tank effluent." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Biosystems Engineering.

C. Roland Mote, Major Professor

We have read this dissertation and recommend its acceptance:

L.R. Wilhelm, R.B. Robinson

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a dissertation written by Efrain Enrique Ruiz entitled "Recirculating Sand Filter Design and Operating Criteria for Removal of Nitrogen from Domestic Septic Tank Effluent." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Agricultural Engineering.

C. Roland Mote

C. Roland Mote, Major Professor

We have read this dissertation
and recommended its acceptance:

Bobby L. Bledsoe

Luther R Wilhelm

R Bruce Robinson

Accepted for the Council:

CW Minkel

Associate Vice Chancellor
and Dean of The Graduate School

RECIRCULATING SAND FILTER DESIGN AND OPERATING CRITERIA FOR REMOVAL OF NITROGEN FROM DOMESTIC SEPTIC TANK EFFLUENT

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Efrain Enrique Ruiz
December 1993

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ABSTRACT

A physical model of a recirculating sand filter (RSF) system was constructed to determine the ability of the system to remove nitrogen from domestic septic tank effluent and to learn the effects on the removal ability of the specific operating parameters depth of sand, recirculation ratio, loading rate.

The RSF system model consisted of a sand filter reactor, denitrification chamber reactor, and a polishing sand filter reactor. A research investigation was conducted with the help of twelve model units in which domestic septic tank effluent was treated on a continuous basis. Then, optimum and appropriate combinations of operating parameters were found and the systems were evaluated on the ability to remove mineral nitrogen, TOC, coliform and streptococcus bacteria.

To measure RSF system performance, water quality samples were collected weekly from the effluent of the three reactors and analyzed for concentration of several quality parameters. The samples collected were analyzed for concentrations of NH_3-N, NO_x^--N, TOC, and bacteria in the form of total coliform, fecal coliform, and streptococcus populations.

The research model units were successful in achieving biological treatment of domestic septic tank effluent. Prediction equations developed from model system data indicated that maximum mineral nitrogen removal for circulation factors (R) of 4 and 6, should be 73.69% at a sand bed depth of 16.50 cm and a wastewater loading rate of 40. 74 cm/day. Results revealed that an increase in circulation factor (R) from 4 to 6 produced no significant impact on the overall system mineral nitrogen removal efficiency.

In the recirculating sand filter reactor system, TOC removal responded significantly to variations in R value. For an R factor of 6, a maximum TOC removal efficiency of 80.70% at a sand depth of 17.00 cm and loading rate of 22.92 cm/day can be expected. The reduction of bacterial count in the RSF system model was in the order of 99%.

The investigation showed that redox potential and NO_3^--N concentration have a definite relationship. An estimate of the obtainable maximum NO_3^--N concentration can be predicted by measuring the redox potential in the DNC water. Measurements of redox potential below -150 mV gave indication of excellent denitrification potential with very high removal efficiency.

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CHAPTER 1

INTRODUCTION

PREFACE

The deterioration of environmental quality on our planet Earth, which began when human beings first collected into groups and utilized fire, exists as a serious risk under the ever-increasing impact of exponential growth of world population and of persistent industrialization of society. Environmental contamination of the ecosystem has become a threat to the continuance of many plants and animals including the human race. It seems apparent that if we are to sustain proper biological equilibrium for the world's population, and improve on the deteriorating standards of the earth's habitat, especially in relation to natural resources and public health, environmental sciences and technology must play a major role. The design and development of systems to maintain excellence in nature must be major goals for waste management work.

BACKGROUND

Evaluation of Sand Filter Systems for Nutrient Removal

Over the years, there has been concern about surface and groundwater contamination and questions of its effects on public health (Allen and Morrison, 1973). Recently, serious questions are being formulated about the effects of high nutrients in septic tank effluent systems on the quality of surface and groundwater (Siegrist, et al., 1984).

To overcome groundwater contamination, researchers have recommended several biological design criteria for on-site domestic wastewater treatment processes. One of those processes investigated by Hines and Favreau (1975) involved redesign of the old wastewater treatment technology of sand filtering. They found that the major problem with the established sand filter systems was the fact that when septic effluent was discharged onto the sand filter surface, a considerable odor problem was generated. The characteristic odors from septic waters are largely attributable to the release into the atmosphere of volatile organic compounds from the fermentative degradation of domestic wastewaters. These compounds are the normal end-products of anaerobic biological processes performed by bacteria. As the organic and inorganic matter are broken down in the septic tank, and when they are transferred into an open environment, some of these gas end-products are released to the atmosphere. Without further treatment these gases produce offensive odors. Now, if this pretreated wastewater is transferred to a second anaerobic biological environment (the first being the septic tank) such as a denitrification chamber (DNC)/recirculating tank, further biological degradation will occur and offencive odors reduced. Thus, to overcome the odor problems a recirculating sand filter (RSF) treatment system was developed by Hines and Favreau in Illinois in 1968. This system consists of a septic tank, a recirculation storage tank and an open recirculating sand filter (see Figure 1). In the RSF system, the pretreated wastewater from the DNC/recirculation tank is dosed onto the sand filter surface, eliminating the odor problem. The RSF system was designed to be coupled to a traditional septic tank for use with conventional subsurface absorption systems. Hines and Favreau also found that the RSF system provides efficient means for on-site domestic waste treatment to be used in areas where absorption fields can not function properly or where space is limited. They observed several operating recirculating sand filter systems that consistently produced effluent that met discharge standards.

The significance of mixing recirculating effluent from the sand filter back with septic tank effluent, up stream of the DNC/recirculation tank, is that by this method oxidized ammonium

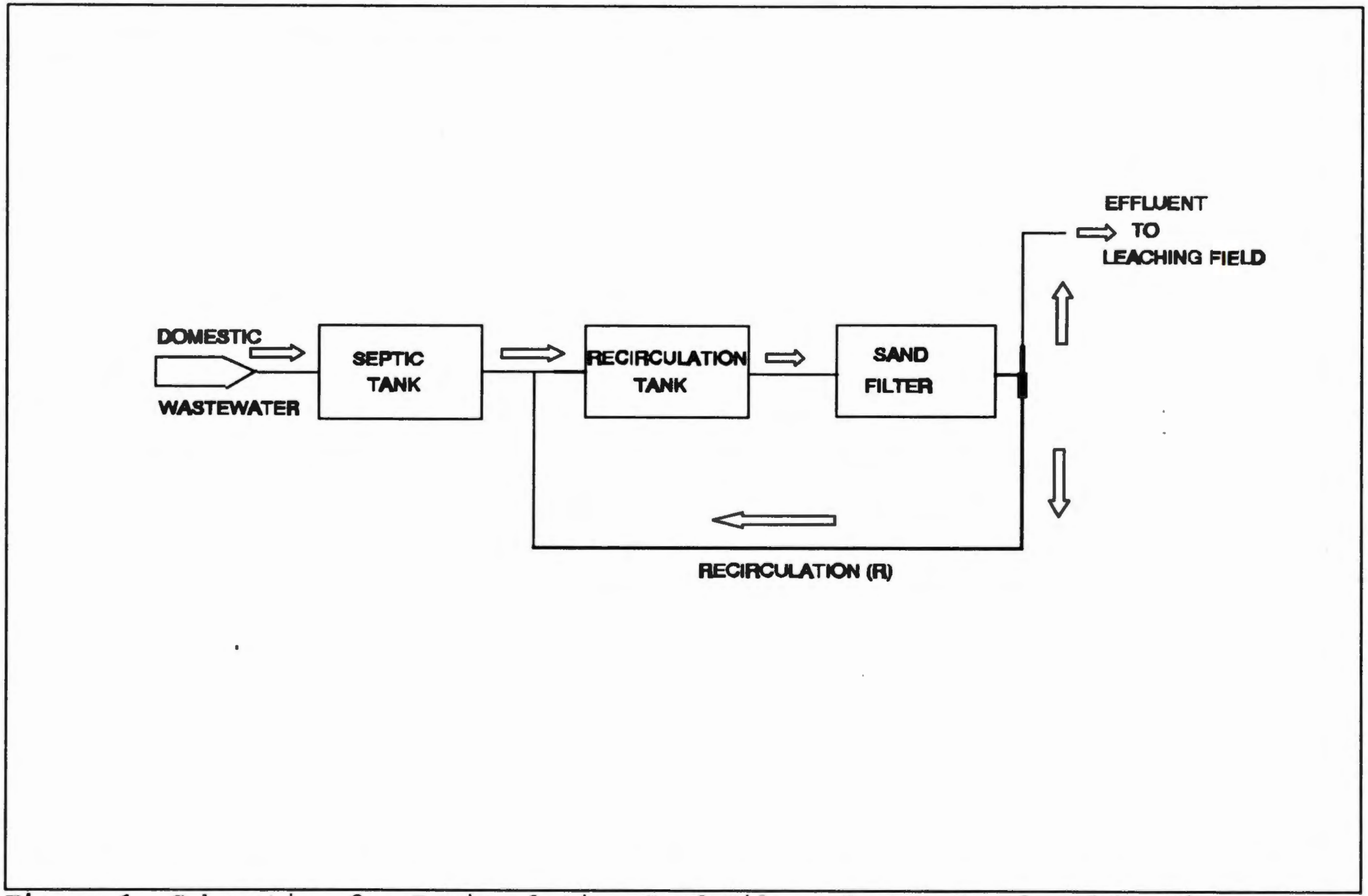

Figure 1. Schematic of a Recirculating Sand Filter System Developed by Hines and Favreau.

compounds (i.e, Nitrate) will be subjected to the denitrification process in the anaerobic environment. If the recirculating sand filter effluent is mixed down stream of the DNC, the process of nitrogen removal will not occur for all effluent due to the fact that some of the nitrate-containing water the part that is not recirculating at all, will never experience the anaerobic environment necessary for denitrification.

In an investigation by Piluk and Hao (1989), a more reliable method of pollutant control was developed by incorporating a polishing sand filter at the discharge of a typical RSF system. A sand filter is used to nitrify the recirculating effluent exiting the DNC tank, and the nitrified effluent flow is then mixed with the septic tank effluent at the entrance of the DNC. A portion of the denitrified effluent exiting the DNC is loaded onto the surface of a polishing sand filter for bacterial reduction and further treatment in an aerobic environment, before final discharge is accomplished into the absorption field system (see Figure 2).

Recirculating sand filter systems are alternatives which are ideally suited to rural communities, small clusters of homes, individual residences and business establishments. These systems are aimed to be means of disposal and treatment of wastewater; the goal is to convert the waste materials present in wastewater into stable oxidized end products, which can be safely discharged to ground waters without any adverse

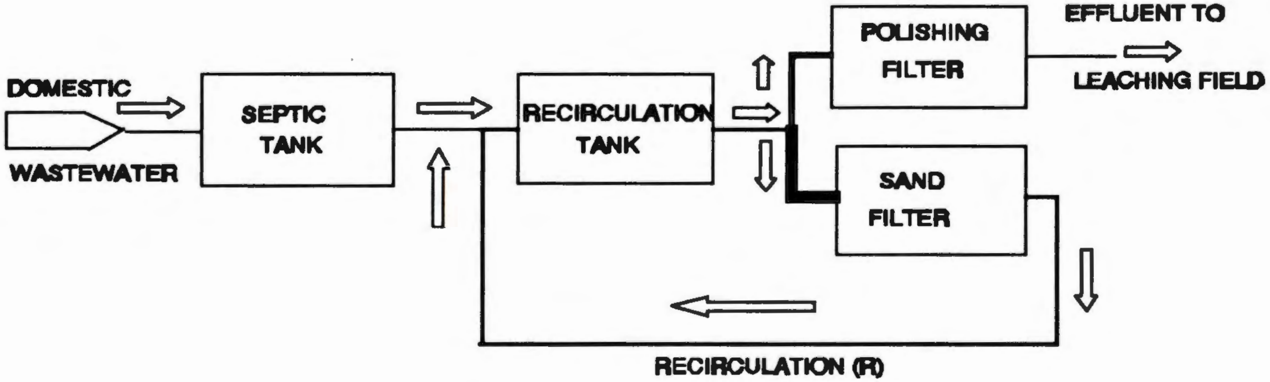

Figure 2. Schematic of a Recirculating Sand Filter System with a Discharge Polishing Filter.

environmental effect. This technology for nitrogen removal in individual on-site systems is relative untested, so, better definition of parameters and interactions are needed (R. W. Whitmyer, et al. 1991).

Despite the long historical use of a great diversity of on-site wastewater disposal systems, and their wide implementation, performance capabilities in system use have not been fully understood. There is a need to optimize and better understand the mechanisms and relationships between design parameters and performance capabilities to lower costs and increase removal efficiencies. The optimal relationship between RSF system parameters and performance capabilities can be found by operating a scaled model system, with findings then incorporated into full-scale systems to remove nitrogen from domestic septic tank effluent.

OBJECTIVE

The purpose of this study was to use laboratory-scale models of a recirculating sand filter system to develop design and operating information for the removal of nitrogen from domestic septic tank effluent. The specific objective was:

> Determine the relationship among septic tank effluent loading rate, recirculation ratio and depth of sand in the filter for optimum removal of nitrogen from domestic septic tank effluent.

CHAPTER 2

PROCESS DEVELOPMENT AND LITERATURE REVIEW

PRINCIPLES OF NITROGEN REMOVAL

The purpose of biological treatment of wastewater is to reduce the organic content including, to some extent, nutrients, such as nitrogen and phosphorus compounds. In biological wastewater treatment, the most widely occurring and abundant group of microorganisms are the bacteria. It is largely this group which utilizes organic matter and nutrients present in wastewater effluent. Nitrogen occurs in many forms in wastewater and undergoes numerous transformations in a biological wastewater treatment process. These transformations convert ammonia-nitrogen to products that can easily be removed from the wastewater.

The two principle mechanisms for the removal of nitrogen from wastewater are: 1) assimilation and 2) nitrification-denitrification. Nitrogen removal in a RSF system occurs by these two well defined biological-treatment processes, both in the same type process unit, the attached-growth or fixed-film unit. The attached-growth process unit is one in which the microorganisms responsible for conversion of organic matter or other constituents in the wastewater to gases and cell tissue are attached to some inert medium such as sand, rock or plastic media. The required contact between the biofilm and the wastewater is achieved by allowing the wastewater to pass over the stationary medium in which the microbial film has developed. Because nitrogen is a nutrient, in the first (assimilation) mechanism microbes present in the biofilm will convert or assimilate ammonia-nitrogen compounds and incorporate them into cell mass. In the second mechanism (nitrification-denitrification), ammonia is converted to nitrate (ammonia oxidation); then the resulting nitrate is converted to free nitrogen gas (nitrate reduction) by action of bacteria in the biofilm (Gold et al. 1985).

Biological Assimilation

The first process or biological assimilation (microbial cell formation) removes little nitrogen. This is because there is low bacterial growth; also a portion of the ammonia-nitrogen converted to cell mass will be returned to the wastewater at death of the microbes and lysis of the cells. In assimilatory denitrification, nitrate is reduced to ammonia, which then serves as the nitrogen source for cell synthesis and maintenance (Bliss and Barnes, 1979; Seidel and Crites, 1970). Synthesis of bacterial cellular mass occurs in all areas of a typical recirculating sand filter system: aerobic recirculating sand filter reactor, aerobic polishing sand filter reactor and anaerobic denitrification chamber

(DNC/recirculation tank) reactor. The biological activity in the RSF system is regulated by the substrate (organic carbon and nutrients) utilization of bacteria attached to the support media. In terms of substrate removal, the rate of carbonaceous oxidation and nitrogen assimilation depends on the rate of microbial growth (Williamson and McCarty, 1976; Gullicks and Cleasby, 1986). Due to the mixed trophic levels (heterotroph and autotroph) of bacteria population in the RSF system, substrate (organic and nutrient loading) and oxygen (ventilation/aeration) utilization are also regulated by the type of microorganisms present.

Nitrifying bacteria (Nitrosomonas and Nitrobacter) are microorganisms with a very long generation time (Gee and Pfeffer, 1990). The low energy yield from the oxidation of ammonia results in low cellular mass production in the sand filter reactor. Also, low formation of microbial cell in general occurs in attached growth systems with either aerobic or anaerobic environments (Young and McCarty, 1967). The limitation of food and energy moving across the slime layers slows down the synthesis of cellular mass. Also, because facultative microbial yield under anoxic conditions is considerable lower than under aerobic conditions, less cytoplasmic material is produced in the DNC reactor. Therefore, nitrogen as nutrient for bacterial cell synthesis will be utilized in lesser quantities in the anaerobic reactors, thus producing a lower potential for assimilatory nitrogen removal in sand filter recirculating systems.

There are biological treatment systems, such as the activated sludge process, where high amounts of nitrogen removal can be accomplished by assimilatory denitrification, but with production of large quantities of organic matter in the form of microbial cells. The bacterial cells produced present a sludge handling problem since they must be removed from the system. It is important to note that unless the cell tissue that is produced from the nitrogen and organic assimilation is removed efficiently from the solution, complete treatment has not been accomplished in the system. Therefore, for on-site domestic disposal, systems that will remove nitrogen with a low cell synthesis rate are attractive from a simplicity of management point of view.

Biological Nitrification-Denitrification

The second process for biological nitrogen removal is nitrification-denitrification; that is the formation of nitrate followed by the conversion of the nitrogen in the nitrate to nitrogen gas (also called denitrification), with a greater nitrogen removal potential than the assimilation process (Gayle, et al., 1989). Nitrate reduction obtained in RSF systems is the major pathway for biological nitrogen removal and can be accomplished under "anoxic" (absence of oxygen) conditions. The process of nitrate reduction consists in the biological oxidation of ammonia to nitrate and then to nitrogen gas as the end-product. The ammonia is oxidized to nitrate in the sand filter reactor, then, it discharges to the DNC/recirculation tank where the nitrate is reduced to nitrogen gas and released to the atmosphere. For complete nitrogen removal in a RSF system, total ammonia oxidation and nitrate reduction must occur in the sand filter and DNC/recirculation tank reactors respectively. No nitrate must exit in the circulating water. Thus, denitrification will be carried out with a very high potential for removal efficiency. Typically, 90 percent of the nitrogen present in domestic septic tank effluent is in the form of free ammonia or unstable organic compounds, which are readily transformed to ammonia. Some nitrogen is removed by cell synthesis, some is discharged from the system, and another portion is removed by nitrate reduction to nitrogen gas in the RSF system (Ball, 1991; Lamb et al.,1987). Therefore, recirculating sand filter systems, as on-site domestic wastewater treatments, have a significant potential for removal of nitrogen from domestic septic tank effluent.

RECIRCULATION RATIO

Significance for Nitrogen Removal Potential

Recirculation ratio (R) in a RSF system can be defined as the ratio of the total flow across the sand filter to the forward discharge flow from the system. Recirculation ratio in RSF systems is important because by recirculating a portion of mixed domestic septic tank effluent back to the filter system, wastewater will be allowed to remain a longer time in contact with the bacteria. Figure 3 shows the typical schematic representation of a unit RSF system. This principle of recirculating a portion of the effluent from the DNC to the sand filter will permit an extended biological treatment for the processed wastewater. Recirculation ratio sets the real residence time in the reactor for a larger portion of the wastewater (it is there more than once). Higher opportunities for the substrate to return to the biological reactor system will give occasion for the bacteria to remove potentially a greater portion of the organic and nutrient compounds present in the domestic septic tank effluent.

Complete nitrogen removal will not be accomplished in the treatment process, since with constant throughput for the system an amount of wastewater equal to the input loading, but which has been diluted in the DNC, will be discharged through the polishing filter, maintaining steady state flow. Consequently, nitrogen, organic or inorganic, must be discharged out of the recirculating sand filter system. Under steady state conditions, the diluted water discharged onto the polishing filter must contain a minimum nitrogen concentration as a direct function of the influent concentration and the inverse of the recirculation ratio (1/R); that is, the influent raw water concentration divided by the recirculation

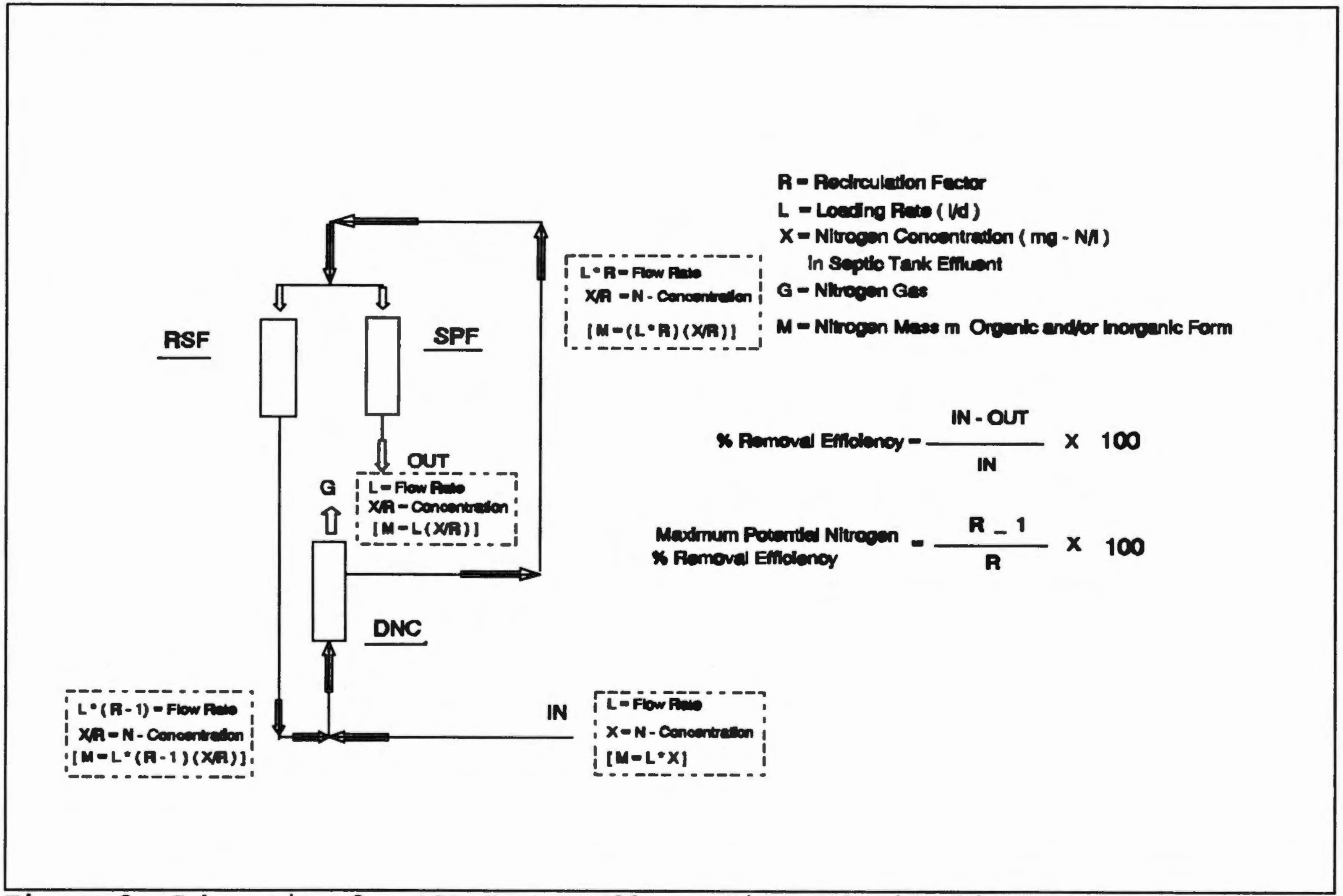

Figure 3. Schematic of a RSF System Illustrating Relationships Between R and Potential Nitrogen Removal.

ratio (R). Setting R not only fixes the theoretical minimum amount of nitrogen exiting the system, but also specifies the theoretical efficiency of the biological nitrogen removal. Figure 3 illustrates the principle of recirculation and theoretical removal potential in a recirculating sand filter system.

Process analysis

In predicting the theoretical performance of nitrogen removal of a RSF system, the nutrient loading (nitrogen) and the degree of treatment (maximum efficiency) are the important factors that must be considered. In the following discussion, the theoretical mass-balance approach was used in the modeling of a recirculating sand filter system process in terms of nitrogen removal from domestic septic tank effluent.

Using Figure 3, we can describe the total nitrogen concentration difference encountered in the liquid volume at the discharge of the polishing filter. Assuming that there is a biological nitrification-denitrification process in the RSF system, the concentration depletion must be calculated from the influent load of total nitrogen mass entering the DNC reactor and the load of total nitrogen mass that comes out of the discharge filter.

1. General consideration:

The following mass-balance relationship is developed assuming steady state conditions in the RSF model.

Depletion N mass in system = Mass of N into the system - Mass of N out of the system - Mass of N assimilated by bacteria

where N considers all forms of nitrogen (organic or inorganic) present in the water.

2. Simplified consideration:

Depletion = Inflow - Outflow - Assimilation

3: Symbolic representation:

(Depletion)mg-N/liter+(Assimilation)mg-N/liter=(In)mg-N/liter -(Out)mg-N/liter

4. Simplified representation:

(Depletion + Assimilation) mg-N/liter = ($\mathbf{Total_{IN}}$) mg-N/liter -($\mathbf{Total_{OUT}}$) mg-N/liter

The above analysis presents the mass-balance equation which in turn illustrates the general depletion of nitrogen in the model system.

For a recirculating sand filter system, the theoretical nitrogen removal potential as a function of recirculation factor (R) can be expressed with an equation which takes into consideration all nitrogen forms (organic and inorganic) entering and leaving the entire system. This development is shown in the following procedure (refer to Figure 3):

$$\%\ REMOVAL = \frac{TotalN_{(INFLUENT)} - TotalN_{(EFFLUENT)}}{TotalN_{(INFLUENT)}} * 100 \quad . \qquad (1)$$

where:

$$\text{Total Nitrogen}_{\text{Influent}} = (L)*(X) = (l/day)*(mg\text{-}N/l)$$

$$\text{Total Nitrogen}_{\text{Effluent}} = (L)*(X/R) = (l/day)*[(mg\text{-}N/l)/R]$$

by canceling the L and X terms, the following equation is developed:

$$\%\ REMOVAL = \frac{R-1}{R}*100 \qquad (2)$$

Equation 2 shows theoretical nitrogen removal efficiency as function of R.

If we consider R equal to 2 recirculations, the maximum nitrogen removal efficiency for the system will be 50 percent. Now, if R is equal to 8 recirculations, then the removal efficiency for the system will be 87.5 percent. Recirculation at higher R produces a greater theoretical nitrogen removal potential, thus suggesting that maximum nitrogen removal requires high recirculating ratios.

In an investigation conducted by Jimenez et al. (1987) of design considerations for a biological nitrogen removal in a bench scale system, they concluded that the efficiency of nitrogen elimination in a recirculating sand filter system is a function of the recirculation ratio. Their findings were that for low denitrification efficiencies there was an increase in the oxidized nitrogen (NO_3^--N) concentration in the effluent, while increasing the recycle ratio decreased the effluent nitrogen concentration. With a recirculation ratio

(R) of 2, the oxidized nitrogen in the effluent was 12.0 mg N-NO_3^-/l, while for an R of 3.5 the oxidized nitrogen in the effluent was 6.8 mg N-NO_3^-/l. In a prototype study of a partially saturated recirculating sand filter, Mote et al. (1991) demonstrated that recirculation ratio is critical to the ability of the system to remove nitrogen. They found that for an initial recirculation ratio of 4.4 that was then increased to 7.3, there was an average nitrogen system removal efficiency of 71% and 83% respectively.

Significance for Actual Nitrogen Removal

Although high recirculation ratio enable high nitrogen removal potential, high recirculation ratio can also lead to environmental conditions which limit nitrogen removal in a recirculating sand filter system. Since nitrification (aerobic sand filter reactor) and denitrification (anoxic DNC/recirculation tank reactor) are the main pathways for biological nitrogen removal, factors controlling or limiting these processes control nitrogen removal. The process of ammonia oxidation can be negatively affected by too high a recirculation ratio. Water circulating too frequently through the recirculating sand filter can reduce natural media aeration by increasing the duration of water-filled pore conditions. When wastewater volume occupies the free spaces between the sand grains, air will not be permitted to enter. Oxygen will then be absent, converting the aerobic environment to an anoxic one (Metcalf and Eddy, 1979). This type of condition will not be appropriate for the nitrification process to take place.

Recirculation ratio not great enough to restrict aeration might also be detrimental in that the circulating water might become overly aerated. Water circulating through an aerobic environment might aerate (increase dissolved oxygen content) the circulating water to a level where anoxic conditions can be destroyed in the receiving DNC reactor. As the wastewater percolates downward through the sand depth, the oxygen present in air in the void space is absorbed by the passing water. Then, the dissolved oxygen (DO) which is carried on by the wastewater will be discharged into the denitrification cell, thus adding oxygen to a reactor with a desired anoxic environment. At this point, the anoxic environment is changed to an aerobic one. At higher dissolved oxygen concentration, the facultative bacteria will shift electron acceptors from NO_3^- to O_2 during the respiration process, letting the nitrate ions pass freely to the discharge system (Wilderer, et al. 1987). If the DNC/recirculating tank is not maintained in an anoxic environment (absence of oxygen), reduction of nitrate to nitrogen gas will be impossible.

MEDIA DEPTH

The effect of media on performance of a recirculating sand filter system is generally related to the specific surface area of the media to which bacteria are attached. An adequate amount of properly sized media will give sufficient surface area for support of the microbial slime and enough space between the particles for free flow of the wastewater. In nitrification, the oxidation rate of ammonia is affected by biofilm accumulation, as well as oxygen availability. Although depth may not be a direct factor in controlling filter performance, total available surface area obviously is. But, in order to maintain a specific amount of surface area within a reactor with a given cross sectional area, media depth must be properly established.

A nitrification process must occur in the sand filter as a first step for the ultimate nitrogen removal in the system. This process consists of the oxidation of ammonium to nitrite and then to nitrate by autotrophic bacteria in an aerobic environment. A sand filter of too little media volume might give conditions of not enough grain surface area to support the nitrifying bacteria. This in turn would negatively impact the efficiency of the sand filter to oxidize ammonium compounds to nitrite and nitrate. Also, too little sand volume, at shallow depth, might shorten the time available for the substrate to be in contact with the nitrifying microorganisms, thus diminishing nitrification. Both sufficient numbers of nitrifying bacteria and adequate detention time in the aerobic filter are required for effective production of nitrate. If nitrate is not supplied to the anaerobic DNC reactor, the overall system-nitrogen-removal efficiency will be impacted negatively.

Sand filter of too much sand depth can affect negatively the process of denitrification. Here, the circulated wastewater through the sand filter takes oxygen from the aerated column and mixes it in the DNC reactor increasing dissolved oxygen content in the anoxic environment. As anoxic conditions are decreased in the DNC cell, denitrification will be impossible. So, too much sand depth will have a negative impact in the overall system-nitrogen-removal efficiencies.

RECIRCULATION RATIO AND MEDIA DEPTH INTERRELATIONSHIP

Recirculation ratio sets the theoretical removal efficiency potential in a recirculating sand filter system and, since depth of the sand filter reactor affects the process of nitrification-denitrification; these two parameters, recirculation and sand depth, are theoretically interrelated. As recirculation ratio increases, sand depth must decrease to the point where environmental conditions in the denitrification chamber will not be changed. That is, aeration in the DNC might occur with increased circulation, thus, to eliminate this condition the sand filter requires shallower media. Now, if recirculation ratio is reduced, the options for contact between wastewater and active biofilm are minimized, then longer depth for extended intimate contact time must be required.

WASTEWATER LOADING

Loading Rate

Bacteriological processes are performed by living microorganisms (i.e, bacteria) which need energy and nutrients for their growth and support. Heterotrophic microorganisms (i.e., denitrifiers) utilize the organic matter and nutrients, present in the domestic septic tank effluent, for the production of energy by cellular respiration and for the synthesis of protein and other cellular components in the manufacture of new cell tissue. On the other hand, autotrophic (i.e., nitrifiers) bacteria use carbon dioxide or bicarbonates as source of carbon and use oxygen for respiration and production of energy. In terms of pollutant removal, the rate of the oxidation-reduction process, nitrification and denitrification, depends on the rate of microbial growth in each particular reactor.

Since the main pathway for nitrogen removal in a RSF system occurs by nitrification and denitrification processes, and since those processes are conducted by different bacterial populations located in different environmental conditions, the energy and carbon source requirements for each process are also different. The removal efficiency of nitrogen from wastewater is linked to the bacterial population of the growing film. This biofilm in turn is controlled by the availability of food and energy supplied to the support media through the hydraulic loading.

An excessively high organic loading rate will affect negatively the nitrification process in the sand filter. By increasing organic load, the heterotrophic bacterial growth will predominate, consuming the available molecular oxygen for their aerobic respiration. As the wastewater circulates to the sand filter, high hydraulic loading might approach a condition of ponding, where large accumulation of microbial film can over populate the surface of the sand filter. Also the surge of wastewater ensures more distribution of substrate and nutrients within the filter bed, extending the depth of heterotroph activity and encouraging a more abundant and even distribution of biofilm. This overgrown production of heterotroph bacteria will make it more difficult for the nitrifiers to compete for space and thus have a reduced growth rate in a competitive condition. The high demand for oxygen will limit the oxygen content in the filter reactor, destroying the habitat for the nitrifiers which are strict aerobes. In consequence, the conditions for nitrification will be impossible.

Bacterial physiology is an important consideration in biological denitrification and is a function of feed rate and feed composition (Polprasert and Park, 1986). High organic loads in the DNC reactor will increase the growth of heterotrophic bacteria and other range of trophic levels (i.e, anaerobic bacteria) to the point where the system will have bacteria overgrowth. This condition accelerates filter clogging, which will cause a collapse in the DNC reactor ceasing the treatment process.

On the other hand, too low organic loadings will limit the heterotrophic bacterial growth in the DNC reactor affecting negatively the denitrification process. Here, the denitrifying bacteria will be growth limited making nitrogen removal minimal and sometimes impossible. For the nitrification process (recirculating sand filter reactor), too low organic concentrations will diminish nitrate formation. Competition between heterotroph and nitrifiers (autotroph) can occur at somewhat too low an organic concentration and result in a partial reduction of nitrification performance (Guillicks and Cleasby, 1986).

No direct reference was found in the literature concerning applied hydraulic loading rates to the DNC reactor in a RSF system. Most of the data found in the literature refers to hydraulic loading related to the volume of wastewater applied onto the sand filter surface over a specified period of time. Hydraulic loading rate is typically expressed as gallons per day per square foot (gpd/ft^2), or as centimeters per day (cm/day). Hines and Favreau (1975) recommended that a RSF system should be designed on the basis of the raw sewage loaded to the recirculating tank and not on the recirculating flow. A DNC loading rate of 300 gallons per day (3 gpd/ft^2) was presented in their system designed for a single family residence. Also a minimum sand area surface of 100 ft^2 (10′X10′) was recommended for serving the recirculating sand filter.

Dose Volume

For a RSF system, the method of application and dose volume of the septic effluent into the DNC is very important for the nitrate reduction process. At DNC loading, the dose of raw wastewater is discharged into the bottom of the DNC, via a submerged pipe, where the wastewater flows upward through the column. This mode of operation facilitates a considerably higher build up of biomass in the DNC compared to the downflow mode. The upflow mode enhances separation of the suspended slime, which then agglomerates in the interstices and attaches to the surface media allowing greater accumulation of biological mass in the reactor.

Readily degradable organic carbon must be supplied in the correct amount to the DNC reactor to serve as an energy source for bacterial metabolism and growth. This organic carbon promptly supplied is also required for aerobic respiration in the presence of molecular oxygen. Any dissolved oxygen will be depleted as aerobically-facultative organisms oxidize the readily degradable carbon. Depletion of oxygen is essential for maintenance of an anoxic environment. When a large dose of septic effluent is applied infrequently (longer time between doses), the amount of organic carbon available (food supply) in the influent water will be readily utilized by the bacteria in an unrestricted growth rate. The substrate conversion is at its maximum rate during this period. Carbon is simultaneously used as a reducing agent in the nitrate reduction. In time, the bacteria will reproduce through cell division increasing the microbial population which metabolize the food supply at a faster rate. As the concentration of the carbon source declines, cell growth rate will decrease until the substrate is depleted. Then, the microbial population will start endogenous respiration with a high bacterial death rate. At this instant the rate of denitrification starts to decline and perhaps reaches a point when nitrate reduction ceases.

Since the overall effect of the denitrification reaction is to raise the wastewater pH by the formation of hydroxide ions, these ions replace part of the alkalinity consumed by the oxidation of ammonia during the process of nitrification; also part of the positive ion reduction is replaced by carbon compounds present in the septic effluent. The denitrification reaction is pH-sensitive; as the system proceeds in the reduction of nitrate, the carbon source has to be readily added to maintain conditions and source of the reducing agent. As the alkalinity is exhausted during the process, the pH will begin to decline in the DNC as will denitrification (McCarty, 1970). Thus, at DNC loadings of large dosages too infrequently spaced, the overall effect on nitrogen removal efficiency might be detrimental.

If high frequency, small dose volumes of septic effluent are loaded, the system will reach a condition of continuous and stable performance for the biological process to occur. The source of organic carbon will be regularly supplied to the DNC, maintaining a mode of exponential growth phase in the microbial population. This condition will produce a steady state microbial generation, where the rate of metabolism and, in particular, the growth rate is limited only by the microbial generation and its ability to process substrate. It is expected that the rate of reproduction and bacteria depletion will be maintained balanced in this type of system. As the substrate is processed, the carbon reducing agent will be maintained for the nitrate reduction; in addition, alkalinity will also be formed to counterbalance the pH abatement due to nitrification. This type of system will have good performance for nitrogen removal in a RSF system, since bacterial growth and environmental conditions will be conserved in time without oscillative peaks. Therefore, dosing frequency must consider both maximizing the nutrients supply and adequately maintaining alkalinity.

The purpose of recirculation in a RSF system is to enhance nitrogen removal efficiency. If the recirculating nitrified effluent is readily mixed (in phase) with the loading dosage coming from the septic tank, the mixture of water entering the DNC will facilitate a better contact performance of all the elements involved in the nitrate reduction process. A more efficient biological treatment will be accomplished. In contrast, if nitrate recirculating effluent opposes the septic tank effluent loading on a half cycle situation (out of phase), the biological system might present a contact imbalance between all the elements required in the biological process of nitrate reduction. This condition reduces the optimum removal of nitrogen in the system. That is, nitrate, and substrate will not be readily available in time, making it more difficult for the bacteria to perform proficiently.

From the above analysis, for on-site systems receiving wastewater from a typical single family residence, some constraints can be encountered due to loading frequencies. Variation of domestic wastewater flow rates occurs on and during 24 hour period. Minimum flows occur in the early mornings; peak flows occur around noon and also late afternoons. These peak volumes will affect the environmental condition of the DNC receiving tank. Thus, some flow regulation for effluent leaving the septic tank is required for practical and efficient operation of a recirculating sand filter system.

SUMMARY

Recirculating sand filter (RSF) systems are frequently chosen for small wastewater treatment facilities, especially where soil conditions are not suitable for the conventional subsurface disposal system. Typical RSF systems accomplish excellent organic removal and often achieve a high degree of ammonification. Unfortunately, these systems are known to release undesirable levels of nitrogen contamination to surface and ground waters due to the low efficiency of the RSF systems in removing nitrogen.

The need for better understanding of mechanisms contributing to the good performance of RSF systems in disposing of effluent nitrogen contamination led to the present investigation.

This research centered around obtaining more complete understanding of the complex inter-relationships that exist among the principal operating parameters that directly affect efficient nitrogen removal by recirculating sand filter system. These parameters are sand filter depth, recirculation ratio and loading rate. Selection of the appropriate optimum combination of these parameters will give maximum efficiency

to an RSF system in removing nitrogen from domestic septic tank effluent. With capability to efficiently remove nitrogen, these systems can play an important role as septic treatment systems serving rural-residential developments.

CHAPTER 3

METHODS AND MATERIALS

DESCRIPTION OF THE RSF RESEARCH SYSTEM

Twelve laboratory bench scale units of a RSF system modelled nitrogen removal from domestic septic tank effluent. Each unit operated with a different combination of the operational parameters depth of sand filter (**SD**), recirculation ratio (**R**) and loading rate (**LD**).

Wastewater obtained from a domestic septic tank was used continuously in the experiments. During the time of research, five to seven containers of 20 liters capacity were filled and brought directly from a septic tank site twice a week, on Tuesdays and Fridays, and stored in a refrigerator at approximately 4^0 C until needed. As tank space demanded, they were emptied into the holding tank for transferring to the research units.

The domestic septic tank effluent was conveyed from the refrigerated container into the DNC reactors at timed intervals. Each loading interval was divided into 13 different timed dosages, controlled by electric signals, which sequentially loaded the DNC cell of each model unit with the appropriate dosage level of effluent through solenoid valves and associated hoses. The thirtenth dosage was collected as the control sample of raw wastewater. The loading cycle was repeated at 15 minute intervals throughout a 24-hour day; that is, each model unit was loaded 96 times in a 24-hour day. A low rate (2.17 liter/hour) chemical metering loading pump (LP) was adapted to feed the domestic septic tank effluent into the reactor cell of each test unit (see Figure 4). A normally closed solenoid valve (LV) was energized permitting the designated amount of raw wastewater to be loaded, through the plastic hose, into the inlet pipe of each model unit DNC cell. The input dosage of raw wastewater was diluted in the inlet pipe by treated recirculation effluent from the recirculating sand filter cell. From the upper water level of the partially filled vertical loading pipe, the wastewater delivered, now diluted with recirculation effluent, drained freely to the bottom of the DNC cell. Then, the diluted dosage, after passage throughout the bottom of the loading pipe, travelled "up-flow" across the biological fixed film medium. A portion of the treated wastewater from the upper level of the DNC cell was transferred by a metering pump (CP) through a plastic hose to a position on the surface of the recirculating sand filter for a gravity release. This volume of recirculating water, (septic loading rate)*(R-1), was transported from the DNC to the recirculating sand filter by means of a 9.84 liter/hour chemical metering pump (CP). After this, treated wastewater, with a volume equal to septic loading dosage,

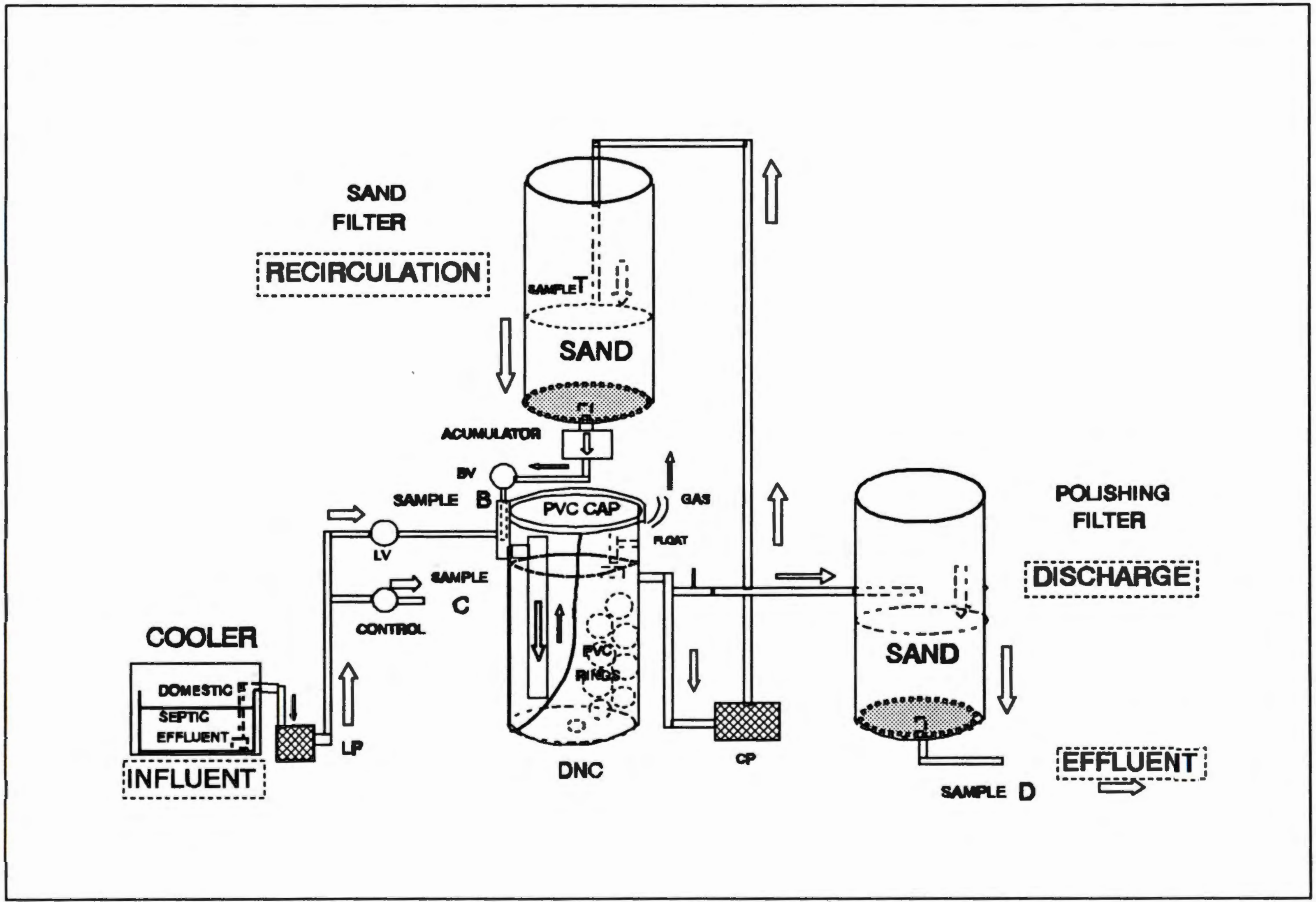

Figure 4. Recirculating Sand Filter System Model Unit Components.

overflowed the DNC and was conveyed by gravity onto the polishing filter for further treatment and finally released to the drain pipe.

When the recirculated wastewater drained from the recirculating sand filter, a normally open solenoid valve (BV), which is located below the accumulator tank, temporarily stopped the flow of water advancing toward the DNC cell. This valve was closed every time pump CP was energized and commenced the transfer cycle, which allowed the nitrified water to remain in the accumulator tank while all the accumulated volume was pumped out of the DNC cell. A float switch stopped the pump when all the water volume contained above the DNC fixed level was pumped out; in addition, the valve BV was opened when the timed cycle elapsed. The normally open valve, when de-energized, allowed the nitrified effluent to return to the DNC reactor, where it blended with the existing water when it penetrated through the vertical submerged pipe. As the nitrate and nitrite moved "up-flow" in the supported biological media, the nitrate reduction process was developed inside the reactor, releasing nitrogen gas which flowed to atmosphere through the vented loading openings of the loading port and the loose spaces present in the PVC cap on the reactor cell.

After the RSF dosing pump action, when the volume of treated wastewater (equal to the load dosage) overflowed the DNC fixed level, it moved across the polishing filter achieving further treatment of organic and bacterial removal. Also ammonia oxidation was performed in the water percolating through the polishing sand filter. Both sand filters, recirculating and polishing, operated in parallel such that a continuous, pulsed steady state flow occurred through both sand filter cells of each model unit.

DETAILS OF TEST UNIT EVALUATION

The RSF system units were operated continuously for 12 month (June 23, 1992 to June 8, 1993). Treated wastewater samples were collected at three different ports for each of the 12 research units comprising the experiment. Location of those ports were: at the exit from the sand filter, at the discharge of the polishing filter and at the exit from the denitrification chamber (designed as B, D and T ports in Figure 4). One additional sample of untreated septic tank effluent was obtained at the middle of the loading manifold (C port) for control purposes.

All the samples, 37 per collection, were analyzed in the laboratory for total organic carbon (TOC); nitrogen in the forms of ammonia, nitrate and nitrite; bacteria populations in the forms of fecal coliform, total coliform and fecal streptococcus. Analysis of phosphorus in the forms of PO_4^{3-} and chloride was also performed on the collected sample. The concentration analysis conformed to the standard methods for automated analysis described in the Standard Methods for the Examination of Water and Wastewater (American Public Health Association, 1985).

Ammonia-nitrogen concentrations were performed with the Thechnicon Autoanalyzer II. Concentrations of NO_x^--nitrogen, PO_4^{3-}-P and Cl^- were performed with the EPA Method #300.0 with Ion Chromatography and with Chemical Suppression of Element Conductivity. The concentration of total organic carbon (TOC) was determined with the Persulfate-Ultraviolet Oxidation Method, Examination of Water and Wastewater (American Public Health Association, 1985). The measurement of organic nitrogen was not possible due to laboratory difficulties. For this reason data values for organic nitrogen concentrations were not available.

Bacterial populations were determined using the Membrane Filtration Technique procedure described in the Standard Methods for Examination of Water and Wastewater (American public Health Association, 1985).

A measure of the redox potential (E_h) was taken with a platinum electrode on the top (5 cm depth) of DNC liquid level for each of the 12 reactor units. The method used was as described by Dirasian (1968). A platinum electrode prepared with Ag/AgCl reference electrode filling solution was used to determine the redox values. The electrode was connected to a portable digital voltmeter where direct readings were observed in mV and then recorded. The electrode response was standardized against a solution of known redox potential values (237 to 238 mV and 306 to 307 mV) before each measurement was taken.

In practical terms, the E_h is used to indicate whether oxidation or reduction occurs within a wastewater system and is particularly useful in the management of anaerobic systems. In water, redox potential measured in mV gives an indication of the dissolved oxygen present in the water and reflects the aerobic or anaerobic condition (Quispel, 1946). Anaerobic processes for the treatment of sludge (lagoon and digester systems) have low values of E_h (<-450 mV), whereas aerobic processes have much higher values (>+50 mV). Values of E_h -150 mV to -420 mV are found in anoxic environments, whereas aerobic environments vary between -150 mV to +420 mV.

Facultative bacteria shift from oxygen bound compounds (i.e, NO_3^-) to molecular (O_2) in environments with redox conditions greater than -150 mV to about +100 mV (Gray, 1989). Smith et. al (1975) found in a wastewater disposal field that redox potential readings are not quantitative measures; but they are good indicators in determining conditions to stimulate denitrification (nitrogen removal) in ground waters.

INSTRUMENTATION AND EQUIPMENT

Recirculation Sand Filter

Configuration and Components

The described biological recirculating sand filter system incorporated three separate operational cell reactors: (1) sand filter recirculating reactor, (2) DNC tank (denitrification chamber) reactor and (3) discharge polishing sand filter reactor.

As previously described, and shown diagrammatically in Figure 4, the model unit provided a sequential biological treatment process (train-dependance operation) for the removal of nitrogen from domestic septic tank effluent.

Domestic Septic Tank Effluent Loading Components

The domestic septic tank effluent (raw wastewater) was stored in an 80-liter plastic tank placed inside an ordinary refrigerator and maintained at a temperature of approximately 5° C.

The domestic septic tank effluent transfer system consisted of a 1.9 cm ID PVC pipe (manifold) connected in line with an AC 120 volt, 2.17 liter/hour chemical metering loading pump (LP) with the intake port submerged in the refrigerated tank. Suspended solids were screened at the inlet port by a fine filter, which was suspended about 10 cm from the bottom and in the middle of the storage tank.

To regulate transfer of raw wastewater to the test units from the main line, an AC 24 volt, solenoid valve (LV), normally closed, was connected to the manifold. Then, a 1.27 cm ID plastic tube was coupled from the valve to the upper part of the loading port of the model unit DNC cell. This arrangement enabled the domestic septic tank effluent to move freely to the bottom of the DNC cell after each loaded dosage. In the same manner the recirculating volume of nitrified effluent from the sand filter, after each recirculation event, was transferred back to the DNC/recirculation cell.

A sample port along the transfer manifold, also actuated with a normally closed AC 24 volt, solenoid valve (control), transferred raw wastewater during each loading event for sample collection purposes.

DNC Cell (Reactor) Components

Each DNC cell was constructed as a circular tank from schedule 40 PVC pipe 60 cm in length and 10 cm ID. The inlet port for raw wastewater loading was constructed at 3.0 cm from the top edge of the cell. This inlet port was connected to a 1.9 cm ID PVC pipe 53.4 cm in length placed vertically into the DNC cell for bottom loading. The inlet pipe is open to atmosphere on top by a tee PVC fitting (1.9 cm ID) to maintain atmospheric pressure on the liquid column for free gravity flow to the bottom of the reactor. The DNC cell discharge had a 90 degree 1.27 cm ID by 3.8 cm long connector, which was placed at 40 cm from the bottom and on the opposite side of the loading inlet. Each reactor cell included a loose-fitting cover cap to restrict air entering the DNC cell. An electric float switch was located inside the reactor cell to control the complete pumping of the recirculating volume event.

The float was calibrated in such a way that for each recirculation event, the pump would transfer only the volume accumulated over a fixed level; that is, the draw-down of the float was fixed to maintain a specified volume of wastewater in the reactor tank and only the wastewater above this fixed level was allowed to move out. The electric float switch shut off power to the pump circuit when the float dropped to a level just above the exiting outlet of the reactor tank. As a consequence, a minimum volume of 2.6 liters specified for the DNC reactor cell was always maintained.

The DNC reactor fixed-film support structure was constructed of 1.58 cm ID, 2.22 cm OD by 1.27 cm long PVC rings. Each ring had an available specific surface area of 15.2 cm^2, which gave a total area of approximately 2300 cm^2 for biofilm attachment. With the PVC support structure set inside the DNC cell, the available wastewater volume capacity of the denitrification reactor was approximately 2.6 liters of wastewater.

Sand Filter and Recirculating Components

The sand filter cell was constructed also as a circular tank from a schedule 40 PVC pipe 60 cm in length and 10 cm internal diameter. The accumulator vessel was a circular container constructed of PVC schedule 40 pipe 12.5 cm in length and 5 cm ID. A normally open, AC 24 volt solenoid valve (BV) was placed below the accumulator to retain the flow of water while the recirculating volume event was in progress. At the base of the cell, the concave bottom of the filter contained approximately a 2.54 cm depth of fine (0.5 cm in diameter) gravel as support media for the sand column. The gravel also maintained natural ventilation in the filter reactor. A piece of nylon mesh fabric (i.e, mosquito netting) was placed below and above the gravel to prevent washout of the sand. Coarse sand of 0.76 mm effective size (D_{10}) and 1.45 uniformity coefficient (UF) was packed on top of the gravel in thin layers for uniform settlement and at the specified sand depth for that particular RSF unit (see Figure 4). A mosquito netting was also placed on the surface of the sand filter to reduce velocity of the falling water drops and to overcome hole formation on the upper part of the filter; also to break water droplets for better distribution over the surface area of the filter.

Sand and Polishing Filter Loading Components

Two different apparatus arrangements were used to divide the DNC discharge and transfer different portions to the recirculating sand filter and the polishing filter. During the early part of the project period (June 23 to December 2, 1992), the filters were loaded with a volume divider placed on top of the filter cells which allowed water to free fall to the sand surface.

On December 2, 1992, in an effort to overcome the predicament of overabundance of O_2 in the travelling wastewater, the loading of the sand and polishing filters was altered. The altered configuration is detailed in Figure 4. In the altered configuration, loading of the recirculating sand filter was accomplished by a direct hose connected to the recirculating pump. This hose was laid on top of the surface of the mesh located over the sand media. Then, the polishing filter cell was placed below the DNC tank to be loaded by gravity with the overflow of water exiting the DNC reactor.

Polishing Filter and Discharge Components

The polishing sand filter reactor had the same specifications of size, construction and filter media as the recirculating sand filter cell; but with the discharge effluent directly connected to the drain pipe. A sampling port was located at this point for the discharged effluent collection. Sand depth was constant at 30 cm for each of the test units.

The top of the polishing filter cell was positioned, below and opposite and 15 cm lower than the wastewater surface level of the DNC cell. Then, a 0.635 cm ID PVC tee was coupled to the side of the recirculation discharge of the DNC cell. From this position, a 50 cm plastic hose was coupled to the horizontal end of the tee and then connected, 25 cm below the top edge of the PVC pipe, onto the polishing discharge cell. This arrangement permitted the plastic hose to discharge an amount of treated wastewater equal to a dose volume loaded into the DNC.

System Command and Electric Components

The electrical control system was designed to regulate flow rates and event schedules as set for the research units. This system included a portable computer and a series of solid state relay panels which interfaced the various pumps, solenoid valves, and float switches with a programmable controller. The electronic signals were viewed on a computer screen to indicate the status of each event (loading, recirculation or delay) and whether the pumps, floats and valves were on or off. The programmable controller had a clock time function which was instructed to activate in time delayed pulses and take programmed action when given specified orders. This command system was monitored on a computer screen, which displayed the results of the timed sequential orders set for the system and governed by the controller.

Each loading interval and dosage event, all recirculating cycles, and time delay events were energized by sequential orders given by the control system. These orders were fixed in the control memory through a program written on bases of a software ROBASIC LANGUAGE (see Appendix A). The wastewater level float valve was connected in series to the pump solid state relays to control the recirculating volume events. This float was calibrated initially to only allow the specified circulating water to be pumped out from each DNC reactor. Electric power of AC 24 volt came from a transformer connected to primary line input of AC 120 volt electric energy, as were other 120 volt AC powered components. Three independent relay stations were required for the command system. Two boxes controlled the valves and motors and the third one controlled the float switches. Figure 5 shows a circuit diagram for the command and electric components in a typical unit system.

To maintain operation in event of an AC power failure, a back-up battery power supply was connected in series with the regular AC power to the controller system. This power mode kept the computer memory running for approximately 30 minutes without energizing the valves and pumps across the solid state relays. Thus in case of a power outage, the RSF system units would continue their process cycle at that instant regular input electrical energy is restored.

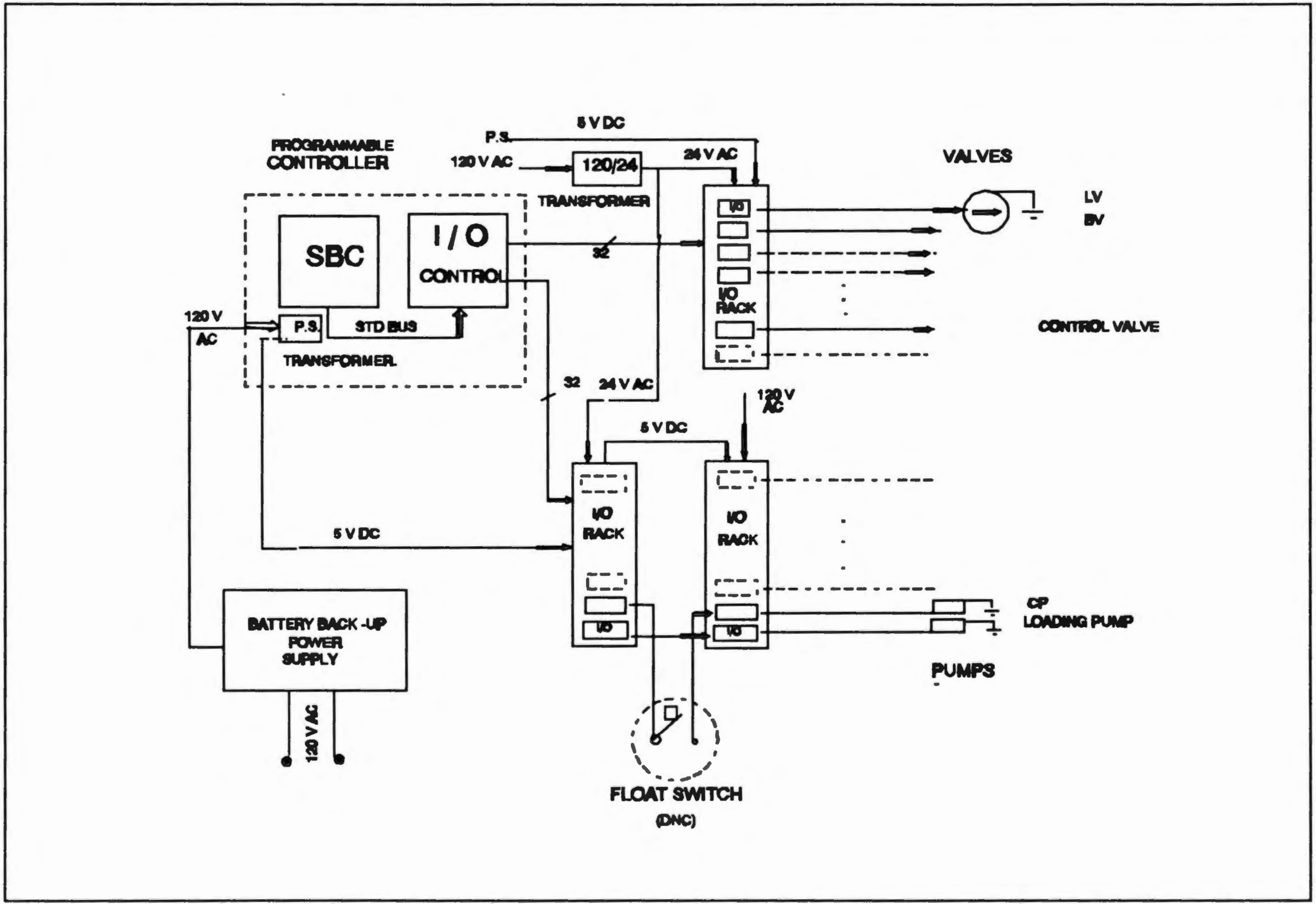

Figure 5. Recirculating Sand Filter System Command and Electronic Components.

Research Parameter Values

Suggested values for sand depth, recirculation ratio, loading rate and loading frequency can be found in literature describing research and prototype field work. Some design data found in the literature were:

1) media depths between 61 to 91 cm,
2) recirculation ratios from 3:1 to 5:1 (R factors of 4 to 6),
3) hydraulic loadings from 12.2 to 20.4 cm/day (0.96 to 1.6 liter/day), and
4) dosing frequencies 5 to 10 minutes every 30 minutes

(U.S. EPA, 1980; Otis, 1982; Anderson, et al., 1985; Hines and Favreau, 1975).

Observations during the early stages of the project (i.e, prior to December, 1992) indicated that sand depths greater than 15 cm (depths of 15, 30, and 45 cm were tested) were excessive. At the higher sand depths, observed system performance was not sensitive to sand depth. Values for the various parameters incorporated into the experimental design for the latter stages of the project are summarized below.

1. Loading rates of 3.84 liter/day (48.49 cm/day), 2.88 liter/day (36.72 cm/day) and 1.92 liter/day (24.45 cm/day),
2. Recirculating filter depths of sand of 5, 10, and 20 cm,

3. Recirculation factors (R) of 4 and 6, and

4. Dose frequency of 96 doses per day.

Values were selected with an eye toward bracketing optimum values for loading rate, sand depth, and recirculation factor.

Experimental Design

The modeled experiment used a fractional factorial design. Out of the [3 loading rates]*[3 sand depths]*[2 recirculation rates] full factorial experimental design, (18 treatments), 12 combinations were chosen for the fractional factorial experimental design. A model design incorporating the 12 system research units was determined and had the composition of the following fractional factorial design.

LOADING RATE (liter/day)	R FACTOR FOR VARYING SAND FILTER DEPTHS		
	5 cm	10 cm	20 cm
1.92	4	6	4
2.88	6	4/6/6/4	6
3.84	4	6	4

The numbers in the boxes of the three sand filter depths are values for recirculation factor (R).

This system operational parameter combination was accomplished with help of the statistics software E4 (User's Guide, Version 91.1, Evolutionary Software, Inc. 1991).

Table 1 shows the design parameter combinations of loading rate, sand depth and R factor for the investigation.

Sample Collection Procedure

Samples of treated and raw wastewater were collected on a weekly bases from each RSF system unit. The sampling ports were as marked in Figure 4: influent to the recirculating sand filter (effluent from DNC) (sample **T**), effluent from the sand filter (influent to DNC) (sample **B**) and effluent from polishing filter (RSF system effluent) (sample **D**). Also a sample of raw domestic septic tank effluent was collected for the control treatment in calculations of nitrogen removal process (sample **C**).

A minimum volume of approximately 40 ml of sample water was collected from ports **B** and **T**. From port **D** and **C**, much larger, about 560 ml sample volumes were collected. Since a portion of the effluent wastewater from each port was used in the sampling procedure, a volume equal to that used for sample was placed back into the system to keep total wastewater per cycle constant. This procedure maintained steady state conditions in the research units. Readings of the redox potential and pH for each DNC cell, as well as the reading of the room (laboratory chamber) temperature were recorded at time of sampling. The samples collected each week were a total of 37, distributed as follows: 12 from discharge

Table 1. Experimental Design of Variable Combinations for the RSF System Model Investigation.

UNIT No.	SAND DEPTH	WASTEWATER LOADING			SYSTEM RECIRCULATION			
		liter/day	event/hr	ml/event	R	liter/day	event/hr	ml/event
1	10	2.88	4	30	4	8.64	4	90
2	20	3.84	4	40	4	11.52	4	120
3	5	2.88	4	30	6	14.40	6	90
4	10	3.84	4	40	6	19.2	6	120
5	5	3.84	4	40	4	11.52	4	120
6	20	2.88	4	30	6	14.40	6	90
7	5	1.92	4	20	4	5.76	4	60
8	10	1.92	4	20	6	9.60	6	60
9	20	1.92	4	20	4	5.76	4	60
10	10	2.88	4	30	4	8.64	4	90
11	10	2.88	4	30	6	14.40	6	90
12	10	2.88	4	30	6	14.40	6	90

and 1 from the control port.

RSF System Discharge Sample

The RSF system treated wastewater sample was collected at port **D** in a sterilized bottle. A 560 cc sterilized collection bottle was placed inside a 2 litter plastic beaker overnight (approximately 16 hours) and, by placing the drainage hose inside the bottle to overflow, a sample of fully treated wastewater large enough for proper analysis was collected. With the total wastewater (bottle and beaker) collected for that sampling period known, the daily loading rate was calculated to monitor the uniformity of the steady state flow of the system.

Septic Tank Effluent Control Sample

Septic tank effluent (raw wastewater) was collected in the same fashion as the discharge effluent. The **C** port is in line with the transferred septic tank effluent into the system. Once per week the sterile bottle and beaker were filled with raw wastewater and the fill-up time and total volume (beaker plus sterile bottle) were recorded.

DNC Effluent Sample

The nitrate reduced water, sample **T**, was collected from the end of the plastic hose at the moment of recirculation onto the sand filter. A sterilized bag was placed under the drain of the tube, on top of the sand filter, and filled with circulating water. The volume of wastewater collected in the sample was replaced into the system with the water overflowed in the beaker or collected in the bottle at port D.

Sand Filter Effluent Samples

The nitrified effluent was collected at the bottom of the accumulator, port **B**, after the circulating cycle was completed and percolating process had occurred through the sand depth. A sterilized calibrated plastic cylinder was used to accumulate about 40 cc of effluent water, which in turn was transferred to the sterilized bag. The volume collected was replaced immediately with wastewater from the discharge effluent (port D) and loaded into the inlet of the DNC as if it was directly from the sand filter.

Flow Rate Samples

The discharge effluent (**D**) of the RSF system unit was used to monitor loading rates. Values were recorded initially on a daily bases. But, after the system was debugged and running smoothly, they were recorded weekly. Rates were calculated from the measured volumes and recorded sample-collection-period durations. Observed values were compared to the values established for the experimental design.

Differences triggered system maintenance (e.g., unplugging valves, pumps, hose lines, etc.) to reestablish design loading rates.

Data Analysis Procedure

Biological systems like the ones investigated in this study are dynamic and readily respond to changes in environmental and operating conditions. Temporary operation changes, such as a partially plugged solenoid valve, can result in obvious variations in system performance. For purposes of this study, it was important that performance data analyzed reflect system performance in response to the design operating conditions and not some aberration of those conditions. One monitored parameter that appeared to be very responsive to operating conditions was reduction-oxidation (redox) potential in the denitrification chamber (DNC). Since low redox values are essential for effective denitrification, any operational change that permitted extra oxygen to enter the DNC and raise the redox certainly resulted in an overall change in system performance. Redox was therefore used as an indicator of operational stability, and the performance data set was screened on the basis of operational stability before differences in observed performance were statistically compared. For comparison purposes, data were excluded if collected from a given unit at times when the observed redox was appreciably greater than the lowest observed value for that unit. "Appreciable" was arbitrarily defined as greater than 20%.

Data were also screened for analytical errors before performance comparisons were made. Any one calculation of nitrogen removal for any one system relied on data from laboratory analysis of three independent samples. Any error (e.g., sample measurement error, instrument malfunction, etc.) in any of the analyses resulted in an erroneous estimate of system performance. Data integrity was checked by performing an ammonia mass balance on the DNC. Theoretically, no ammonia should be lost in the DNC, and independent samples were taken from two streams entering and one leaving the DNC. Therefore, a set of data for which the indicated total ammonia entering the DNC did not approximately match that leaving obviously contained an error. For screening purposes, the balance for a given sampling event was permitted to be off by as much as 50% for a given unit before all data for a sampling event were rejected for that unit.

Additionally, observations that indicated impossible system performance (i.e., greater than 100% or less than 0% nitrogen removal) were excluded from the data set prior to making performance comparisons.

Ammonia Removal in the Recirculating Sand Filter Reactor

The amount of ammonia removed (i.e., converted to nitrite and/or nitrate) was estimated from a mass balance analysis for the recirculating sand filter cell. Since there are no data values for the portion of the organic nitrogen present in the influent wastewater and since influent organic nitrogen transforms to ammonia and then to NO_x^- in the recirculating sand filter, it is not possible to know for sure the amount of ammonia-nitrogen going into the filter. By estimating the amount of mineral nitrogen entering and leaving the recirculating sand filter reactor, the value for the influent ammonia-nitrogen was determined. It was estimated from the values of NH_3-N and NO_x^--N in the effluent at B sample minus the value of NO_x^--N in the influent at T sample.

The relationship used for ammonia-nitrogen removal calculations is as follows:

$$\%\ NH_3\text{-}N\ REMOVAL = \frac{(NH_3\text{-}N)_{Influent} - (NH_3\text{-}N)_{Effluent}}{(NH_3\text{-}N)_{Influent}} * 100 \tag{3}$$

where:

$(NH_3\text{-}N)_{Influent} = [NH_3\text{-}N + (NO_x^-\text{-}N)]_B - [NO_x^-\text{-}N]_T$

$(NH_3\text{-}N)_{Effluent} = [NH_3\text{-}N]_B$

B = Discharge sample port at the sand filter cell.

T = Discharge sample port at the DNC cell.

Nitrate Removal in the DNC Reactor Cell

The amount of denitrification or nitrate removal was estimated from a mass balance analysis on the DNC/recirculation tank reactor. Since recirculation is performed from the DNC cell, the measures of NO_x^--N are performed from the DNC cell, the measures of NO_x^--N are dependent on the volumes of water entering and leaving the reactor cell at a given time. The B sample effluent has a flow rate equal to Q*(R-1), while T and C samples have flow rates equal to Q*R. For the determination of the nitrate/nitrite mass balance relationship, the flow rate (Q) terms cancel.

The following relationship was developed to estimate nitrogen removal in the reactor.

$$\%\ NO_x^- \text{-} N\ REMOVAL = \frac{(NO_x^- \text{-} N)_{Influent} - (NO_x^- \text{-} N)_{Effluent}}{(NO_x^- \text{-} N)_{Influent}} * 100 \qquad \textbf{(4)}$$

where:

$(NO_x^- \text{-} N)_{Influent} = (R-1) * (NO_x^- \text{-} N)_B + (NO_x^- \text{-} N)_C$

$(NO_x^- \text{-} N)_{Effluent} = R * (NO_x^- \text{-} N)_T$

R = Recirculation factor.

C = Discharge sample port at the polishing filter cell.

RSF System Mineral Nitrogen Removal Performance

The overall system performance was evaluated based on the mineral nitrogen present in the input and output of the recirculating system (recirculating sand filter and DNC reactors). Since nitrate reduction takes place in the DNC reactor, the total mineral nitrogen removal was calculated from a basic mass balance performed at boundary conditions considering the influent and effluent wastewaters of the organic nitrogen were available, the amount of mineral nitrogen entering the DNC cell was determined and considered the possible mineralization of the organic nitrogen in the reactor.

The following relationship was developed for estimating total system mineral nitrogen efficiency.

$$SYSTEM\ \%\ MINERAL\ N\ REMOVAL = \frac{(N)_{Influent} - (N)_{Efflunt}}{(N)_{Influent}} * 100 \quad (5)$$

where:

$(\text{Mineral N})_{Influent} = R * (NH_3\text{-}N)_T + (NO_x^{-}N)_C - (R-1) * (NH_3\text{-}N)_B$

$(\text{Mineral N})_{Effluent} = (NH_3\text{-}N)_T + (NO_x^{-}\text{-}N)_T$

RSF system TOC Removal

Organic carbon removal in the total system, as well as each system component, was estimated from a basic mass balance as indicated below.

$$TOC\ \%\ removal = [(TOC)_{In} - (TOC)_{out})]/(TOC)_{In} * 100 \quad (6)$$

1. Mass balance relationship for the overall RSF system TOC removal:

$$OVERALL\ \%\ TOC\ REMOVAL = \frac{(TOC)_C - (TOC)_D}{(TOC)_C} * 100 \quad (7)$$

2. Mass balance relationship for the recirculating sand filter reactor TOC removal:

$$SAND\ FILTER\ \%\ TOC\ REMOVAL=\frac{(TOC)_T-(TOC)_B}{(TOC)_T}*100 \tag{8}$$

3. Mass balance relationship for the DNC/recirculating tank reactor TOC removal:

$$DNC\ \%\ TOC\ REMOVAL=\frac{(R-1)*(TOC)_B+(TOC)_C-R*(TOC)_T}{(R-1)*(TOC)_B+(TOC)_C}*100 \tag{9}$$

4. Mass balance relationship for the system before polishing TOC removal

$$\%\ TOC\ REMOVAL\ BEFORE\ POLISHING=\frac{(TOC)_C-R*(TOC)_T}{(TOC)_C} \tag{10}$$

RSF System Fecal, Total Coliform and Streptococcus Removal

Bacteria removal efficiency was estimated from a basic mass balance as indicated below.

$$BACTERIA\,\%\,RMVL=\frac{BACTERIA_{Influent}-BACTERIA_{Effluent}}{BACTERIA_{Influent}}*100 \tag{11}$$

Comparison of Nitrogen Removal Performance

Estimated system nitrogen removal, sand filter ammonia removal, DNC nitrate and TOC removal were statistically compared among the 12 systems. This procedure fits the parameters of complete quadratic response surface and then determines critical values to maximize the response removal efficiency with respect to the operational RSF system factors present in the model.

The analysis model led to development of standard response surface curves describing significant combinations of parameters (GLM procedure of SAS, 1990). The standard response surface model (Prediction Equation) included linear, quadratic and linear crossproducts which were represented as follows:

Term determination,

R = Recirculation ratio (-).

SD = Sand depth (cm).

LR = Loading rate (liter/day).

R^2 = Recirculation ratio * Recirculation ratio.

SD^2 = Sand depth * Sand depth.

LR^2 = Loading rate * Loading rate.

SD*LR = Sand depth * Loading rate.

SD*R = Sand depth * Recirculation ratio.

LR*R = Loading rate * Recirculation ratio.

The prediction equation had the following form:

$$Y_i = \alpha+\beta_0+\beta_1 * R+\beta_2 * SD+\beta_3 * LR+\beta_4 * SD^2+\beta_5 * LR^2 \\ +\beta_6 * (SD * R)+\beta_7 * (LR * R)+\beta_8 * (SD * LR) \tag{12}$$

where:

Y_i = % Removal Efficiency (E).

The procedure fit the parameters of a complete quadratic response surface and then determined critical values to optimize the response with respect to the essential factors in the model. Each term was considered to be significant if probability values were less than 0.10 ($P < 0.10$). The term effects that were not significant, P greater than 0.10, were dropped from the initial model to determine the new response-surface including only the remaining factors. This routine proceeded by eliminating non-significant terms one at a time and only using the statistically significant ones. This approach was required because the adjustment for non-significant terms can make other significant terms appear to be non-significant. For this reason, partial sums of squares were used throughout the analysis since the model had multiple regressors. For example, it was felt that adjustment of R for SD^2 effects was appropriate, which would not be done if sequential sum of squares were used. Since the design introduced two levels of R in the crossproduct term, the quadratic effects of R were not used.

The final quadratic response surface model obtained is the prediction Equation (12).

After the response-surface equation of best fit was determined, the output was plotted by running Surfer (Golden Software, Inc.,1990).

CHAPTER 4

RESULTS AND DISCUSSION

The RSF model systems were designed to remove organic compounds, nitrogen and bacteria from domestic septic tank effluent through biological treatment processes. The laboratory models provided means of testing effects of specific system operating parameters on the ability of a recirculating sand filter system to remove nitrogen. Presentation of results for these tests is divided into two sections: (1) System performance and (2) Reduction/oxidation potential and Denitrification.

SYSTEM PERFORMANCE

Septic Tank Effluent Loading

Hydraulically the model systems were designed and calibrated to operate with variable loading rates delivered by the loading pump and controlled by the computer unit. The system input was designed for loadings of 1.92 l/day (24.45 cm/day), 2.88 l/day (36.67 cm/day) and 3.84 l/day (48.89 cm/day). Actual rates were maintained at a minimum of variation from the hydraulic targets (±5%). Variability in the system input loading rates generally derived from clogging of the intake filter at the bottom of the loading tank. To keep balanced loadings, the screen at the intake filter was rotated for a clean one on weekly basis to keep the loading rates at target values. Figure 6 shows the averaged weekly system collections for the loading rate values collected during the research period. The designed loading inputs (septic tank effluent) were compared to the target values for the system output (polishing filter effluent). Loading rates were maintained very stable and output discharge flow rates were obtained within ± 5% of target values.

Wastewater Renovation Performance

The RSF system investigation was evaluated on the bases of mineral nitrogen removal, TOC and bacterial removals. Combination of operational parameters were required to determine maximum relationships and optimal removal efficiencies. The combinations tested included different levels of depth of sand, recirculation ratio and loading rate.

Wastewater renovation performance was evaluated with respect to mineral nitrogen removal (actual and actual as percent of theoretical). Data presented include nitrification in the sand filter reactor and denitrification in the DNC reactor. Estimates of overall total organic carbon removal in the RSF system were based on the wastewater exiting the polishing filter. Also sectional carbon removal was estimated based on wastewater leaving two locations within the system:

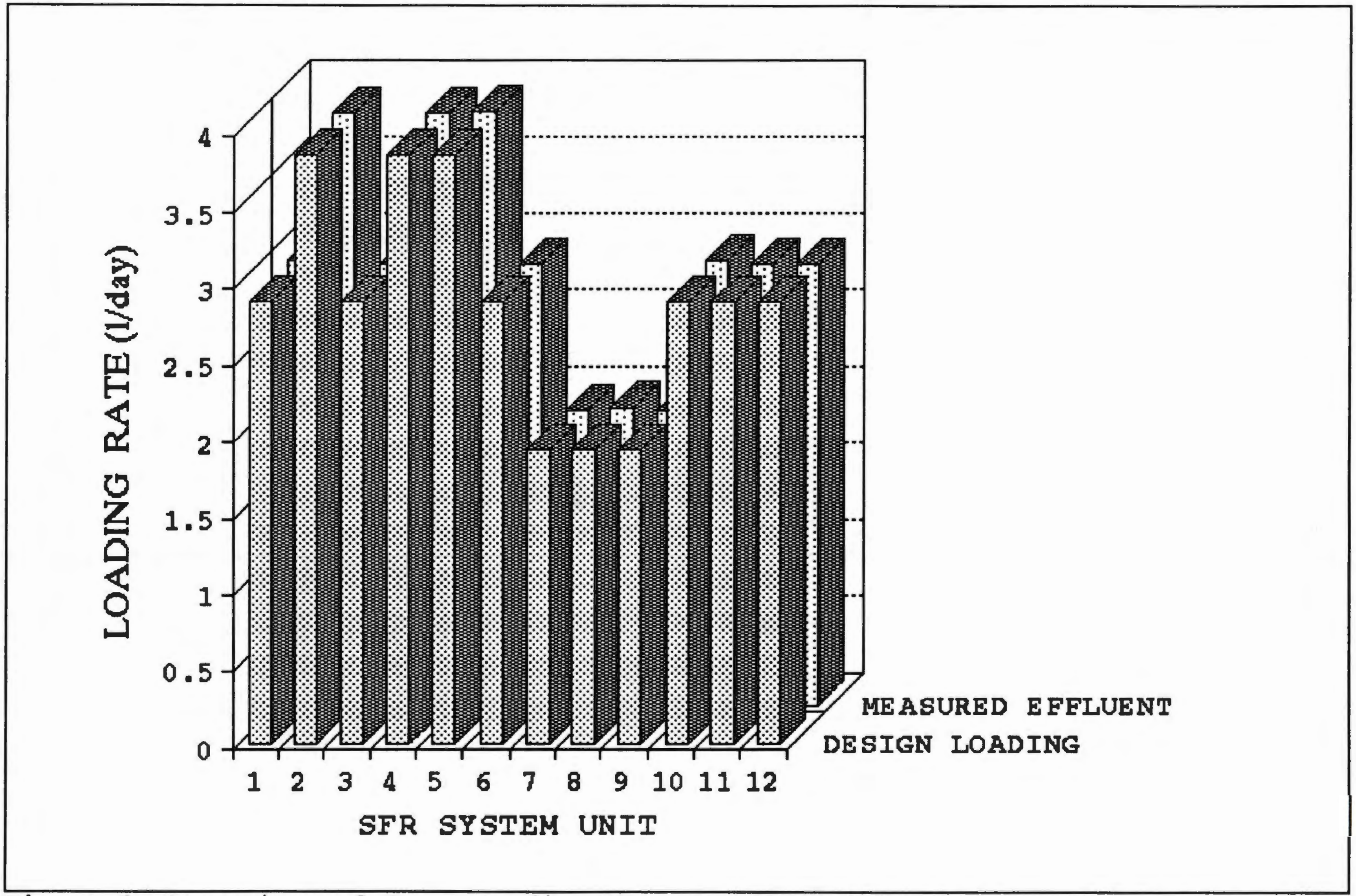

Figure 6. Comparison of Input Loading Rates to Mean Effluent Output Rates.

the recirculating sand filter, and the DNC reactor (system removal before polishing (SBP)). System bacterial removal was estimated based on effluent discharge of the polishing filter. Tables 2 and 3 show the values for mineral nitrogen and TOC removals.

Ammonia removal in the recirculating sand filter

The removal of ammonia by nitrification in the sand filter was calculated using Equation (3). Table 2 shows the ammonia removal efficiency value for the sand filter reactor of each RSF unit system. Unit nine produced the highest ammonia removal efficiency of 91.91%, while unit five produced the lowest ammonia removal efficiency of 14.16%. The highest ammonia removal was experienced in a sand bed of 20 cm depth and a low loading rate (1.92 l/day). Lowest ammonia oxidation occurred at the lowest sand bed depth (5 cm) and highest loading rate (3.84 l/day).

Statistical regression analysis on linear, quadratic and crossproduct combinations showed that the recirculating ratio, R, did not significantly ($P > 0.10$) effect ammonia removal. The regression model best fitting ammonia removal results combined the factors of sand depth, loading rate and the quadratic term of sand depth. Equation (13) shows this best fit model predicting ammonia removal efficiency in the recirculating sand filter.

Table 2. Treatments and Resulting Mean Performance Values Relating to Nitrogen Removal for the Twelve Experimental Systems.

UNIT NO.	SYSTEM OVERALL MINERAL-N REMOVAL (%)	SYSTEM OVERALL MINERAL-N REMOVAL AS A PERCENT OF THEORETICAL MAXIMUM	NH_3 REMOVAL IN SAND FILTER (%)	NO_x^- REMOVAL IN DNC (%)	REDOX POTENTIAL IN DNC (mV)	pH
1	62.86	83.82	59.61	90.88	-207.17	6.83
2	71.37	95.15	77.03	78.30	-197.25	6.68
3	43.54	52.25	18.46	95.49	-244.50	6.95
4	54.74	65.69	28.89	75.94	-222.83	6.85
5	30.90	41.20	14.16	95.14	-252.63	6.98
6	68.04	81.65	85.83	51.69	-149.57	6.69
7	44.40	59.19	31.51	98.75	-228.25	6.96
8	64.68	77.62	71.38	58.40	-122.80	6.76
9	56.68	75.58	91.91	50.84	-116.60	6.74
10	62.99	83.98	80.35	76.37	-114.83	6.72
11	68.12	81.75	60.67	64.61	-101.14	6.69
12	64.02	76.82	68.76	55.01	-99.86	6.73

Table 3. Mean TOC Removal Efficiencies for Twelve Experimental Systems Including Overall and Component Contribution to Overall.

UNIT No.	TOC REMOVAL				
	OVERALL RSF SYSTEM %	SAND FILTER REACTOR %	SYSTEM BEFORE POLISHING %	DNC REACTOR %	POLISHING * FILTER (SYST-SBP) %
1	77.57	46.49	54.01	-1.99	23.55
2	86.16	54.20	68.72	-3.25	17.44
3	90.79	17.03	42.09	-2.09	48.70
4	83.51	24.39	53.14	-0.37	30.37
5	89.00	16.72	35.64	1.44	53.37
6	81.31	49.56	72.81	8.23	8.50
7	90.25	22.36	72.86	2.53	17.39
8	86.23	38.95	70.16	5.93	16.08
9	84.87	63.98	71.79	13.48	13.08
10	84.82	52.17	62.85	3.23	21.96
11	81.72	40.32	63.92	-4.34	17.81
12	86.63	44.82	68.87	2.93	17.75

* Contribution to overall system efficiency. Not an individual component efficiency.

$$E_{NH_3}=-0.65+13.78*SD-12.96*LR-0.38*SD^2 \qquad (13)$$

$$R^2 = 0.887365$$

where the standard errors of regression estimates are:

β_0 (%) = -0.65 $^+_-$ 22.861885

β_1 (%/cm) = 13.78 $^+_-$ 3.352052

β_2 (%/cm) = -12.96 $^+_-$ 4.545834

β_3 (%/cm^2) = -0.38 $^+_-$ 0.126814

and β_x are the regression coefficients or "parameters".

The proximity of the intercept to the origin (-0.65%), suggests that the efficiency of ammonia removal is very small at low sand depth and low loading rate, although the standard error for regression estimate is large ($^+_-$ 22.86). At low sand depth (5 cm) and loading rate (22.92 cm/day) the model predicted ammonia removal efficiency of 35.15%. At low sand depth (5 cm) and high loading rate (48.38 cm/day) the model predicted lower ammonia removal (8.94%). The model showed ammonia removal increased linearly (β_1 = 13.78) with sand depth but decreased linearly (β_2 = -12.96) with loading rate. The model suggests that for each increase of one unit of ΔSD, ΔE increases 13.87 units. At the same time, the increase of one unit in ΔLR decreases ΔE 12.96 units.

The surface graph of the regression equation for ammonia removal for both levels of recirculation ratio is shown in Figure 7, where 100% ammonia removal is predicted at sand filter depths in the range of 17.5 to 19 cm and a loading rate

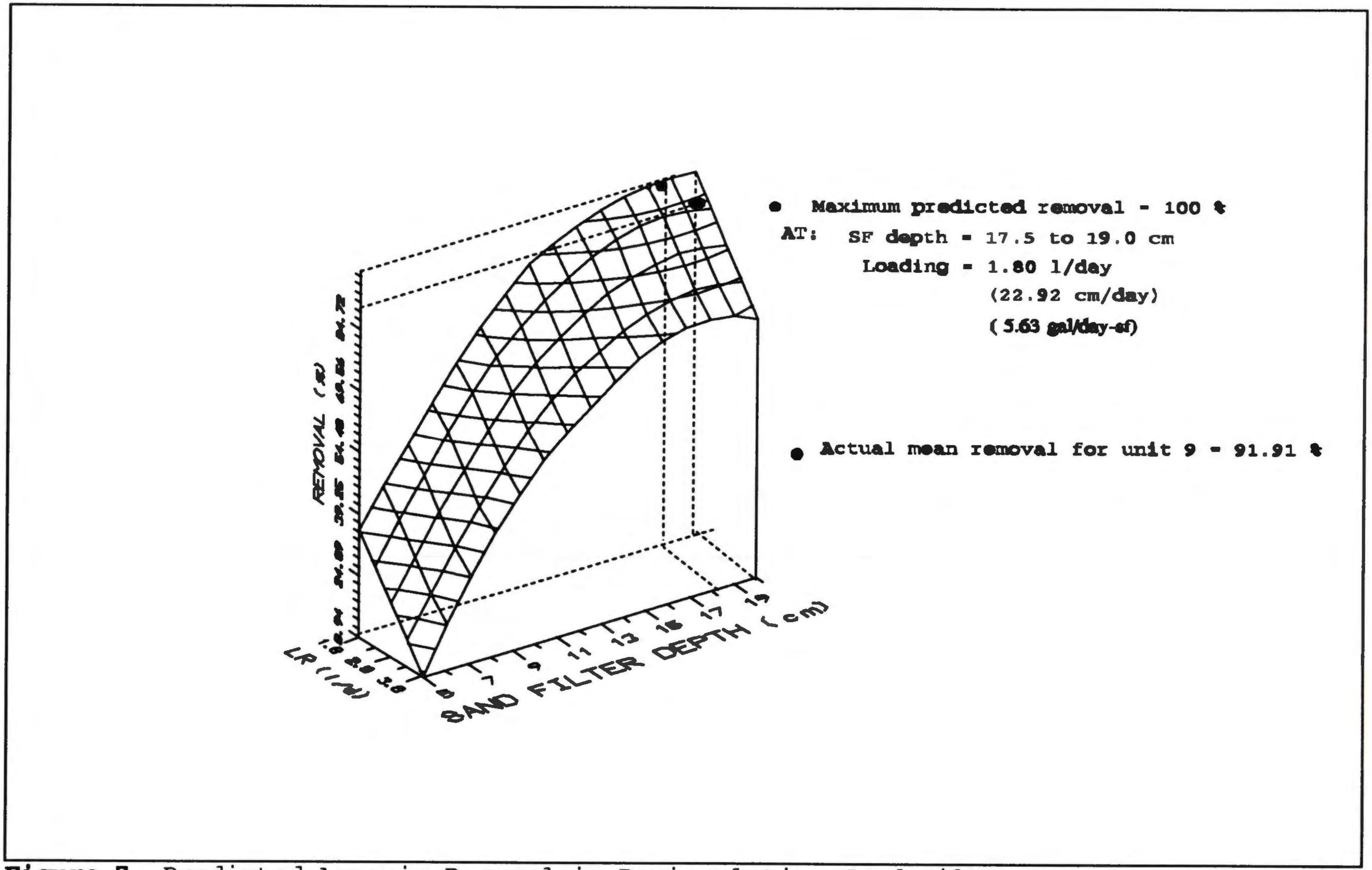

Figure 7. Predicted Ammonia Removal in Recirculating Sand Filter Reactor as a Function of Sand Depth and Loading Rate.

of 22.92 cm/day. The actual value (91.91%) obtained in unit nine was very close to the one predicted by the regression equation (100%). The process of ammonification in the recirculating sand filter is enhanced by high sand depths and low loading rates.

Nitrate removal in the DNC/recirculating tank

The results for the process of NO_x^- reduction (denitrification) were determined with the help of Equation (4), obtained from the nitrogen mass balance on the effluent waters of the DNC reactor cell. Table 2 shows the averaged denitrification value for each research unit. Units seven and three gave the highest value of nitrogen removal efficiency at 98.75% and 95.49% respectively, while units nine and six the lowest at 50.84% and 51.69% respectively. The corresponding values of redox potential readings on those level of denitrification were -228.25 mV for seven, -244.50 mV for three, -116.60 mV for nine and -149.57 mV for unit six. It can be seen that for a higher denitrification capacity (maximum nitrogen removal potential), the redox potential measurement was at its high negative value. On the contrary, lower denitrification capacity (minimum nitrogen removal potential), the redox potential readings had a lower negative value. The above analysis is supported by the fact that at low sand depth and low recirculation factor (unit seven) there was less reaeration of the anoxic reactor; thus, the reactor had better potential for the denitrification process to take place. Higher sand depth and recirculation (unit six) present more capability for water to carry oxygen into the anoxic environment diminishing the reduction capacity of the system. All four units had different amounts of substrate (loading rate) to fulfill the requirements of food in the system.

Both recirculation ratio, R, and sand depth played important roles affecting the potential for nitrate reduction in the DNC reactor. With a larger R factor (6) there are more opportunities for the circulating water to carry O_2 to the anoxic system and change the environmental condition of the cell. Equation (14) predicts the best statistical fit for data observed for removal of nitrate in the DNC reactor. Only sand depth and R are significant ($P < 0.10$) for the predicted model; loading rate and the other factors were dropped due to their non-significance ($P > 0.10$).

$$E_{NO_x^-}=141.17-2.23*SD-8.36*R \tag{14}$$

$$R^2 = 0.6811$$

where the standard errors of the regression estimates are:

$$\beta_0 \ (\%) = 141.17 \ ^{+}_{-} \ 18.345007$$

$$\beta_1 \ (\%/cm) = -2.23 \ ^{+}_{-} \ 0.596119$$

$$\beta_2 \ (\%/cm) = -8.36 \ ^{+}_{-} \ 3.251298$$

The large value (141.17) of the intercept suggests that low sand depth and low values of recirculation ratio were required to obtain maximum efficiency in denitrification. The efficiency of nitrate reduction declined (slope of -2.23) as sand depth increased (a decrease of 2.23 units of ΔE when sand depth changed one unit). The contribution of the recirculation ratio also suggested that there was a decrease (negative slope) of 8.36 units of ΔE when R changed one unit. The low value of R^2, statistical "goodness of fit" indicator, (0.6811) indicated denitrification is not fully explained by the parameters considered in the statistical model.

The surface graphs showing the parameter's relationships for the model with R factors of 4 and 6 are presented in Figure 8. The prediction surfaces show a high value of nitrate reduction (96.58%) at an R of 4 and a lower value (79.87%) at an R of 6. Actual nitrate removals for the same levels of R factors were 98.75% (unit seven) and 95.49% (unit three). For unit seven the value was very close to the predicted one (96.58%). These maximum values of denitrification were obtained at a sand filter bed of 5 cm depth. In summary, nitrate reduction was enhanced by low sand depth and low recirculation factor; actual results varied somewhat from predicted performance.

<u>Mineral nitrogen removal in the RSF system</u>

<u>Actual:</u> RSF system performance was evaluated from the

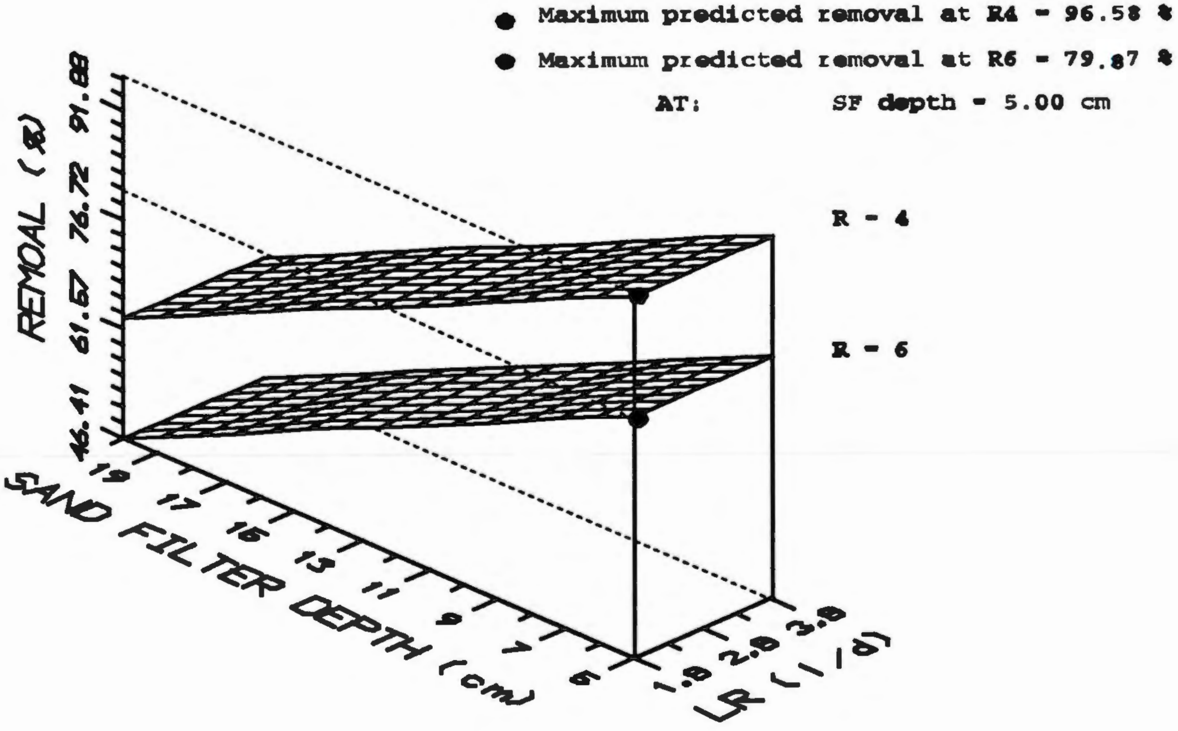

Figure 8. Predicted NO_x^- Removal in the DNC Reactor as a Function of Sand Depth and Recirculation Ratio.

wastewater samples collected. These samples were collected at ports B, C and T. Then, overall mineral nitrogen removal was calculated by performing a mass balance, Equation (5), with the system discharge being defined as the discharge from the DNC chamber. The removal efficiencies so determined were averaged over the investigation period and are summarized for each experimental system unit in Table 2 (p 65). Figure 9 illustrates the system removal efficiencies for the 12 units given in Table 2 (p 65). The highest value for actual mineral nitrogen removal was 71.37% (theoretical maximum being 75%) represented in unit two. In contrast, unit five had the lowest actual mineral nitrogen removal of 30.90% (theoretical maximum being 83.33%). The corresponding averaged redox potential measures for units two and five were -197.25 and -252.63 mV respectively. Possibly higher system mineral nitrogen removal in unit two compared to unit five occurred because there was a more satisfactory nitrification (77.03%, Table 2) process in a larger sand bed (20 cm depth) reactor. The low mineral nitrogen removal produced in unit five was affected by the low ammonia oxidation (14.16%) produced in a smaller bed of sand (5 cm depth) in the sand filter, in spite of nearly completed nitrate reduction (95.14%) in its respective DNC reactor. In unit five most of the ammonia passed through unchanged. As a measure of the denitrification process, the redox potential reading (-228.25 mV) in unit five showed a high negative measurement, due possibly to the

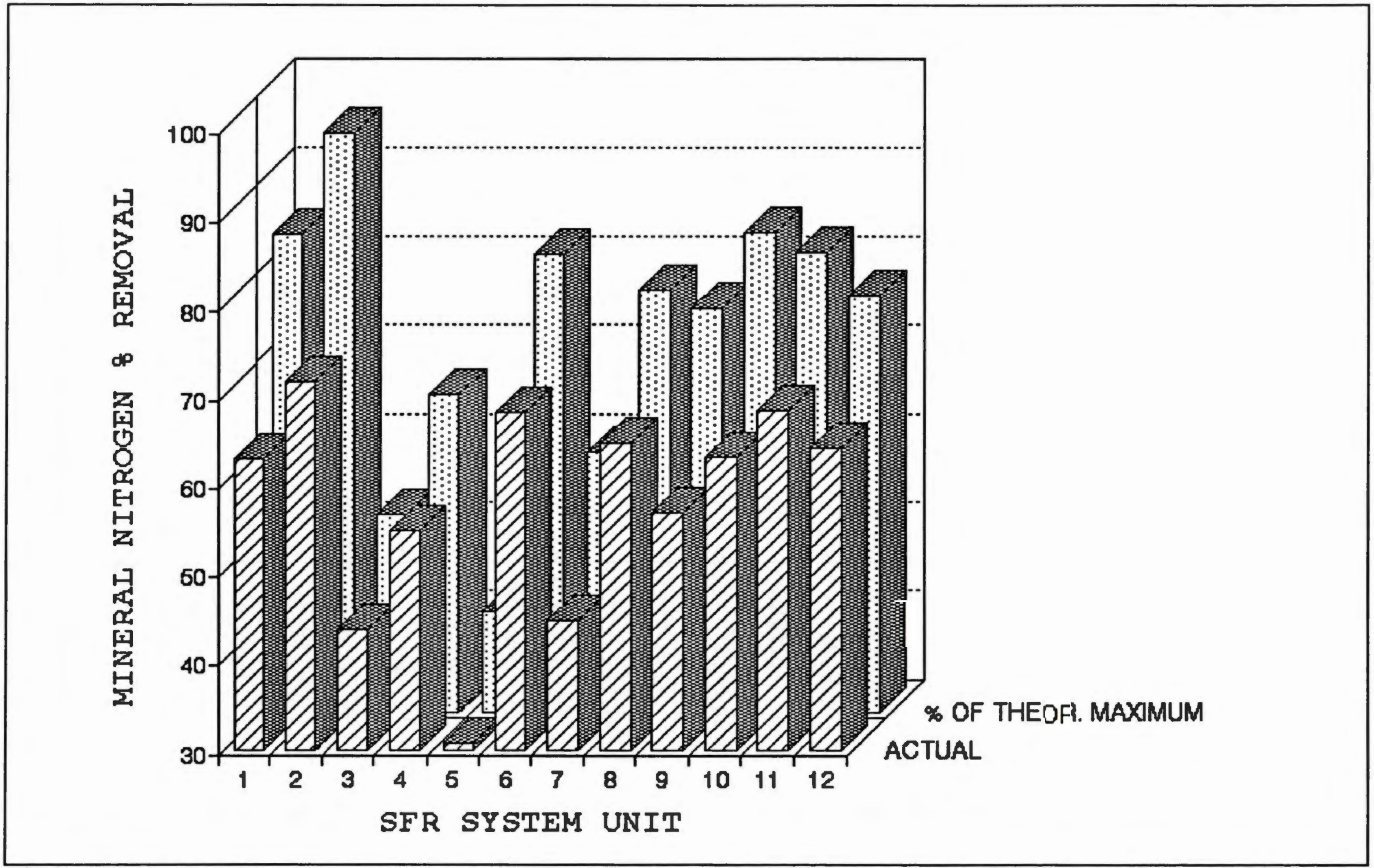

Figure 9. Actual and Percent of Theoretical Maximum Averaged Values for Mineral Nitrogen System Removal Efficiency.

minimum oxygen carry over by smaller sand bed. On the contrary, unit two drew more oxygen in a larger sand column and showed a lower negative redox potential (-116.6 mV).

Equation (15) gives the response-surface for mineral nitrogen removal efficiency where sand depth and loading rate were the significant parameters involved.

$$E_{M\,N}=3.00+5.31*SD+16.99*LR-0.26*SD^{2}-5.28*LR^{2}+1.02*SD*LR \qquad \textbf{(15)}$$

$$R^{2} = 0.981561$$

where the standard errors of regression estimates are:

β_0 (%) = 3.00 $^{+}_{-}$ 12.715716

β_1 (%/cm) = 5.31 $^{+}_{-}$ 0.864993

β_2 (%/cm) = 16.99 $^{+}_{-}$ 8.857578

β_3 (%/cm^2) = -0.26 $^{+}_{-}$ 0.028261

β_4 (%/cm^2) = -5.28 $^{+}_{-}$ 1.496759

β_5 (%/cm^2) = 1.02 $^{+}_{-}$ 0.153609

Equation (15) indicated that, for 5 cm of sand depth and 22.92 cm/day of loading rate, there was a predicted efficiency of 44.42% in mineral nitrogen removal. Lower mineral nitrogen removal efficiency (29.99%) was predicted at 48.38 cm/day loading rate and low (5 cm) sand depth. The surface equation showed positive linear slopes suggesting an increase in efficiency (ΔE) at unit variable changes; on the contrary, quadratic terms presented negative slops suggesting a declining curve. The high value of the statistical "goodness of fit" parameter R^2 (0.981561) indicated that linear, quadratic and crossproduct factors in the equation accounted well for the nitrogen removal efficiency of the RSF.

The predicted surface model of the RSF system for mineral nitrogen removal efficiency was plotted using equation (15) and is shown in Figure 10. The recirculation ratio, R, was not significant ($P > 0.10$), so did not influence the response surface. Thus, a predicted maximum mineral nitrogen removal efficiency of 73.69% at sand depth of 16.50 cm and loading rate of 40.74 cm/day was obtained for the RSF system model regardless of recirculation ratio. Maximum actual mineral nitrogen removal was obtained in unit two at a value of 71.37% with sand depth of 20 cm and loading rate of 48.49 cm/day.

Percent of Theoretical Maximum: Equation (2) established that the theoretical maximum nitrogen removal efficiency for the RSF system with R factors of 4 and 6 were 75% and 83.33% respectively. Table 2 shows the actual removal efficiency expressed as a percentage of the theoretical maximum removal efficiency for each of the twelve experimental systems. The range was from 95.15% in unit two to 41.20% in unit five.

Statistical analysis of data in Table 2 indicated that recirculation ratio, R, had a linear effect, while sand depth and loading rate had significant ($P < 0.10$) linear and crossproduct effects on mineral nitrogen removal when expressed as a percent of theoretical maximum. Equation (16)

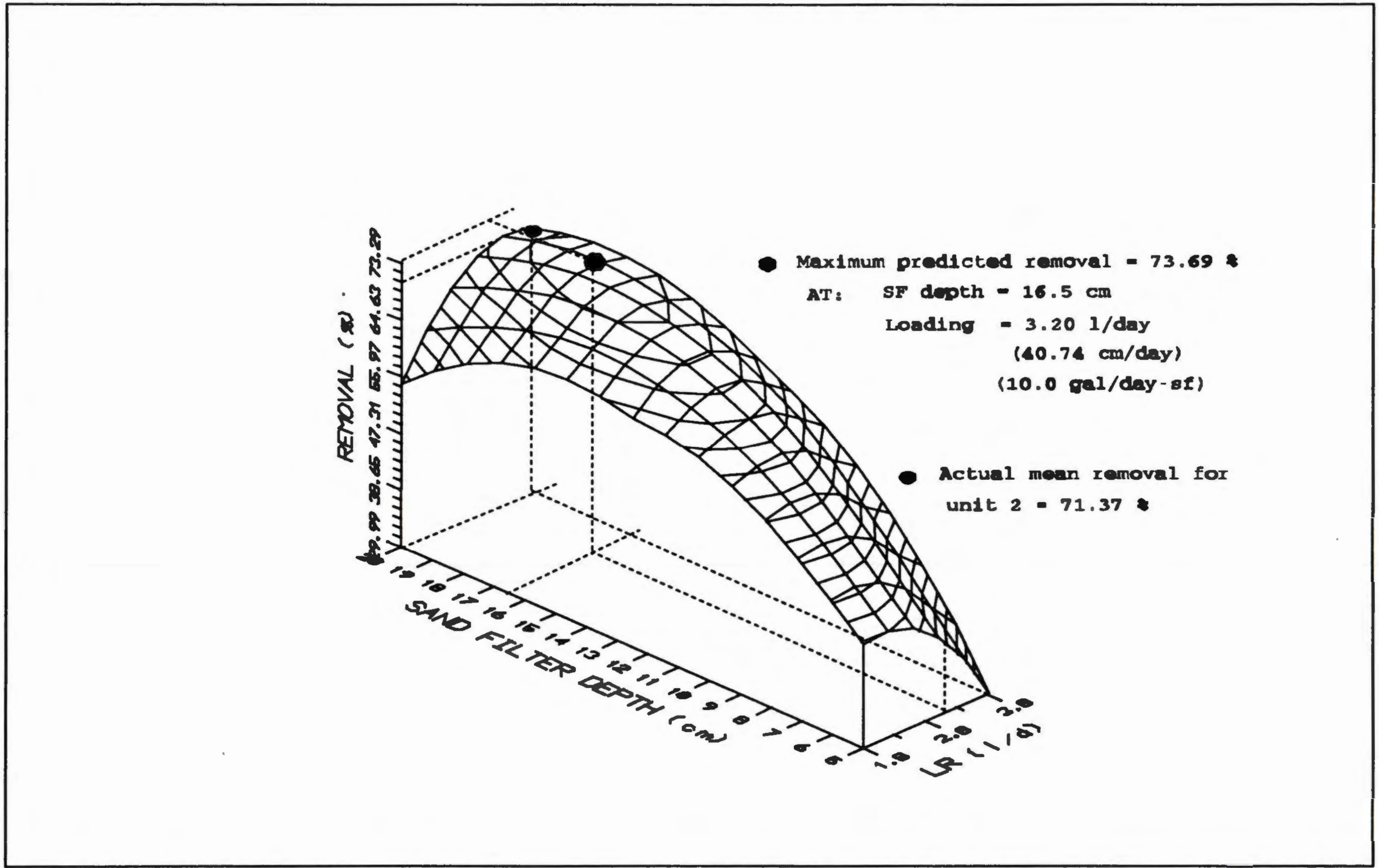

Figure 10. Predicted Mineral Nitrogen Removal in the RSF System Unit as a Function of Sand Depth and Loading Rate.

expresses the observed relationship.

$$\begin{aligned}E_{Th}=21.32+6.49*SD+20.5*LR-3.07*R-0.33*SD^2\\-6.61*LR^2-1.35*SD*LR\end{aligned}\qquad \textbf{(16)}$$

R^2 of 0.984426

where the standard errors of regression estimates are:

β_0 (%) = 21.32 $^{+}_{-}$ 16.095779

β_1 (%/cm) = 6.49 $^{+}_{-}$ 1.116953

β_2 (%/cm) = 20.50 $^{+}_{-}$ 11.556193

β_3 (%/cm^2) = -3.07 $^{+}_{-}$ 0.901321

β_4 (%/cm^2) = -0.33 $^{+}_{-}$ 0.036879

β_5 (%/cm^2) = -6.61 $^{+}_{-}$ 1.955992

β_6 (%/cm^2) = -1.35 $^{+}_{-}$ 0.194365

In contrast to the analysis of "actual" nitrogen removal where R was not significant, recirculation ratio, R, was significant when predicting nitrogen removal as a % of theoretical.

Response surfaces described by Equation (16) for recirculation (R) ratios of 4 and 6 are shown in Figures 11 and 12 respectively. For an R factor of 4, the system is predicted to achieve 96.47% of the theoretical mineral nitrogen removal potential at a sand depth of 16.5 cm and loading rate of 40.74 cm/day. For an R factor of 6, the system is predicted to come closest to its theoretical removal potential at this same sand depth and loading rate. However, the system is predicted to be able to achieve only 90.32% of its potential maximum removal. Considering the theoretical

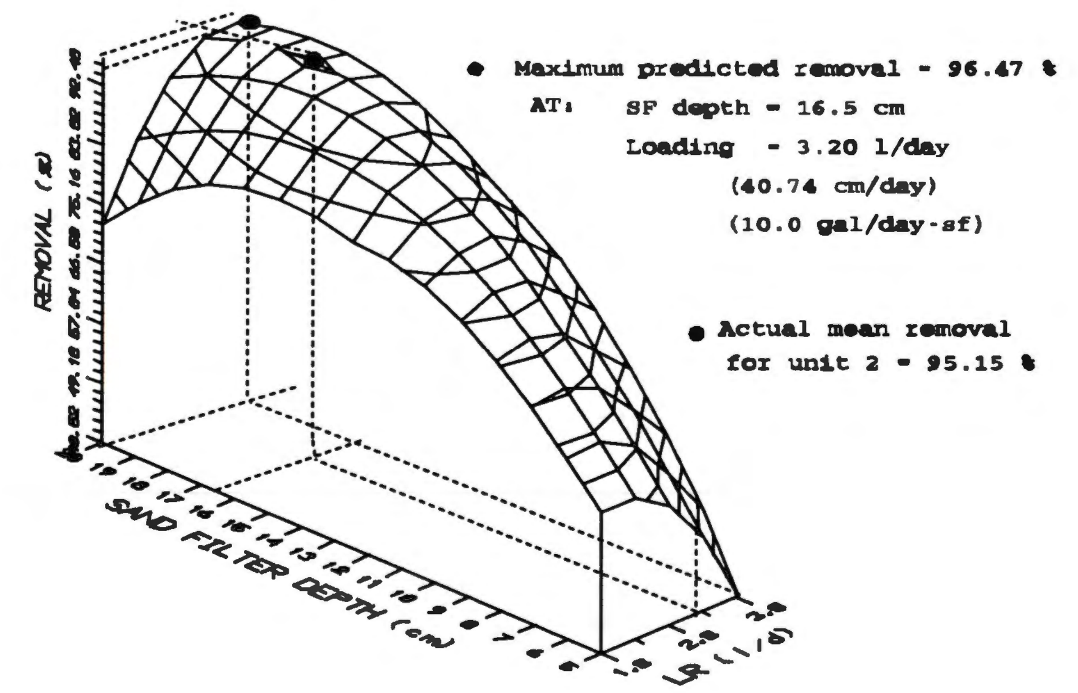

Figure 11. Predicted Mineral Nitrogen Removal by the Total System Expressed in Percent of Theoretical Maximum Removal as a Function of Sand Depth and Loading Rate for a Recirculation Ratio of 4.

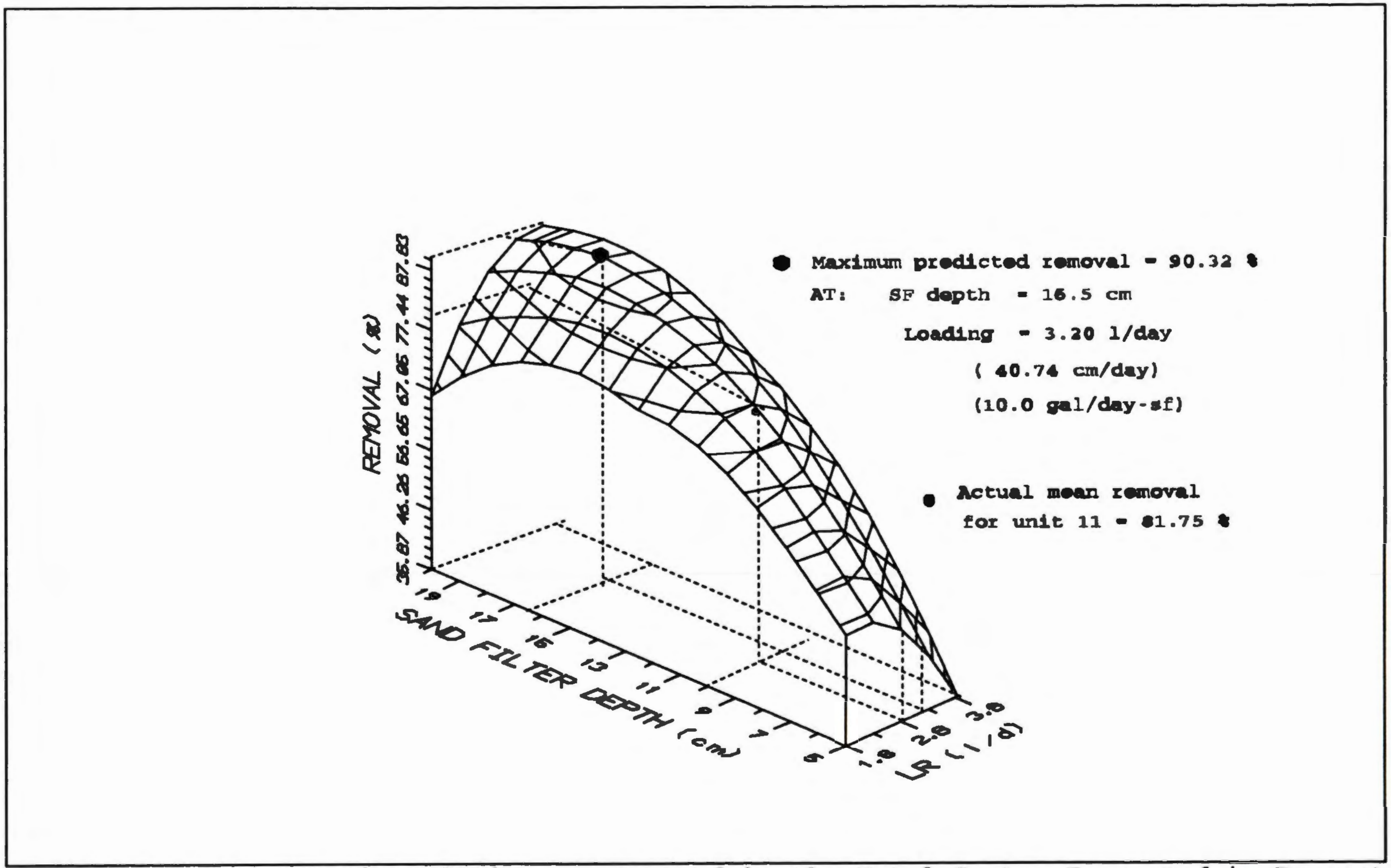

Figure 12. Predicted Mineral Nitrogen Removal by the Total System Expressed in Percent of Theoretical Maximum Removal as a Function of Sand Depth and Loading Rate for a Recirculation Ratio of 6.

maximum removal potential associated with an R of 4 and 6 indicates that system is predicted to actually remove a maximum of 72.35% of the mineral nitrogen when R is 4 and 75.26% when R is 6.

TOC removal in the RSF system

The RSF model system was also monitored for its TOC removal. The microorganisms (i.e, bacteria) convert organic matter into various gases (i.e, CO_2) and into cell tissue. Table 3, p 66, shows the TOC removal efficiencies for each of the 12 units modeled in the investigation. It includes TOC removals in the overall RSF unit system, as well as in the sand filter and DNC reactors, also the TOC removal that occurred in the system before the polishing filter. Overall system performance was based on the recirculating sand filter system unit, and a mass balance relationship for TOC was determined from system input (control sample) and polishing sand filter output (D sample) using Equation (7).

Organic carbon removals in the sand filter, DNC and system before polishing were calculated from mass balances performed on each reactor cell and for the whole system unit with its boundary condition at the exit effluent of the DNC reactor. These calculations were done as follows:

1. Sand filter, system input: T sample and system output: B sample, Equation (8).
2. DNC, system input: B and Control samples and system

output: T sample, Equation (9).

3. System before polishing filter (SBP), system input: C sample and system output: T sample, Equation (10).

The overall system performance in TOC removal efficiencies were (Table 3, p 66) high for all the units. Removal was over 80% in all but unit one, which had a slightly lower removal efficiency of 77.57%. Units three and seven had the highest values of 90.79% and 90.25% respectively. The remaining units had removal efficiency values between eighty and ninety percent.

TOC removal estimates for the recirculation components of the system without the polishing sand filter were made by considering the DNC effluent (T sample) as the system discharge. The polishing sand filter provided further treatment and its contribution was estimated. Table 3, p 66, shows the TOC removal efficiencies due to the further action of the polishing sand filter. This additional filter produced a maximum increase of 48.70% in unit three and a minimum of 8.50% in unit six for carbon removal.

The contribution of each of the reactors (recirculating sand filter, DNC and polishing filter) in the overall total RSF system TOC removal was determined and obtained as a partial contribution based on the overall systems's performance of each unit. Table 4 shows component contribution expressed as a percent of the total system performance in removing total organic carbon (TOC). Unit six

Table 4. Component Contribution Expressed as a Percent of Total System Performance in Removing TOC for the Twelve Experimental Units.

UNIT No.	TOC REMOVAL AS A PERCENT OF TOTAL SYSTEM'S PERFORMANCE			
	RSF SYSTEM %	SAND FILTER REACTOR %	DNC REACTOR %	POLISHING FILTER %
1	79.30	65.71	-3.89	27.40
2	84.67	76.40	-20.30	28.58
3	57.20	50.70	-10.69	17.20
4	73.31	57.86	-7.66	23.11
5	53.10	32.74	2.03	18.33
6	92.53	58.57	13.22	20.74
7	84.72	38.67	2.48	43.57
8	85.87	60.72	8.30	16.84
9	88.57	57.92	12.13	18.45
10	80.70	61.79	-1.24	20.15
11	84.35	74.53	-11.33	21.16
12	84.40	71.66	-3.85	16.59

had the highest percent removal (92.53%) for the system at a sand depth of 20 cm, R factor of 6 and loading rate of 2.88 l/day. The lowest percent removal (53.10%) was obtained in unit three at 5 cm of sand depth, R factor of 6 and 3.84 l/day of loading rate. The DNC reactor for unit six showed the highest performance of the twelve in removing TOC (13.22% removal). No removal of organic carbon occurred in the DNC reactor units one, two, three, four, ten, eleven and twelve; low carbon removal was observed in the DNC reactors of units five, seven, and eight.

The results suggest that TOC is removed mainly in the rectors with sand filter components. Thus, recirculation ratio, sand depth and loading rate are possible factors affecting TOC removal in a RSF unit.

The regression model for predicting overall RSF system TOC removal is given by Equation (17).

$$E_{TOC} = 16.13+7.22*SD-6.36*LR+2.55*R-0.21*SD^2 \qquad \textbf{(17)}$$

$$R^2 = 0.941681.$$

where the standard errors of regression estimates are:

$$\beta_0 \quad (\%) \quad = 16.13 \ {}^{+}_{-}\ 9.014819$$

$$\beta_1 \ (\%/\mathrm{cm}) = 7.22 \ {}^{+}_{-}\ 1.254492$$

$$\beta_2 \ (\%/\mathrm{cm}) = -6.36 \ {}^{+}_{-}\ 1.617732$$

$$\beta_3 \ (\%/\mathrm{cm}^2) = 2.55 \ {}^{+}_{-}\ 1.164767$$

$$\beta_4 \ (\%/\mathrm{cm}^2) = -0.21 \ {}^{+}_{-}\ 0.047727$$

The linear effect coefficients of sand depth (7.22) and recirculation ratio (2.55) show increased (positive slope) removal efficiency with increase of these parameters, while the linear effect of loading rate (-6.36 coefficient) and the quadratic effects of sand depth (-0.21 coefficient) show a decrease of TOC removal with increase of these parameters. Total organic carbon system removal is enhanced by high sand depth and recirculation ratios at low loading rates. The proximity to unity of the "goodness of fit" indicator, R^2, indicates the parameters included account for observed system removal of TOC.

Figure 13 shows the surface plot of equation 17 for overall RSF system TOC removal efficiency where all three operational parameters are significant. Predicted maximum removal occurs at recirculation ratio of 6 with 80.70% efficiency at sand depth of 17 cm and loading rates of 22.92 cm/day. More contact time (larger R) of the recirculating wastewater across the recirculating sand filter gave higher opportunity for the bacterial population to utilize carbon compounds as energy for the production of cell tissue and also convert it to gas.

Contribution of the recirculating sand filter reactor to total system TOC removal was determined. The removal efficiency values for the recirculating sand filter reactor showed significant effects from sand depth, loading rate and recirculation ratio. TOC removal in the recirculating sand filter reactor is predicted by regression Equation (18).

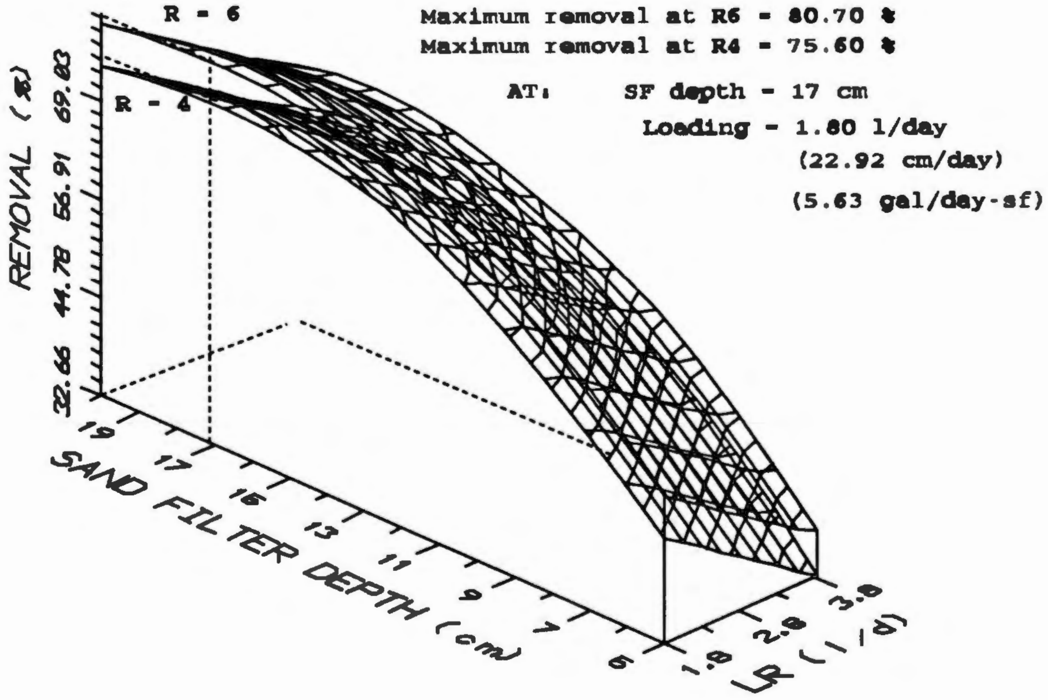

Figure 13. Response Surface for Total System TOC Removal as a Function of Sand Depth, Loading Rate, and Recirculation Ratio (R).

$$E_{TOC}=-33.24+8.19*SD+37.52*LR-5.41*R-0.23*SD^2-7.42*LR^2 \qquad (18)$$

$$R^2 = 0.966621$$

where the standard errors of the regression estimates are:

β_0 (%) = -33.24 $^{+}_{-}$ 20.005324

β_1 (%/cm) = 8.18 $^{+}_{-}$ 1.314381

β_2 (%/cm) = 37.52 $^{+}_{-}$ 15.409224

β_3 (%/cm^2) = -5.41 $^{+}_{-}$ 1.225666

β_4 (%/cm^2) = -0.23 $^{+}_{-}$ 0.050148

β_5 (%/cm^2) = -7.42 $^{+}_{-}$ 2.659867

The surface model for the best fit is plotted in Figures 14 and 15 for recirculation ratios of 4 and 6 respectively. Predicted maximum efficiency was 55.13% with a recirculation ratio of 4 and was 65.96% with a recirculation ratio of 6. Sand depth of 18.0 cm and loading rate of 31.83 cm/day gave the maximum.

A sand filter TOC removal efficiency of 5.43% is predicted with a sand depth of 5 cm and a loading rate of 48.38 cm/day. At the same sand depth and a loading rate of 22.92 cm/day, the removal efficiency went up to 15.78%.

Coliform and streptococcus bacterial removal in the RSF system

The RSF system performance in removal of coliform and streptococcus bacteria from domestic septic tank effluent was evaluated. The difference in bacterial content of system input wastewater and system treated output wastewater (from

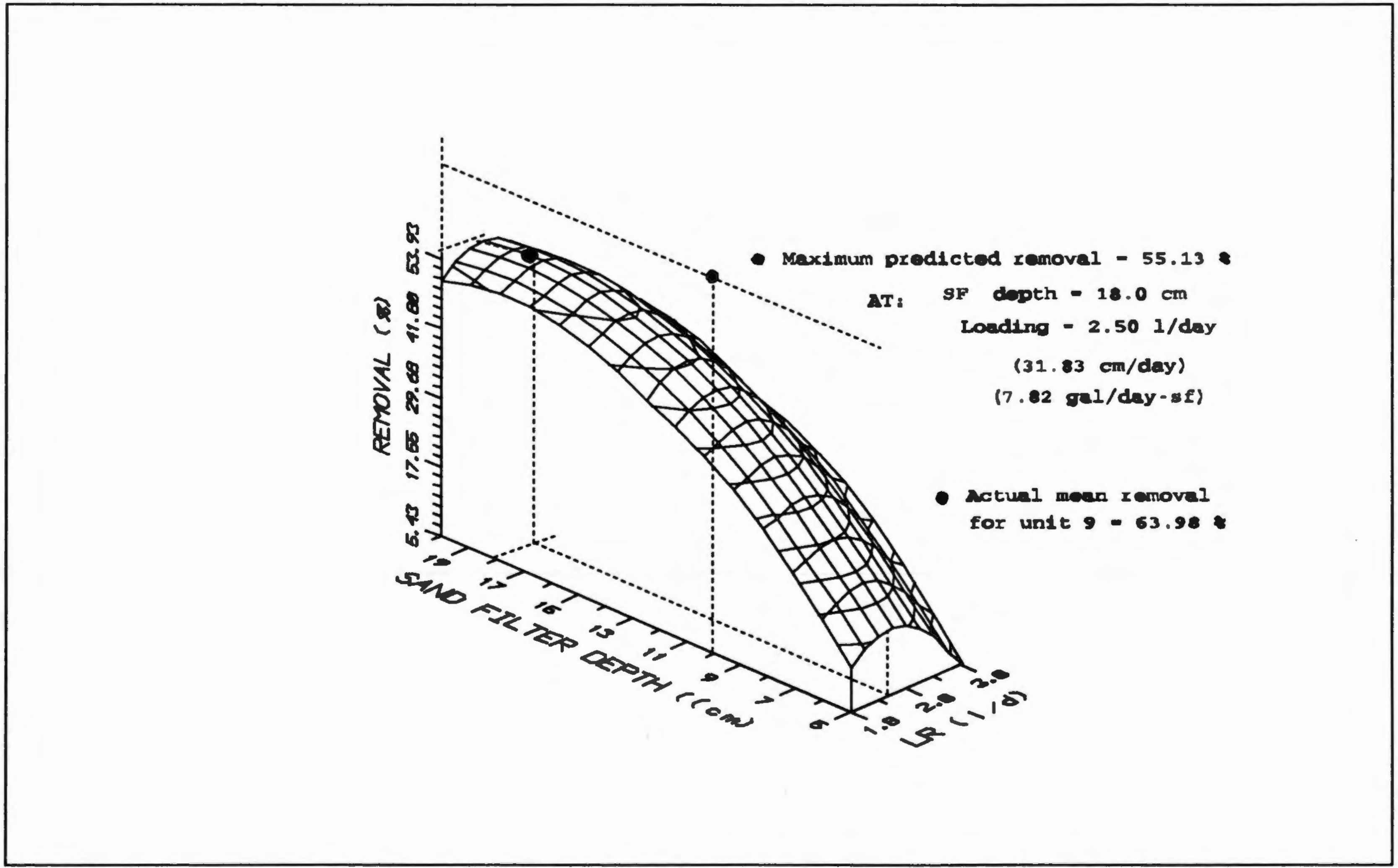

Figure 14. Response Surface for Contribution of the Recirculating Sand Filter Reactor to Total System TOC Removal as a Function of Sand Depth and Loading Rate for a Recirculation Ratio of 4.

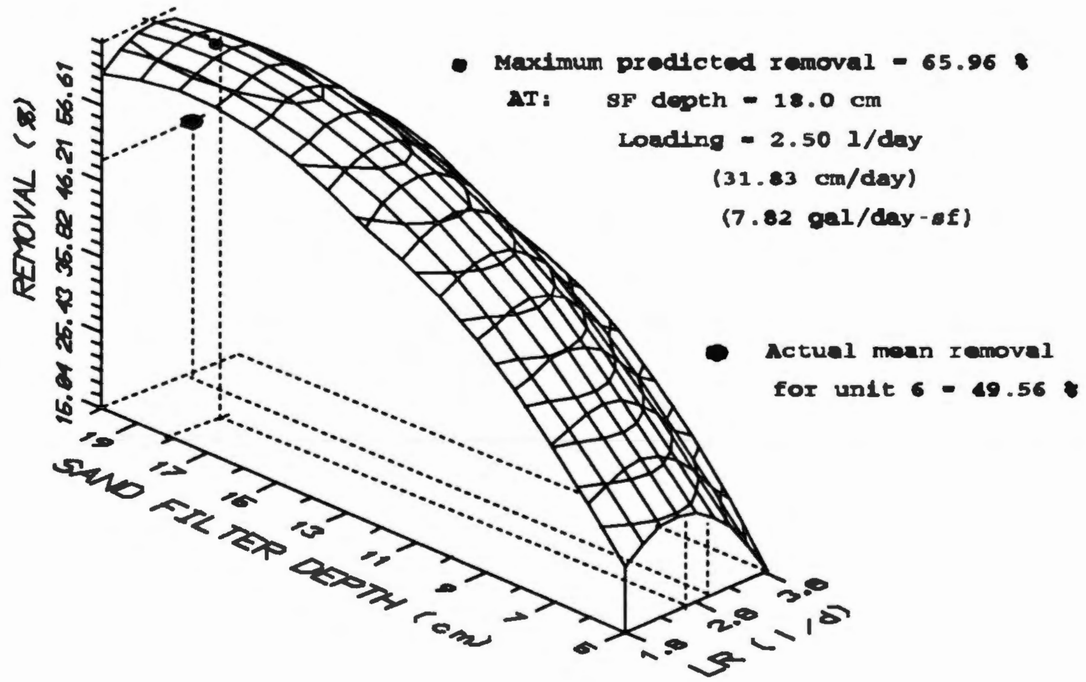

Figure 15. Response Surface for Contribution of Recirculating Sand Filter Reactor to Total System TOC Removal as a Function of Sand Depth and Loading Rate for a Recirculating Ratio of 6.

the polishing sand filter) determined bacteria removal. Table 5 lists values for averaged removal efficiency for all twelve experimental systems during the research period. All units had similar performance; bacterial count was very low after the treatment. The removal in each unit was well over 99%, except for streptococcus bacteria, for which removal efficiencies varied from 87 to 100%. Figure 16 illustrates bacterial removals efficiency for units one through twelve.

REDUCTION-OXIDATION POTENTIAL AND DENITRIFICATION

Throughout the course of this study, evidence of a definite relationship between reduction-oxidation (redox) potential in the denitrification reactor (DNC) and disappearance of nitrite/nitrate (NO_x^-) was observed. In general, NO_x^- concentrations in the DNC effluent varied with observed redox values. When redox values were at their lowest levels, little or no NO_x^- was present. This phenomenon is illustrated by the plot of observed redox values and NO_x removal efficiencies for the 47-week operating period of experimental system seven shown in Figure 17.

As explained earlier, initial arrangements for moving wastewater among system components permitted excessive transport of oxygen into the DNC and kept its redox potential high. The change in both redox potential (mV) and NO_x^- removal resulting from a modification in flow management during the

Table 5. Recirculating Sand Filter System Performance for the Removal Efficiency of Coliform and Streptococcus Bacteria from Domestic Septic Tank Effluent.

UNIT No.	TOTAL COLIFORM REMOVAL (%)	FECAL COLIFORM REMOVAL (%)	FECAL STREPT REMOVAL (%)
1	99.01	99.21	93.58
2	100	100	100
3	99.93	99.92	99.01
4	99.26	99.22	97.97
5	99.91	99.87	93.23
6	99.94	99.94	98.97
7	99.63	99.63	99.14
8	99.86	99.90	96.82
9	99.98	99.97	87.30
10	99.96	99.95	99.00
11	99.89	99.89	98.74
12	99.79	99.84	97.52

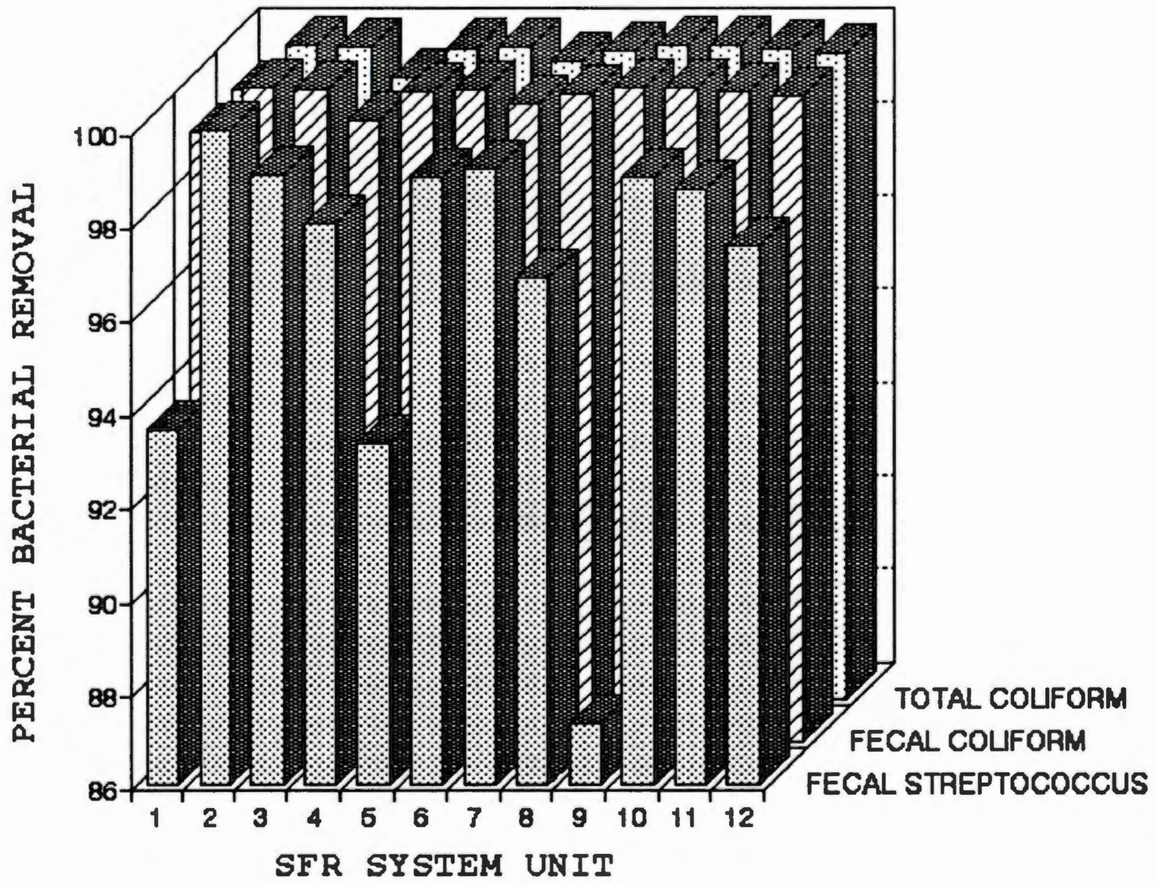

Figure 16. RSF System Mean Bacterial Removal Efficiencies for the 12 Research Units.

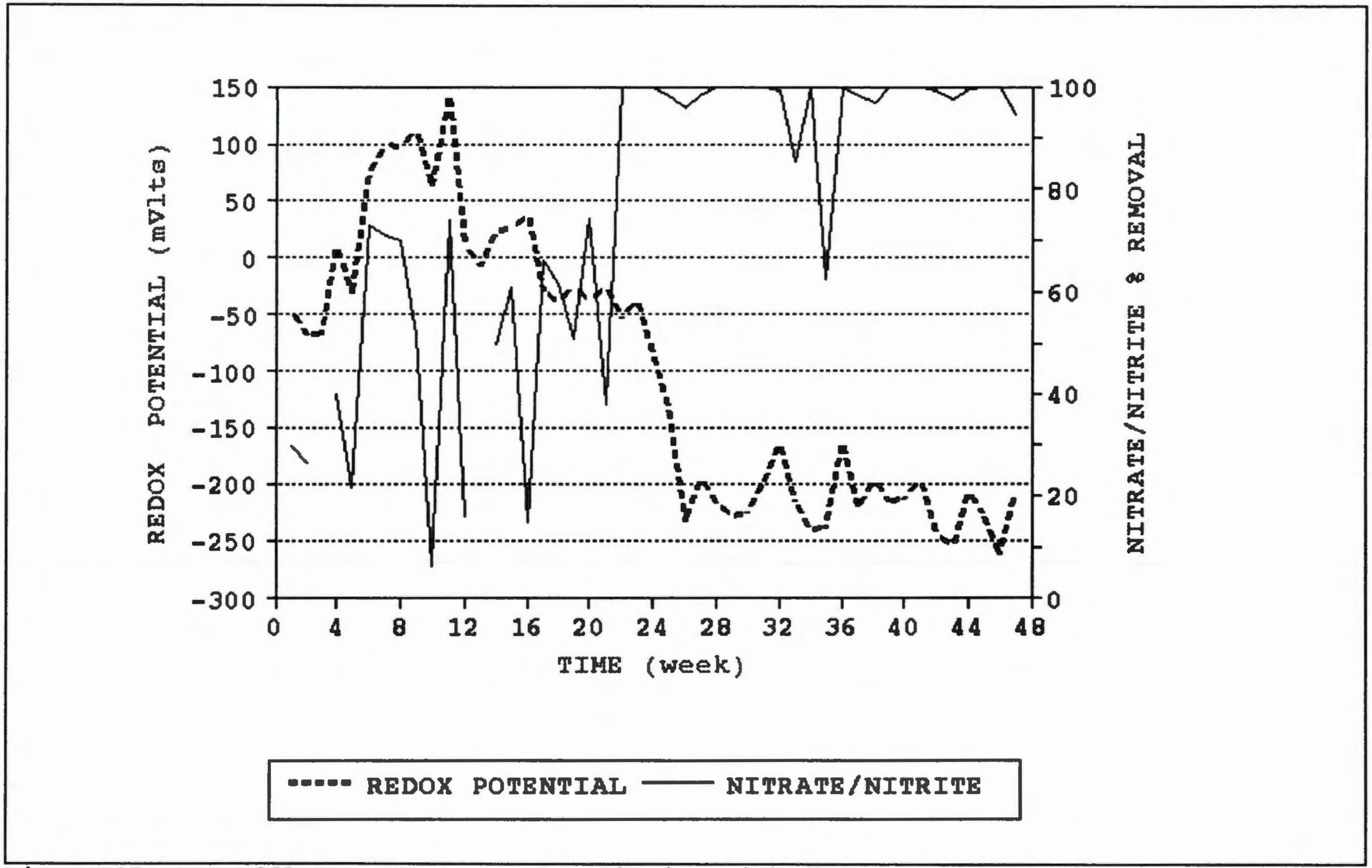

Figure 17. DNC Effluent NO_x^- Removal Variation with Observed Redox Values During 47-week Operation Period of Experimental Unit Seven.

22nd week of operation is obvious in Figure 17. Also obvious in Figure 17 is the fact that once redox was firmly established at values below -150 mV, NO_x^- removal became much more stable from observation to observation. When redox potential was above -150 mV, NO_x^- removal was highly variable. Removals commonly shifted from relatively high at a given observation to very low at the following one.

The above observation suggests that redox potential (mV) can be used as an indicator of stability of the denitrification process. Low values of redox potential (< -200 mV) indicate active and stable denitrification within the reactor. The nature of the relationship and validity of the concept of using redox voltage measure as indicator of active denitrification is clearly illustrated by Figure 18 in which observed redox voltage values for all DNC units throughout the 47-week observation period are plotted against measured NO_x^- concentration values.

A curve fitting maximum observed NO_x^- concentration values to observed redox potential values defines a relationship for establishing a criteria value of redox potential for desired denitrification activity within a reactor. Equation 19 describes such a curve for the system observed in this study (see Figure 19).

Such an equation could be helpful in predicting the minimum NO_x^- removal for a system, given an observed redox value. With such an equation, the relatively quickly measured

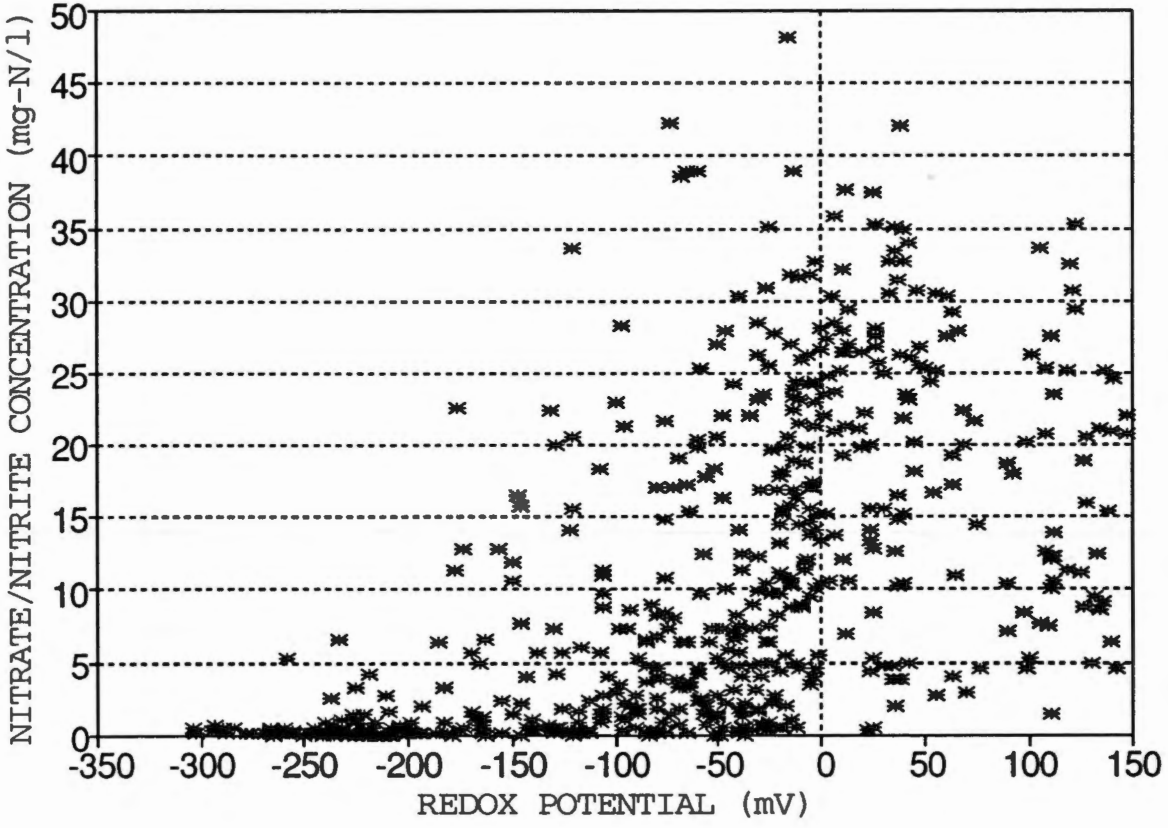

Figure 18. NO_x^- Concentration in DNC Effluent Versus Measured Redox Potential Values.

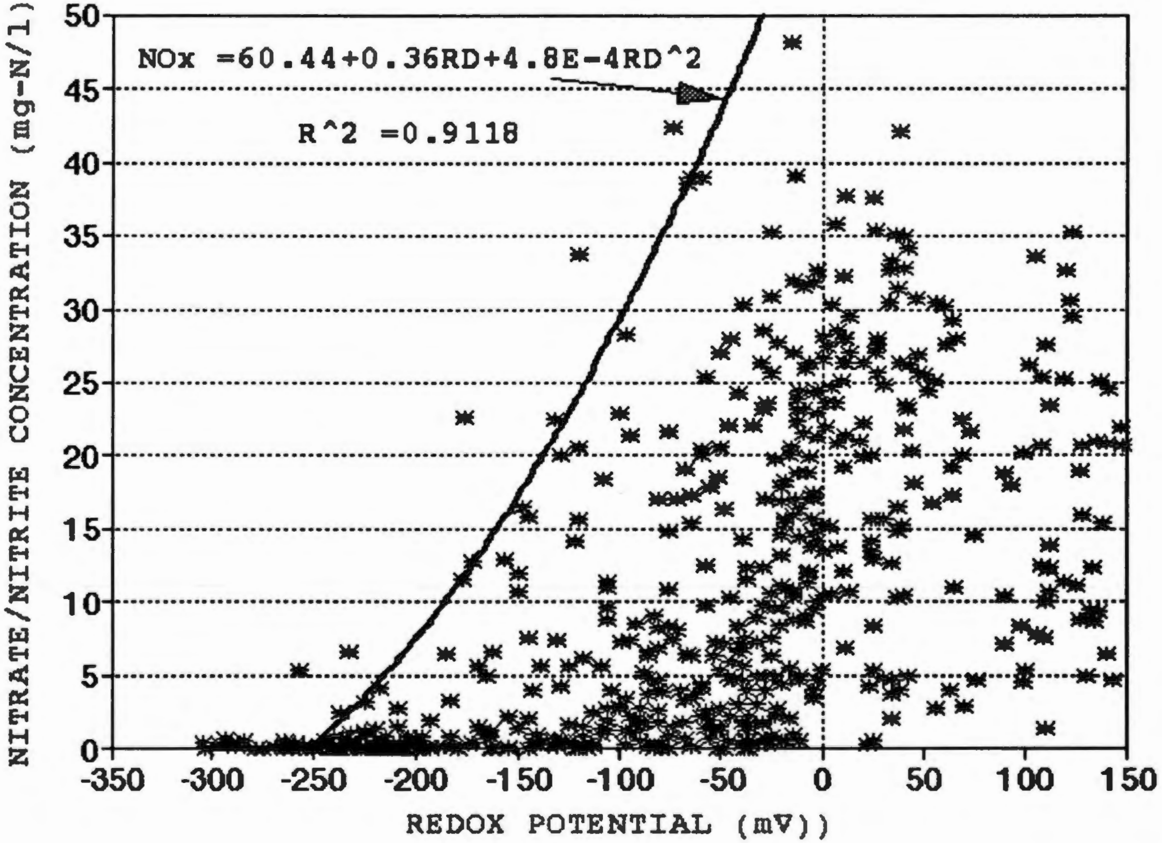

Figure 19. Regression Curve Predicting Maximum NO_3^--N Concentration of a DNC Effluent at a Given Redox Potential.

redox potential becomes a valuable parameter for monitoring performance of denitrification.

$$C_{NO_3^-} = 60.44 + 0.36*RD + 4.8E\text{-}4*RD^2 \tag{19}$$

$$R^2 = 0.9118$$

where:

RD = Redox potential measurement in mV.

C = Nitrate/Nitrite concentration in mg-N/liter.

CHAPTER 5

SUMMARY AND CONCLUSIONS

SUMMARY

Removal of organic compounds is a major function in on-site treatment of domestic septic tank effluent. Recirculating sand filter systems comprise a promising technology for use in organic compound removal. However, to develop an optimized system, a better understanding of the mechanisms and relationships between design parameters and performance capabilities is needed. Thus, this study aimed to determine and present definite relationships between RSF system operational parameters and removal efficiencies.

This investigation used domestic septic tank effluent as the wastewater source for the biological treatment, which was accomplished by RSF system model units. The specific operational system parameters of sand depth, recirculation ratio, and loading rate were combined at different levels and tested for their impact on the removal of mineral nitrogen, TOC, and bacteria from domestic septic tank effluent.

Prediction equations were developed and graphed for RSF system mineral nitrogen and TOC removals. For mineral nitrogen, the maximum predicted removal efficiency was 73.69%

when level of sand depth was 16.50 cm and loading rate was 40.74 cm/day. Recirculation ratio of 4 and 6 were no different, statistically, in effect on mineral nitrogen removal efficiency. Equation (15), graphed in Figure 10, presents the mineral nitrogen removal in a RSF system model.

For TOC removal, the recirculation ratio, R, plays an important role in the removal efficiency for a RSF system. According to the equation that best fit the data, a recirculation ratio of 6 should result in a maximum system removal efficiency of 80.70%, while a recirculation ratio of 4 results in a maximum removal efficiency of only 75.60%. Both maximum removal efficiencies occur at a sand depth of 17.00 cm and loading rate of 22.92 cm/day (see Figure 13). Equation (17) defines the quadratic response surface that best fit TOC system removal data.

Results showed that bacteria was removed with an efficiency of 99% in almost all the model systems. For bacterial removal, the polishing sand filter performed the final treatment in eliminating most of the bacteria present in the domestic septic tank effluent. The 30 cm of sand depth in the polishing filter was very effective in removal of bacteria.

The experimental RSF system units showed a definite response to environmental changes. Redox potential (mV) was measured inside the DNC reactor and gave an indication of the oxygen content of the wastewater. Redox potential value was used to monitor the denitrification response of the DNC reactor during the research period. A redox potential of -150 mV corresponded to an anoxic environment in the reactor where nitrate reduction began to maintain stability and increase removal efficiencies (60% to 100%).

Based on DNC redox potential readings between +150 mV to -350 mV, Equation (19) was developed to predict maximum concentration of NO_x^--N ions that can remain in the effluent waters of the DNC reactor. Figure 19 shows the regression curve for predicting remaining nitrate-nitrogen in treated wastewater.

CONCLUSIONS AND RECOMMENDATIONS

The simulation scale models successfully predicted parameter's importance to removal of mineral nitrogen, TOC and bacteria from domestic septic tank effluent in a recirculating sand filter system. Results indicated that:

1. The specific operating system parameters, sand depth in the recirculating sand filter and loading rate to the DNC, are definitive in predicting the performance of a RSF system model in removing mineral nitrogen from domestic septic tank effluent. The investigation showed that recirculation ratios of 4 and 6 were not different in effect on removal of nitrogen in a RSF model system.

2. The specific operating system parameter sand depth in

the recirculating sand filter showed definite linear and quadratic effects ($P < 0.10$) on TOC removal by a RSF model unit; loading rate to the DNC had only linear effects ($P < 0.10$).

3. Bacterial removal was achieved at very high levels of efficiency in all of the 12 units. The polishing filter played an important role in obtaining these results.

4. The DNC reactor performance is sharply affected by changes in the reactor from aerobic to anaerobic conditions. When the redox potential readings prevailed below a level of -150 mV, the nitrate/nitrite removal (denitrification) in the DNC was at its highest level (> 75%).

There was a definite correlation between redox potential reading and maximum nitrate-nitrogen concentration exiting the DNC. Equation (19) can be used in predicting the performance capabilities of a system by measuring its redox potential.

5. The results and environmental changes observed in the DNC reactor cell indicated that some modifications are needed to help maintain stability in the denitrification process. It was observed that, in time, the DNC reactor started to build an overabundance of slime. A mode of backwash should be implemented. Also there should be sufficient space at the bottom of the DNC cell, free of attachment media, to allow a better up-flow of the traveling wastewater across the DNC cell reactor, preventing clogging.

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APPENDICES

APPENDIX A.

ROBASIC Computer Software Program

ROBASIC COMPUTER SOFTWARE

```
 1 CYCLE=1
10 PRINT "CYCLE No. "; CYCLE "30 MINUTES CYCLE"
20 PRINT "LOADING RAW WASTEWATER TO DNC SYSTEMS: 1 TO 12 &
         CONTROL"
30 COUNT=0
40 SBIT 4,0
50 FOR X=0 TO 1
60 FOR Y=0 TO 7
70 COUNT=COUNT+1
80 PRINT "LOADING SYSTEM N0. "; COUNT " 2 EVENTS/30 MIN.
90 READ A
100 SBIT X,Y
110 DELAY A
120 RBIT X,Y
130 IF COUNT=13 THEN GOTO 160
140 NEXT Y
150 NEXT X
160 RBIT 4,0
170 PRINT "END OF DNC SYSTEM LOADING: FIRST EVENT OF 2
          EVENTS/30 MIN."
198 PRINT "              SYSTEMS 1-2-5-7-9-10 RECIRCULATION"
199 PRINT " SFR CYCLE RF-4 RECYCLE EACH 15 MIN.: FIRST EVENT
           OF 2"
200 GOSUB .RECYCLE
210 PRINT "END OF FIRST EVENT FOR SYSTEMS 1-2-5-7-9-10"
298 PRINT "                SYSTEMS 3-4-6-8-11-12 RECIRCULATION"
299 PRINT " SFR CYCLE RF-6 RECYCLE EACH 10 MIN.: FIRST EVENT
           OF 3"
300 GOSUB .RECYCLE
310 PRINT "END OF FIRST EVENT  FOR SYSTEMS 3-4-6-8-11-12"
320 PRINT "TIME DELAY":DELAY 468000
398 PRINT "              SYSTEMS 3-4-6-8-11-12 RECIRCULATION"
399 PRINT " SFR CYCLE RF-6 RECYCLE EACH 10 MIN.: SECOND EVENT
           OF 3"
400 GOSUB .RECYCLE
410 PRINT "END OF SECOND EVENT FOR SYSTEMS 3-4-6-8-11-12"
500 PRINT "LOADING RAW WASTEWATER TO DNC SYSTEMS: 1 TO 12 &
          CONTROL"
510 COUNT=0
515 SBIT 4,0
520 FOR X=0 TO 1
525 FOR Y=0 TO 7
530 COUNT=COUNT+1
535 PRINT "LOADING SYSTEM No. "; COUNT" 2 EVENTS/30 MIN."
540 READ A
545 SBIT X,Y
550 DELAY A
555 RBIT X,Y
```

```
560 IF COUNT = 13 THEN GOTO 575
565 NEXT Y
570 NEXT X
575 RBIT 4,0
580 PRINT "END OF DNC SYSTEM LOADING: SECOND EVENT OF 2
      EVENTS/30 MIN."
598 PRINT "              SYSTEMS 1-2-5-7-9-10 RECIRCULATION"
599 PRINT " SFR CYCLE RF-4 RECYCLE EACH 15 MIN: SECOND EVENT
       OF 2"
600 GOSUB .RECYCLE
610 PRINT "END OF SECOND EVENT FOR SYSTEMS 1-2-5-7-9-10"
620 PRINT "TIME DELAY":DELAY 68000
648 PRINT "               SYSTEMS 3-4-6-8-11-12 RECIRCULATION"
649 PRINT "SFR CYCLE RF-6 RECYCLE EACH 10 MIN.: THIRD EVENT OF
     3"
650 GOSUB .RECYCLE
651 PRINT "END OF THIRD EVENT FOR SYSTEMS 3-4-6-8-11-12"
655 PRINT "TIME DELAY":DELAY 500000
820 PRINT "END OF 30 MINUTES CYCLE"
900 CYCLE=CYCLE+1
950 RESTORE
960 GOTO 10
1000 .RECYCLE
1005 READ C,D,E,F,G,H,I,J,K,L,M,N,O,P,Q,R,S,T,U,V,W,X,Y,Z,A
1010 SBIT C,D
1015 SBIT E,F
1020 SBIT G,H
1025 SBIT I,J
1030 SBIT K,L
1035 SBIT M,N
1040 SBIT O,P
1045 SBIT Q,R
1050 SBIT S,T
1055 SBIT U,V
1060 SBIT W,X
1065 SBIT Y,Z
1070 DELAY A
1075 RBIT C,D
1080 RBIT E,F
1085 RBIT G,H
1090 RBIT I,J
1095 RBIT K,L
1100 RBIT M,N
1105 RBIT O,P
1110 RBIT Q,R
1115 RBIT S,T
1120 RBIT U,V
1125 RBIT W,X
1130 RBIT Y,Z
1135 RETURN
4000 DATA 8000,14000,10800,14000,14000,11000,5000,7300,7500,
     7300,11300,10500,11300
```

```
5000 DATA 4,1,2,4,4,2,2,5,4,5,5,5,4,7,5,7,5,1,6,1,5,2,6,2,
          100000
6000 DATA 4,3,2,6,4,4,2,7,4,6,5,6,5,0,6,0,5,3,6,3,5,4,6,4,
          100000
8000 DATA 4,3,2,6,4,4,2,7,4,6,5,6,5,0,6,0,5,3,6,3,5,4,6,4,
          100000
10000 DATA 8000,14000,10800,14000,14000,11000,5000,7300,7500,
           7300,11300,10500,11300
11000 DATA 4,1,2,4,4,2,2,5,4,5,5,5,4,7,5,7,5,1,6,1,5,2,6,2,
           100000
13000 DATA 4,3,2,6,4,4,2,7,4,6,5,6,5,0,6,0,5,3,6,3,5,4,6,4,
           100000
END
```

APPENDIX B

Data Used for Analysis of System Performance

Table B1. Data for Analysis of RSF System Performance of Unit One.

SAMPLE DATE	UNIT PORT	TOC (mg/L)	NH_3-N (mg/L)	T.Coliform (CFU/ml)	F.Coliform (CFU/ml)	F.Strepto (mg/L)	NO_2^--N (mg/L)	NO_3^--N (mg/L)	PO_4^--P (mg/L)	Cl (mg/L)	REDOX (mV)	pH
4/13/93	1 B	26.56	9.03	190.00	160.00	50.00	0.00	6.63	9.84	45.60		
4/20/93	1 B	25.55	4.19				0.00	10.74	10.54	39.26		
4/27/93	1 B	23.00	4.69	260.00	110.00	30.00	0.00	14.82	9.93	31.12		
5/4/93	1 B	27.78	5.57				0.00	13.81	13.79	41.81		
5/11/93	1 B	49.41	13.51	270.00	180.00	160.00	0.00	12.19	14.52	49.31		
6/8/93	1 B	26.31	12.49				0.00	19.18	10.86	47.40		
4/13/93	1 D	24.48	3.51	73.00	46.00	5.00	0.00	9.94	10.61	46.93	-264.00	6.90
4/20/93	1 D	23.94	0.74				0.00	14.97	12.01	39.72	-235.00	6.80
4/27/93	1 D	29.01	5.34	38.00	10.00	12.00	0.00	12.14	10.83	33.10	-181.00	6.80
5/4/93	1 D	31.62	4.56				0.00	13.92	12.73	39.90	-155.00	6.80
5/11/93	1 D	35.22	2.61	45.00	33.00	7.00	0.00	19.36	13.70	47.57	-175.00	6.90
6/8/93	1 D	15.43	1.98				0.00	32.31	11.10	48.13	-233.00	6.80
4/13/93	1 T	50.10	21.26	400.00	200.00	99.00	0.00	0.00	10.07	47.82		
4/20/93	1 T	48.37	15.66				0.00	0.08	11.45	39.13		
4/27/93	1 T	49.46	18.39	99.00	400.00	100.00	0.00	0.42	9.96	31.05		
5/4/93	1 T	55.22	18.35				0.00	0.06	13.62	40.82		
5/11/93	1 T	75.88	29.89	99.00	100.00	10.00	0.00	0.33	15.44	48.52		
6/8/93	1 T	49.35	23.88				0.00	6.59	11.92	48.00		

Table B2. Data for Analysis of RSF System Performance of Unit Two.

SAMPLE DATE	UNIT PORT	TOC (mg/L)	NH_3-N (mg/L)	T.Coliform (CFU/ml)	F.Coliform (CFU/ml)	F.Strepto (mg/L)	NO_2^--N (mg/L)	NO_3^--N (mg/L)	PO_4^--P (mg/L)	Cl (mg/L)	REDOX (mV)	pH
4/13/93	2 B	19.96	3.13	40.00	30.00	9.00	0.00	8.57	9.86	47.14		
4/20/93	2 B	23.13	2.06				0.00	12.07	10.49	39.14		
6/1/93	2 B	23.89	4.66				0.00	16.76	12.67	43.67		
6/8/93	2 B	16.93	4.56				0.00	25.25	11.16	43.31		
4/13/93	2 D	25.52	0.29	5.00	3.00	0.90	0.00	9.96	9.46	46.18	-220.00	6.70
4/20/93	2 D	25.45	0.00				0.00	14.82	11.34	39.57	-209.00	6.70
6/1/93	2 D	19.12	0.10				0.00	22.47	10.40	43.18	-183.00	6.60
6/8/93	2 D	19.63	2.67				0.00	25.86	10.40	47.24	-177.00	6.70
4/13/93	2 T	47.42	18.76	1200.00	700.00	99.00	0.00	0.00	9.80	48.16		
4/20/93	2 T	47.09	14.12				0.00	0.00	11.55	39.22		
6/1/93	2 T	43.25	15.12				0.00	3.32	10.40	44.67		
6/8/93	2 T	46.08	20.43				0.00	11.44	12.31	47.48		

Table B3. Data for Analysis of RSF System Performance of Unit Three.

SAMPLE DATE	UNIT PORT	TOC (mg/L)	NH_3-N (mg/L)	T.Coliform (CFU/ml)	F.Coliform (CFU/ml)	F.Strepto (mg/L)	NO_2^--N (mg/L)	NO_3^--N (mg/L)	PO_4^--P (mg/L)	Cl (mg/L)	REDOX (mV)	pH
4/13/93	3 B	56.82	35.45	570.00	41.00	9.00	0.00	2.74	10.05	47.69		
4/20/93	3 B	51.56	23.93				0.00	5.49	10.42	39.87		
4/27/93	3 B	43.26	17.86	290.00	140.00	70.00	0.00	5.00	10.25	34.05		
5/4/93	3 B	63.68	29.72				0.00	4.82	13.61	42.71		
5/11/93	3 B	58.45	18.41	40.00	40.00	10.00	0.00	6.25	13.21	49.11		
5/18/93	3 B	51.48	25.03				0.00	16.72	12.40	43.43		
6/1/93	3 B	61.54	31.98				0.00	5.43	11.10	45.51		
6/8/93	3 B	67.01	38.35				0.00	4.59	11.38	48.35		
4/13/93	3 D	9.05	1.45	7.00	7.00	0.90	0.00	22.69	10.42	46.44	-250.00	6.90
4/20/93	3 D	9.33	0.00				0.00	35.71	12.19	39.64	-241.00	6.90
4/27/93	3 D	9.99	0.18	6.00	10.00	2.00	0.00	28.66	10.92	33.97	-225.00	6.90
5/4/93	3 D	10.09	0.55				0.00	42.04	13.97	41.83	-238.00	7.00
5/11/93	3 D	10.69	5.17	2.00	1.00	0.90	0.00	43.11	13.02	46.88	-240.00	7.00
5/18/93	3 D	10.27	0.01				0.00	38.61	12.65	43.77	-200.00	6.90
6/1/93	3 D	10.63	1.64				0.00	46.06	10.78	42.33	-257.00	6.90
6/8/93	3 D	16.40	8.56				0.00	37.50	10.94	47.74	-305.00	7.10
4/13/93	3 T	63.31	40.46	400.00	300.00	99.00	0.00	0.00	10.07	48.32		
4/20/93	3 T	66.35	31.02				0.00	0.00	11.63	39.43		
4/27/93	3 T	53.62	25.78	300.00	200.00	99.00	0.00	0.99	9.40	30.54		
5/4/93	3 T	75.04	35.67				0.00	0.03	13.54	41.54		
5/11/93	3 T	70.47	20.03	300.00	99.00	10.00	0.00	0.02	13.71	48.10		
5/18/93	3 T	65.86	31.96				0.00	0.02	12.48	44.00		
6/1/93	3 T	73.90	36.91				0.00	0.02	11.83	49.30		
6/8/93	3 T	77.58	42.22				0.00	0.41	12.46	47.88		

Table B4. Data for Analysis of RSF System Performance of Unit Four.

SAMPLE DATE	UNIT PORT	TOC (mg/L)	NH_3-N (mg/L)	T.Coliform (CFU/ml)	F.Coliform (CFU/ml)	F.Strepto (mg/L)	NO_2^--N (mg/L)	NO_3^--N (mg/L)	PO_4^--P (mg/L)	Cl (mg/L)	REDOX (mV)	pH
3/30/93	4 B	28.15	9.35	500.00	50.00	9.00	0.00	2.95	6.56	25.83		
4/27/93	4 B	32.87	13.34	260.00	130.00	50.00	0.00	8.91	10.53	33.53		
5/4/93	4 B	46.51	15.29				0.00	7.79	12.76	41.48		
5/11/93	4 B	71.40	30.62	510.00	130.00	20.00	0.00	18.51	13.28	46.40		
6/1/93	4 B	46.44	22.75				0.00	7.54	11.34	45.36		
6/8/93	4 B	35.62	18.78				0.00	14.35	11.18	48.44		
3/30/93	4 D	18.09	0.18	6.00	0.90	0.90	0.00	9.28	5.74	24.46	-200.00	6.90
4/27/93	4 D	16.55	1.26	19.00	7.00	4.00	0.00	20.60	10.25	31.80	-209.00	6.80
5/4/93	4 D	19.84	2.31				0.00	26.30	12.62	40.98	-226.00	6.90
5/11/93	4 D	35.79	17.04	44.00	40.00	6.00	0.00	30.46	14.36	47.96	-225.00	6.90
6/1/93	4 D	16.19	2.25				0.00	32.47	10.81	42.97	-220.00	6.80
6/8/93	4 D	13.67	1.98				0.00	32.28	10.49	46.61	-257.00	6.80
3/30/93	4 T	40.07	14.53	900.00	500.00	99.00	0.00	0.46	6.62	25.12		
4/27/93	4 T	45.49	19.83	700.00	300.00	99.00	0.00	1.46	9.84	30.80		
5/4/93	4 T	60.00	25.88				0.00	1.31	13.45	42.39		
5/11/93	4 T	85.83	37.84	99.00	99.00	60.00	0.00	3.13	14.68	49.14		
6/1/93	4 T	57.47	27.06				0.00	1.35	10.38	44.75		
6/8/93	4 T	51.17	27.60				0.00	5.33	11.96	47.71		

Table B5. Data for Analysis of RSF System Performance of Unit Five.

SAMPLE DATE	UNIT PORT	TOC (mg/L)	NH_3-N (mg/L)	T.Coliform (CFU/ml)	F.Coliform (CFU/ml)	F.Strepto (mg/L)	NO_2^--N (mg/L)	NO_3^--N (mg/L)	PO_4^--P (mg/L)	Cl (mg/L)	REDOX (mV)	pH
3/23/93	5 B	51.46	26.22				0.00	4.39	10.31	32.18		
3/30/93	5 B	50.99	25.51	560.00	2700.00	10.00	0.00	3.66	6.96	25.56		
4/13/93	5 B	62.03	43.56	540.00	480.00	20.00	0.00	2.89	10.68	48.31		
4/20/93	5 B	62.32	33.98				0.00	5.04	10.49	40.33		
5/4/93	5 B	74.94	38.51				0.00	4.94	13.73	43.48		
5/11/93	5 B	71.98	34.96	130.00	40.00	1200.00	0.00	5.22	13.16	49.05		
5/18/93	5 B	60.16	34.18				0.00	14.39	12.43	44.83		
6/8/93	5 B	60.57	39.46				0.00	8.32	11.24	47.35		
3/23/93	5 D	11.46	0.46				0.00	31.57	10.95	32.66	-255.00	7.00
3/30/93	5 D	11.87	0.26	2.00	0.90	0.90	0.00	20.32	6.78	25.10	-265.00	6.90
4/13/93	5 D	10.62	3.90	4.00	4.00	3.00	0.00	24.97	10.19	47.00	-212.00	6.90
4/20/93	5 D	14.83	5.27				0.00	38.67	12.23	39.87	-246.00	6.90
5/4/93	5 D	13.29	6.45				0.00	48.09	12.64	39.81	-260.00	7.00
5/11/93	5 D	12.69	8.20	5.00	6.00	18.00	0.00	53.32	13.23	47.27	-265.00	7.00
5/18/93	5 D	12.37	3.48				0.00	43.06	11.38	38.37	-225.00	7.00
6/8/93	5 D	13.48	5.25				0.00	48.25	11.37	47.53	-293.00	7.10
3/23/93	5 T	60.68	29.59				0.00	0.24	10.53	33.25		
3/30/93	5 T	62.67	31.10	600.00	600.00	99.00	0.00	0.08	7.21	25.03		
4/13/93	5 T	75.20	47.14	200.00	200.00	99.00	0.00	0.00	9.75	47.90		
4/20/93	5 T	76.15	41.07				0.00	0.14	11.61	39.58		
5/4/93	5 T	91.19	44.79				0.00	0.02	13.64	42.57		
5/11/93	5 T	84.22	46.06	99.00	99.00	60.00	0.00	0.25	13.18	47.30		
5/18/93	5 T	73.73	40.55				0.00	0.80	12.98	44.36		
6/8/93	5 T	70.02	47.06				0.00	0.68	12.16	47.56		

Table B6. Data for Analysis of RSF System Performance of Unit Six.

SAMPLE DATE	UNIT PORT	TOC (mg/L)	NH_3-N (mg/L)	T.Coliform (CFU/ml)	F.Coliform (CFU/ml)	F.Strepto (mg/L)	NO_2^--N (mg/L)	NO_3^--N (mg/L)	PO_4^--P (mg/L)	Cl (mg/L)	REDOX (mV)	pH
4/13/93	6 B	19.03	1.68	10.00	10.00	9.00	0.00	6.76	10.44	48.02		
4/20/93	6 B	21.40	0.62				0.00	9.34	10.53	39.00		
4/27/93	6 B	32.87	0.78	40.00	10.00	10.00	0.00	16.29	11.58	37.11		
5/4/93	6 B	17.35	0.55				0.00	19.06	13.57	42.17		
5/11/93	6 B	14.16	10.30	9.00	9.00	9.00	0.00	23.21	12.83	47.06		
6/1/93	6 B	14.83	0.41				0.00	23.41	12.07	44.96		
6/8/93	6 B	11.73	1.29				0.00	31.56	11.41	48.19		
4/13/93	6 D	23.36	0.06	0.90	1.00	0.90	0.00	7.26	10.21	47.16	-140.00	6.70
4/20/93	6 D	23.09	0.00				0.00	10.67	11.73	39.49	-125.00	6.70
4/27/93	6 D	24.60	0.18	8.00	4.00	2.00	0.00	12.60	9.02	33.03	-138.00	6.70
5/4/93	6 D	26.71	1.05				0.00	15.83	11.78	41.93	-150.00	6.80
5/11/93	6 D	24.79	2.31	2.00	2.00	1.00	0.00	20.45	11.95	47.43	-145.00	6.80
6/1/93	6 D	17.91	0.00				0.00	24.90	11.32	44.71	-173.00	6.60
6/8/93	6 D	13.77	0.00				0.00	35.76	10.96	47.71	-176.00	6.50
4/13/93	6 T	33.31	12.57	100.00	99.00	99.00	0.00	1.05	9.71	47.95		
4/20/93	6 T	35.58	9.16				0.00	1.66	12.51	40.48		
4/27/93	6 T	29.21	8.05	99.00	99.00	99.00	0.00	5.48	9.69	30.42		
5/4/93	6 T	30.33	10.82				0.00	10.70	13.24	41.24		
5/11/93	6 T	37.48	49.75	100.00	99.00	10.00	0.00	7.63	13.37	47.57		
6/1/93	6 T	32.82	11.68				0.00	12.71	9.67	47.58		
6/8/93	6 T	25.95	10.51				0.00	22.61	11.93	47.36		

Table B7. Data for Analysis of RSF System Performance of Unit Seven.

SAMPLE DATE	UNIT PORT	TOC (mg/L)	NH_3-N (mg/L)	T.Coliform (CFU/ml)	F.Coliform (CFU/ml)	F.Strepto (mg/L)	NO_2^--N (mg/L)	NO_3^--N (mg/L)	PO_4^--P (mg/L)	Cl (mg/L)	REDOX (mV)	pH
4/13/93	7 B	33.62	17.58	140.00	90.00	9.00	0.00	8.68	10.73	49.07		
4/20/93	7 B	57.99	27.48				0.00	11.82	10.25	41.52		
5/4/93	7 B	57.95	25.33				0.00	5.84	12.96	41.83		
5/11/93	7 B	56.42	0.94	80.00	40.00	30.00	0.00	4.97	12.76	48.22		
5/18/93	7 B	67.44	40.55				0.00	5.15	12.31	40.59		
5/25/93	7 B	51.64	28.68	275.00	153.00	115.00	0.00	9.45	10.77	46.84		
6/1/93	7 B	51.11	24.60				0.00	6.55	11.23	45.21		
6/8/93	7 B	42.21	20.57				0.00	8.99	10.52	48.05		
4/13/93	7 D	9.03	0.20	1.00	0.90	1.00	0.00	17.26	10.02	45.84	-215.00	7.00
4/20/93	7 D	11.89	2.51				0.00	32.16	11.67	39.33	-213.00	6.80
5/4/93	7 D	10.18	0.02				0.00	38.83	13.59	40.04	-243.00	7.00
5/11/93	7 D	11.44	1.83	2.00	0.90	0.90	0.00	39.37	13.64	47.57	-255.00	6.90
5/18/93	7 D	11.81	25.41				0.00	45.18	13.03	39.22	-206.00	7.00
5/25/93	7 D	17.60	8.70	54.00	28.00	23.00	0.00	33.79	11.62	45.20	-225.00	7.00
6/1/93	7 D	9.73	0.00				0.00	41.85	10.96	47.46	-261.00	7.00
6/8/93	7 D	10.79	0.05				0.00	36.31	11.38	47.58	-208.00	7.00
4/13/83	7 T	60.71	32.11	600.00	500.00	100.00	0.00	0.00	10.09	47.99		
4/20/93	7 T	73.31	36.34				0.00	0.00	11.39	38.81		
5/4/93	7 T	69.36	33.41				0.00	0.03	12.90	39.74		
5/11/93	7 T	65.23	14.55	300.00	100.00	10.00	0.00	0.10	13.23	47.78		
5/18/93	7 T	79.44	45.12				0.00	0.02	13.42	44.55		
5/25/93	7 T	68.81	35.23	760.00	330.00	70.00	0.00	0.02	11.52	45.21		
6/1/93	7 T	61.47	29.52				0.00	0.02	10.15	43.91		
6/8/93	7 T	57.41	29.26				0.00	0.37	11.50	48.00		

Table B8. Data for Analysis of RSF System Performance of Unit Eight.

SAMPLE DATE	UNIT PORT	TOC (mg/L)	NH_3-N (mg/L)	T.Coliform (CFU/ml)	F.Coliform (CFU/ml)	F.Strepto (mg/L)	NO_2^--N (mg/L)	NO_3^--N (mg/L)	PO_4^--P (mg/L)	Cl (mg/L)	REDOX (mV)	pH
4/13/93	8 B	22.01	2.51	30.00	30.00	10.00	0.00	6.54	10.72	48.76		
4/20/93	8 B	23.36	1.55				0.00	8.69	10.54	39.83		
5/4/93	8 B	24.01	5.57				0.00	18.06	13.13	42.00		
6/1/93	8 B	21.66	3.07				0.00	20.04	10.59	47.50		
6/8/93	8 B	16.12	3.13				0.00	26.66	11.20	47.56		
4/13/93	8 D	19.28	0.20	21.00	11.00	7.00	0.00	7.50	10.66	46.35	-108.00	6.80
4/20/93	8 D	21.34	0.00				0.00	11.26	12.15	40.49	-112.00	6.80
5/4/93	8 D	13.77	0.02				0.00	24.88	13.13	40.57	-121.00	6.70
6/1/93	8 D	15.72	0.00				0.00	18.62	11.18	43.37	-128.00	6.80
6/8/93	8 D	10.96	0.00				0.00	35.52	12.88	47.83	-145.00	6.70
4/13/93	8 T	36.92	13.74	99.00	99.00	99.00	0.00	0.88	9.79	46.84		
4/20/93	8 T	39.06	12.47				0.00	0.14	11.90	39.78		
5/4/93	8 T	31.14	10.82				0.00	14.10	12.75	40.26		
6/1/93	8 T	37.23	12.91				0.00	4.23	10.27	44.44		
6/8/93	8 T	31.89	14.64				0.00	15.76	12.67	47.41		

Table B9. Data for Analysis of RSF System Performance of Unit Nine.

SAMPLE DATE	UNIT PORT	TOC (mg/L)	NH_3-N (mg/L)	T.Coliform (CFU/ml)	F.Coliform (CFU/ml)	F.Strepto (mg/L)	NO_2^--N (mg/L)	NO_3^--N (mg/L)	PO_4^--P (mg/L)	Cl (mg/L)	REDOX (mV)	pH
4/13/93	9 B	14.09	0.40	160.00	120.00	9.00	0.00	10.42	10.19	48.59		
4/20/93	9 B	13.95	0.00				0.00	17.80	10.69	40.06		
5/4/93	9 B	14.63	0.02				0.00	21.29	13.13	41.12		
5/11/93	9 B	9.40	5.05	9.00	9.00	9.00	0.00	30.16	12.94	47.40		
6/8/93	9 B	8.50	0.07				0.00	30.65	11.32	47.63		
4/13/93	9 D	19.62	0.20	1.00	0.90	0.90	0.00	9.27	8.71	45.46	-97.00	6.80
4/20/93	9 D	20.91	0.00				0.00	19.80	9.19	39.97	-100.00	6.70
5/4/93	9 D	21.29	0.02				0.00	21.14	9.91	38.31	-117.00	6.70
5/11/93	9 D	16.29	0.00	0.90	0.90	25.00	0.00	29.86	10.92	46.98	-120.00	6.70
6/8/93	9 D	13.80	0.00				0.00	35.65	10.73	48.86	-149.00	6.80
4/13/93	9 T	31.92	13.74	99.00	99.00	99.00	0.00	3.42	9.13	47.89		
4/20/93	9 T	40.18	16.25				0.00	2.77	11.48	39.12		
5/4/93	9 T	37.77	10.82				0.00	6.21	13.02	40.07		
5/11/93	9 T	23.93	15.92	99.00	99.00	10.00	0.00	20.58	13.42	47.64		
6/8/93	9 T	36.58	18.78				0.00	11.85	12.33	47.85		

Table B10. Data for Analysis of RSF System Performance of Unit Ten.

SAMPLE DATE	UNIT PORT	TOC (mg/L)	NH_3-N (mg/L)	T.Coliform (CFU/ml)	F.Coliform (CFU/ml)	F.Strepto (mg/L)	NO_2^--N (mg/L)	NO_3^--N (mg/L)	PO_4^--P (mg/L)	Cl (mg/L)	REDOX (mV)	pH
4/20/93	10 B	21.99	2.91				0.00	13.37	10.49	39.40		
5/4/93	10 B	23.61	3.94				0.00	16.42	12.38	41.30		
5/11/93	10 B	18.15	0.33	20.00	20.00	60.00	0.00	25.97	12.84	47.46		
5/18/93	10 D	19.41	3.71				0.00	18.38	10.48	39.07		
6/1/93	10 B	23.28	5.74				0.00	23.17	10.44	47.55		
6/8/93	10 B	22.24	8.56				0.00	22.39	10.91	48.01		
4/20/93	10 D	24.58	0.00				0.00	18.09	11.25	39.73	-96.00	6.70
5/4/93	10 D	20.65	0.02				0.00	23.71	13.15	42.39	-105.00	6.70
5/11/93	10 D	16.65	0.00	0.90	0.90	1.00	0.00	32.62	12.33	46.73	-105.00	6.70
5/18/93	10 D	16.88	0.01				0.00	25.66	10.18	39.16	-103.00	6.70
6/1/93	10 D	17.06	0.00				0.00	27.42	11.26	45.48	-118.00	6.80
6/8/93	10 D	14.15	0.00				0.00	36.02	11.09	46.84	-162.00	6.70
4/20/93	10 T	40.45	16.72				0.00	0.27	11.92	39.30		
5/4/93	10 T	47.06	18.35				0.00	2.73	13.05	41.47		
5/11/93	10 T	41.78	10.45	99.00	99.00	10.00	0.00	9.62	13.64	48.59		
5/18/93	10 T	42.87	19.07				0.00	4.01	11.38	44.10		
6/1/93	10 T	48.48	19.31				0.00	1.53	10.02	44.04		
6/8/93	10 T	48.68	25.12				0.00	6.52	11.79	47.79		

Table B11. Data for Analysis of RSF System Performance of Unit Eleven.

SAMPLE DARE	UNIT PORT	TOC (mg/L)	NH_3-N (mg/L)	T.Coliform (CFU/ml)	F.Coliform (CFU/ml)	F.Strepto (mg/L)	NO_2^--N (mg/L)	NO_3^--N (mg/L)	PO_4^--P (mg/L)	Cl (mg/L)	REDOX (mV)	pH
4/13/94	11 B	20.97	5.71	50.00	20.00	9.00	0.00	10.03	10.83	47.62		
4/20/93	11 B	27.15	5.56				0.00	9.17	10.57	39.37		
4/27/93	11 B	23.40	4.69	140.00	60.00	90.00	0.00	15.74	10.03	31.58		
5/4/93	11 B	33.50	9.63				0.00	13.76	13.90	42.35		
5/18/93	11 B	22.02	5.56				0.00	15.65	11.38	39.39		
6/1/93	11 B	26.55	6.56				0.00	16.45	11.16	48.49		
6/8/93	11 B	20.93	7.50				0.00	23.21	11.15	48.13		
4/13/93	11 D	20.94	2.85	27.00	18.00	1.00	0.00	12.95	9.33	47.98	-85.00	6.80
4/20/93	11 D	22.25	0.13				0.00	17.79	11.25	40.24	-92.00	6.70
4/27/93	11 D	18.84	0.18	15.00	13.00	4.00	0.00	15.82	9.30	31.36	-80.00	6.70
5/4/93	11 D	39.54	7.58				0.00	15.25	15.44	42.25	-95.00	6.70
5/18/93	11 D	16.50	0.24				0.00	23.51	10.65	41.25	-88.00	6.60
6/1/93	11 D	18.47	0.20				0.00	21.96	10.27	44.62	-112.00	6.70
6/8/93	11 D	13.04	0.00				0.00	34.33	11.53	47.90	-156.00	6.60
4/13/93	11 T	42.68	17.92	400.00	300.00	99.00	0.00	3.64	9.27	48.33		
4/20/93	11 T	42.68	12.70				0.00	1.99	12.52	39.44		
4/27/93	11 T	33.91	11.90	300.00	100.00	99.00	0.00	4.60	9.19	30.29		
5/4/93	11 T	55.72	22.12				0.00	2.18	13.83	41.55		
5/18/93	11 T	38.09	16.71				0.00	5.25	11.50	44.16		
6/1/93	11 T	43.13	15.98				0.00	2.37	11.23	44.15		
6/8/93	11 T	37.04	18.23				0.00	12.95	12.03	47.13		

Table B12. Data for Analysis of RSF System Performance of Unit Twelve.

SAMPLE DATE	UNIT PORT	TOC (mg/L)	NH_3-N (mg/L)	T.Coliform (CFU/ml)	F.Coliform (CFU/ml)	F.Strepto (mg/L)	NO_2^--N (mg/L)	NO_3^--N (mg/L)	PO_4^--P (mg/L)	Cl (mg/L)	REDOX (mV)	pH
4/13/93	12 B	22.64	6.05	40.00	30.00	9.00	0.00	8.05	9.76	47.91		
4/20/93	12 B	26.41	5.07				0.00	9.27	10.92	39.77		
4/27/93	12 B	21.11	4.69	100.00	60.00	9.00	0.00	16.36	10.33	32.85		
5/4/93	12 B	23.35	4.94				0.00	20.46	13.60	42.65		
5/11/93	12 B	15.26	7.08	10.00	10.00	7.00	0.00	33.59	13.06	47.49		
6/1/93	12 B	19.05	2.15				0.00	24.84	12.33	49.01		
6/8/93	12 B	14.39	2.90				0.00	28.00	11.17	47.10		
4/13/93	12 D	19.09	3.08	18.00	11.00	1.00	0.00	9.28	9.56	47.87	-89.00	6.80
4/20/93	12 D	19.84	0.68				0.00	14.80	11.23	39.52	-88.00	6.70
4/27/93	12 D	15.17	0.30	23.00	13.00	6.00	0.00	21.70	10.47	30.89	-80.00	6.80
5/4/93	12 D	17.09	0.55				0.00	25.44	13.26	41.33	-92.00	6.70
5/11/93	12 D	11.76	1.15	6.00	4.00	2.00	0.00	39.84	13.80	47.60	-95.00	6.80
6/1/93	12 D	15.81	0.20				0.00	20.55	10.55	42.47	-108.00	6.70
6/8/93	12 D	10.88	0.37				0.00	34.64	11.70	45.90	-147.00	6.60
4/13/93	12 T	39.91	18.75	100.00	100.00	99.00	0.00	1.33	8.88	48.87		
4/20/93	12 T	40.00	13.29				0.00	1.74	12.37	39.22		
4/27/93	12 T	33.08	12.62	100.00	300.00	100.00	0.00	7.63	8.92	29.79		
5/4/93	12 T	41.62	10.83				0.00	8.59	13.15	41.48		
5/11/93	12 T	30.12	21.40	99.00	99.00	60.00	0.00	21.38	13.04	45.69		
6/1/93	12 T	39.21	14.51				0.00	5.56	11.55	43.30		
6/8/93	12 T	32.44	15.47				0.00	16.42	11.58	47.10		

Table B13. Data for Analysis of RSF System Performance of Control.

SAMPLE DATE	UNIT PORT	TOC (mg/L)	NH_3-N (mg/L)	T.Coliform (CFU/ml)	F.Coliform (CFU/ml)	F.Strepto (mg/L)	NO_2^--N (mg/L)	NO_3^--N (mg/L)	PO_4^--P (mg/L)	Cl (mg/L)	REDOX (mV)	pH
3/23/93	C	84.41	34.81				0.00	0.00	9.21	32.99	-242.00	7.00
3/30/93	C	117.20	74.66	6200.00	2800.00	110.00	0.00	0.38	6.76	26.84	-230.00	6.80
4/13/93	C	114.00	54.46	15000.00	11000.00	220.00	0.00	0.05	10.36	42.83	-245.00	6.80
4/20/93	C	113.90	46.80				0.00	0.00	9.40	39.69	-245.00	6.70
4/27/93	C	101.20	45.19	9600.00	8000.00	120.00	0.00	0.11	9.27	78.00	-240.00	6.80
5/4/93	C	131.50	56.97				0.00	0.00	12.51	42.89	-228.00	6.80
5/11/93	C	134.40	57.64	2200.00	1800.00	100.00	0.00	0.04	13.03	48.50	-240.00	6.80
5/18/93	C	113.60	55.65				0.00	0.72	12.13	44.36	-207.00	6.60
5/25/93	C	113.40	50.94	5300.00	2700.00	1900.00	0.00	0.00	9.73	45.83	-208.00	6.90
6/1/93	C	117.80	58.38				0.00	0.02	11.54	46.81	-256.00	6.70
6/8/93	C	117.00	65.15				0.00	0.02	10.54	43.51	-255.00	6.90

APPENDIX C

Calculated Removal Efficiency Values

Table C1. Calculated Removal Efficiency Values for RSF System Unit One.

SAMPLE COLLECTION DATE	UNIT SYSTEM PORT	SYSTEM MIN-N (%)	NO_3^- DNC (%)	SYSTEM MIN-N AS % OF THEORETICAL	TOC SYSTEM (%)	TOC SAND FILTER (%)	TOC DNC (%)	NH_3 SAND FILTER (%)	TColiform SYSTEM (%)	FColiform SYSTEM (%)	FStrepto SYSTEM (%)
4/1/3/93	1 B					46.99		42.34			
4/20/93	1 B					47.18		71.78			
4/27/93	1 B					53.50		75.43			
5/4/93	1 B					49.69		71.17			
5/11/93	1 B					34.88		46.75			
6/8/93	1 B					46.69		50.20			
4/13/93	1 D	63.34		84.46	78.53				99.51	99.58	97.73
4/20/93	1 D	68.56		91.42	78.98						
4/27/93	1 D	68.44		91.25	71.33				99.60	99.88	90.00
5/4/93	1 D	67.53		90.03	75.95						
5/11/93	1 D	61.78		82.37	73.79				97.95	98.17	93.00
6/8/93	1 D	47.53		63.37	86.81						
4/13/83	1 T		100.00				-1.25				
4/20/93	1 T		99.01				-0.55				
4/27/93	1 T		96.23				-5.83				
5/4/93	1 T		99.42				-0.99				
5/11/93	1 T		96.39				-3.05				
6/8/93	1 T		54.20				-0.27				

Table C2. Calculated Removal Efficiency Values for RSF System Unit Two.

SAMPLE COLLECTION DATE	UNIT SYSTEM PORT	SYSTEM MIN-N (%)	NO_x^- DNC (%)	SYSTEM MIN-N AS % OF THEORETICAL	TOC SYSTEM (%)	TOC SAND FILTER (%)	TOC DNC (%)	NH_3 SAND FILTER (%)	TColiform SYSTEM (%)	FColiform SYSTEM (%)	FStrepto SYSTEM (%)
4/13/93	2 B					57.91		73.25			
4/20/93	2 B					50.88		85.42			
6/1/93	2 B					44.76		74.25			
6/8/93	2 B					63.26		75.18			
4/13/93	2 D								100.00	100.00	100.00
4/20/93	2 D	71.93		95.90	77.66						
6/1/93	2 D	60.36		80.48	83.77						
6/8/93	2 D	53.17		70.90	83.22						
4/13/93	2 T		100.00				-9.09				
4/20/93	2 T		100.00				-2.77				
6/1/93	2 T		73.60				8.69				
6/8/93	2 T		39.61				-9.85				

Table C3. Calculated Removal Efficiency Values for RSF System Unit Three.

SAMPLE COLLECTION DATE	UNIT SYSTEM PORT	SYSTEM MIN-N (%)	NO_x^- DNC (%)	SYSTEM MIN-N AS % OF THEORETICAL	TOC SYSTEM (%)	TOC SAND FILTER (%)	TOC DNC (%)	NH_3 SAND FILTER (%)	TColiform SYSTEM (%)	FColiform SYSTEM (%)	FStrepto SYSTEM (%)
4/13/93	3 B					10.25		7.17			
4/20/93	3 B					22.29		18.66			
4/27/93	3 B					19.32		18.34			
5/4/93	3 B					15.14		13.88			
5/11/93	3 B					17.06		25.28			
5/18/93	3 B					21.83		40.02			
6/1/93	3 B					16.73		14.47			
6/8/93	3 B					13.62		9.83			
4/13/93	3 D	38.29		45.94	92.06				99.95	99.94	99.59
4/20/93	3 D	53.33		64.00	91.81						
4/27/93	3 D	59.12		70.95	90.13				99.94	99.88	98.33
5/4/93	3 D	45.43		54.52	92.33						
5/11/93	3 D	28.82		34.59	92.05				99.91	99.94	99.10
5/18/93	3 D	52.50		63.01	90.96						
6/1/93	3 D	40.03		48.04	90.98						
6/8/93	3 D	30.78		36.94	85.98						
4/13/93	3 T		100.00				4.58				
4/20/93	3 T		100.00				-7.10				
4/27/93	3 T		76.34				-1.33				
5/4/93	3 T		99.25				-0.08				
5/11/93	3 T		99.62				0.90				
5/18/93	3 T		99.86				-6.51				
6/1/93	3 T		99.56				-4.21				
6/8/93	3 T		89.29				-2.97				

Table C4. Calculated Removal Efficiency Values for RSF System Unit Four.

SAMPLE COLLECTION DATE	UNIT SYSTEM PORT	SYSTEM MIN-N (%)	NO_x^- DNC (%)	SYSTEM MIN-N AS % OF THEORETICAL	TOC SYSTEM (%)	TOC SAND FILTER (%)	TOC DNC (%)	NH_3 SAND FILTER (%)	TColiform SYSTEM (%)	FColiform SYSTEM (%)	FStrepto SYSTEM (%)
3/30/93	4 B					29.75		21.03			
4/27/93	4 B					27.74		35.83			
5/4/93	4 B					22.48		29.77			
5/11/93	4 B					16.81		33.43			
6/1/93	4 B					19.19		21.39			
6/8/93	4 B					30.39		32.45			
3/30/93	4 D	63.27		75.93	84.56				99.99	99.97	99.18
4/27/93	4 D	59.36		71.24	83.65				99.80	99.91	96.67
5/4/93	4 D	65.51		78.61	84.91						
5/11/93	4 D	44.62		53.55	73.37				98.00	97.78	94.00
6/1/93	4 D	41.58		49.90	86.26						
6/8/93	4 D	54.09		64.90	88.32						
3/30/93	4 T		81.76				6.80				
4/27/93	4 T		80.39				-2.78				
5/4/93	4 T		79.82				1.11				
5/11/93	4 T		79.72				-4.80				
6/1/93	4 T		78.53				1.48				
6/8/93	4 T		55.44				-4.04				

Table C5. Calculated Removal Efficiency Values for RSF System Unit Five.

SAMPLE COLLECTION DATE	UNIT SYSTEM PORT	SYSTEM MIN-N (%)	NO_x^- DNC (%)	SYSTEM MIN-N AS % OF THEORETICAL	TOC SYSTEM (%)	TOC SAND FILTER (%)	TOC DNC (%)	NH_3 SAND FILTER (%)	TColiform SYSTEM (%)	FColiform SYSTEM (%)	FStrepto SYSTEM (%)
3/23/93	5 B					15.19		13.66			
3/30/93	5 B					18.64		12.31			
4/13/93	5 B					17.51		6.22			
4/20/93	5 B					18.16		12.60			
5/4/93	5 B					17.82		11.33			
5/11/93	5 B					14.53		12.45			
5/18/93	5 B					18.40		28.45			
6/8/93	5 B					13.50		16.22			
3/23/93	5 D	24.86		33.15	86.42						
3/30/93	5 D	35.38		47.17	89.87				100.00	99.97	99.18
4/13/93	5 D	18.63		24.83	90.68				99.97	99.96	98.64
4/20/93	5 D	33.89		45.19	86.98						
5/4/93	5 D	29.58		39.44	89.89						
5/11/93	5 D	41.68		55.57	90.56				99.77	99.67	82.00
5/18/93	5 D	31.52		42.02	89.11						
6/8/93	5 D	31.68		42.24	88.48						
3/23/93	5 T		92.71				-1.65				
3/30/93	5 T		97.18				7.21				
4/13/93	5 T		100.00				-0.24				
4/20/93	5 T		96.30				-1.24				
5/4/93	5 T		99.46				-2.37				
5/11/93	5 T		93.63				3.84				
5/18/93	5 T		92.71				0.29				
6/8/93	5 T		89.11				6.24				

Table C6. Calculated Removal Efficiency Values for RSF System Unit Six.

SAMPLE COLLECTION DATE	UNIT SYSTEM PORT	SYSTEM MIN-N (%)	NO_2^- DNC (%)	SYSTEM MIN-N AS % OF THEORETICAL	TOC SYSTEM (%)	TOC SAND FILTER (%)	TOC DNC (%)	NH_3 SAND FILTER (%)	TColiform SYSTEM (%)	FColiform SYSTEM (%)	FStrepto SYSTEM (%)
4/13/93	6 B					42.87		77.27			
4/29/93	6 B					39.85		92.53			
4/27/93	6 B							93.27			
5/4/93	6 B					42.80		93.83			
5/11/93	6 B					62.22		60.20			
6/1/93	6 B					54.81		96.31			
6/8/93	6 B					54.80		87.40			
4/13/93	6 D	79.69		95.64	79.51				99.99	99.99	99.59
4/20/93	6 D	79.14		94.97	79.73						
4/27/93	6 D	69.60		83.53	75.69				99.92	99.95	98.33
5/4/93	6 D	65.39		78.47	79.69						
5/11/93	6 D	76.77		92.13	81.56				99.91	99.89	99.00
6/1/93	6 D	64.16		76.99	84.80						
6/8/93	6 D	41.52		49.82	88.23						
4/13/93	6 T		81.39				4.44				
4/20/93	6 T		78.67				3.36				
4/27/93	6 T		59.69				34.00				
5/4/93	6 T		32.63				16.62				
5/11/93	6 T		60.57				-9.59				
6/1/93	6 T		34.86				-2.59				
6/8/93	6 T		14.04				11.36				

Table C7. Calculated Removal Efficiency Values for RSF System Unit Seven.

SAMPLE COLLECTION DATE	UNIT SYSTEM PORT	SYSTEM MIN-N (%)	NO_3^- DNC (%)	SYSTEM MIN-N AS % OF THEORETICAL	TOC SYSTEM (%)	TOC SAND FILTER (%)	TOC DNC (%)	NH_3 SAND FILTER (%)	TColiform SYSTEM (%)	FColiform SYSTEM (%)	FStrepto SYSTEM (%)
4/13/93	7 B					44.62		33.05			
4/20/93	7 B					20.90		30.08			
5/4/93	7 B					16.45		18.66			
5/11/93	7 B					13.51		83.82			
5/18/93	7 B					15.11		11.23			
5/25/93	7 B					24.95		24.74			
6/1/93	7 B					16.85		20.98			
6/8/93	7 B					26.48		29.53			
4/13/93	7 D	57.61		76.81	92.08				99.99	99.99	99.55
4/20/93	7 D	42.24		56.33	89.56						
5/4/93	7 D	41.99		55.99	92.26						
5/11/93	7 D	73.57		98.09	91.49				99.91	99.95	99.10
5/18/93	7 D	24.20		32.26	89.60						
5/25/93	7 D	35.77		47.69	84.48				98.98	98.96	98.79
6/1/93	7 D	33.32		44.42	91.74						
6/8/93	7 D	46.47		61.96	90.78						
4/13/93	7 T		100.00				-13.02				
4/20/93	7 T		100.00				-1.87				
5/4/93	7 T		99.32				9.14				
5/11/93	7 T		97.32				14.07				
5/18/93	7 T		99.51				-0.58				
5/25/93	7 T		99.72				-2.58				
6/1/93	7 T		99.59				9.31				
6/8/93	7 T		94.52				57.4				

Table C8. Calculated Removal Efficiency Values for RSF System Unit Eight.

SAMPLE COLLECTION DATE	UNIT SYSTEM PORT	SYSTEM MIN-N (%)	NO_3^- DNC (%)	SYSTEM MIN-N AS % OF THEORETICAL	TOC SYSTEM (%)	TOC SAND FILTER (%)	TOC DNC (%)	NH_3 SAND FILTER (%)	TColiform SYSTEM (%)	FColiform SYSTEM (%)	FStrepto SYSTEM (%)
4/13/93	8 B					40.38		69.28			
4/20/93	8 B					40.19		84.65			
5/4/93	8 B					22.90		41.55			
6/1/93	8 B					41.82		83.74			
6/8/93	8 B					49.45		77.69			
4/13/93	8 D	79.10		94.92	83.09				99.86	99.90	96.82
4/20/93	8 D	81.20		97.44	81.26						
5/4/93	8 D	32.78		39.33	89.53						
6/1/93	8 D	72.41		86.90	86.66						
6/8/93	8 D	57.90		69.48	90.63						
4/13/93	8 T		83.88				1.13				
4/20/93	8 T		98.07				-1.59				
5/4/93	8 T		6.31				25.72				
6/1/93	8 T		74.68				1.20				
6/8/93	8 T		29.07				3.17				

Table C9. Calculated Removal Efficiency Values foe RSF System Unit Nine.

SAMPLE COLLECTION DATE	UNIT SYSTEM PORT	SYSTEM MIN-N (%)	NO_x^- DNC (%)	SYSTEM MIN-N AS % OF THEORETICAL	TOC SYSTEM (%)	TOC SAND FILTER (%)	TOC DNC (%)	NH_3 SAND FILTER (%)	TColiform SYSTEM (%)	FColiform SYSTEM (%)	FStrepto SYSTEM (%)
4/13/93	9 B					55.86		94.59			
4/20/93	9 B					65.28		100.00			
5/4/93	9 B					61.27		99.87			
5/11/93	9 B					60.72		65.48			
6/8/93	9 B					76.76		99.63			
4/13/93	9 D	68.11		90.81	82.79				99.99	99.99	99.59
4/20/93	9 D	70.74		94.32	81.64						
5/4/93	9 D	60.60		80.80	83.81						
5/11/93	9 D	24.85		33.13	87.88				99.96	99.95	75.00
6/8/93	9 D	59.12		78.83	88.21						
4/13/93	9 T		56.31				18.30				
4/20/93	9 T		79.25				-3.19				
5/4/93	9 T		61.11				13.86				
5/11/93	9 T		9.06				41.13				
6/8/93	9 T		48.46				-2.68				

Table C10. Calculated Removal Efficiency Values for RSF System Unit Ten.

SAMPLE COLLECTION DATE	UNIT SYSTEM PORT	SYSTEM MIN-N (%)	NO_2^- DNC (%)	SYSTEM MIN-N AS % OF THEORETICAL	TOC SYSTEM (%)	TOC SAND FILTER (%)	TOC DNC (%)	NH_3 SAND FILTER (%)	TColiform SYSTEM (%)	FColiform SYSTEM (%)	FStrepto SYSTEM (%)
4/20/93	10 B					45.64		81.82			
5/4/93	10 B					49.83		77.65			
5/11/93	10 B					56.56		98.02			
5/18/93	10 B										
6/1/93	10 B					51.98		80.15			
6/8/93	10 B					54.31		64.96			
4/20/93	10 D	70.78		94.38	78.42						
5/4/93	10 D	65.77		87.69	84.30						
5/11/93	10 D	50.87		67.83	87.61				99.96	99.95	99.00
5/18/93	10 D	64.96		86.62	85.14						
6/1/93	10 D	67.84		90.45	85.52						
6/8/93	10 D	57.71		76.95	87.91						
4/20/93	10 T		97.31				10.05				
5/4/93	10 T		77.83				6.96				
5/11/93	10 T		50.64				11.51				
5/18/93	10 T		71.29				0.20				
6/1/93	10 T		100.00				-3.35				
6/8/93	10 T		61.18				-5.99				

Table C11. Calculated Removal Efficiency Values for RSF System Unit Eleven.

SAMPLE COLLECTION DATE	UNIT SYSTEM PORT	SYSTEM MIN-N (%)	NO_x^- DNC (%)	SYSTEM MIN-N AS % OF THEORETICAL	TOC SYSTEM (%)	TOC SAND FILTER (%)	TOC DNC (%)	NH_3 SAND FILTER (%)	TColiform SYSTEM (%)	FColiform SYSTEM (%)	FStrepto SYSTEM (%)
4/13/93	11 B					50.87		52.81			
4/20/93	11 B					36.39		56.36			
4/27/93	11 B					30.99		70.37			
5/4/93	11 B					39.88		54.60			
5/18/93	11 B					42.19		65.16			
6/1/93	11 B					38.44		68.22			
6/8/93	11 B					43.49		57.77			
4/13/93	11 D	72.72		87.26	81.63				99.82	99.84	99.55
4/20/93	11 D	69.65		83.58	80.47						
4/27/93	11 D	65.67		78.80	81.38				99.84	99.84	96.67
5/4/93	11 D	71.27		85.52	69.93						
5/18/93	11 D	69.99		83.99	85.48						
6/1/93	11 D	70.92		85.11	84.32						
6/8/93	11 D	56.63		67.96	88.85						
4/13/93	11 T		56.49				-17.01				
4/20/93	11 T		73.96				-2.58				
4/27/93	11 T		64.98				6.76				
5/4/93	11 T		80.99				-11.81				
5/18/93	11 T		60.11				-2.16				
6/1/93	11 T		82.72				-3.28				
6/8/93	11 T		33.06				-0.27				

Table C12. Calculated Removal Efficiency Values for RSF System Unit Twelve.

SAMPLE COLLECTION DATE	UNIT SYSTEM PORT	SYSTEM MIN-N (%)	NO_x^- DNC (%)	SYSTEM MIN-N AS % OF THEORETICAL	TOC SYSTEM (%)	TOC SAND FILTER (%)	TOC DNC (%)	NH_3 SAND FILTER (%)	TColiform SYSTEM (%)	FColiform SYSTEM (%)	FStrepto SYSTEM (%)
4/13/93	12 B					43.27		52.62			
4/20/93	12 B					33.98		59.76			
4/27/93	12 B					36.19		65.05			
5/4/93	12 B					43.90		70.61			
5/11/93	12 B					49.34		63.30			
6/1/93	12 B					51.42		89.97			
6/8/93	12 B					55.64		79.97			
4/13/93	12 D	75.60		90.73	83.25				99.88	99.90	99.55
4/20/93	12 D	72.37		86.84	82.58						
4/27/93	12 D	61.34		73.61	85.01				99.76	99.84	95.00
5/4/93	12 D	51.79		62.15	87.00						
5/11/93	12 D	54.02		64.83	91.25				99.73	99.78	98.00
6/1/93	12 D	73.71		88.45	86.58						
6/8/93	12 D	59.29		71.15	90.70						
4/13/93	12 T		80.20				-5.40				
4/20/93	12 T		77.48				2.42				
4/27/93	12 T		44.11				4.00				
5/4/93	12 T		49.62				-0.59				
5/11/93	12 T		23.64				14.23				
6/1/93	12 T		73.14				-10.42				
6/8/93	12 T		29.64				7.28				

VITA

Efrain Enrique Ruiz was borne September 19, 1945 in Bucaramanga, Colombia, South America. He entered The University of Georgia, Athens and in June, 1968 received the degree of Bachelor of Science in Agricultural Engineering. The following September he entered Graduate School at The University of Georgia, Athens and in June, 1970 received the degree of Master of Science in Agricultural Engineering. Subsequently, he entered The University of Tennessee, Knoxville where he was a Ph.D. graduate student. For some time Efrain Enrique worked in the private industry in the areas of feed manufacturing and poultry production.

On August, 1990 Efrain Enrique returned to The University of Tennessee, Knoxville and in December, 1993 received a degree of Doctor of Philosophy in Agricultural Engineering.

Efrain Enrique is married to the former Luz Stella Giraldo. They have a son, Enrique, 3 and a daughter, Laura Catalina, 1.