ENERGY AND BIOMASS RECOVERY FROM WASTEWATER

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ABSTRACT

The goal of the project was to demonstrate in a large pilot study that domestic sewage could be converted to useful products, mainly substitute natural gas and clean water, using two low-cost biological processes -- a high-rate anaerobic treatment unit followed by a hydroponic plant treatment system. The anaerobic attached film expanded bed (AAFEB) and the Nutrient Film Technique (NFT) are two innovative technologies developed over more than a decade at Cornell University.

Documentation of this biological system for 52 months at flows up to 40 s/d (greater than 10,000 gal/d) showed the system to be highly successful. This report covers the last 12 months of this jointly sponsored NYSERDA/GRI study.

Efforts were made to document the empirical relationships between system loading rate and effluent quality. Although the sewage temperatures varied from 7°C to 28°C and little modification of reactor temperatures were made, low temperatures had minimal effects on the purification capabilities.

Effluent quality was excellent (BOD and SS less than 5 mg/l) with plant nutrients removed to less than 1 mg/l for total nitrogen and total phosphorus at low hydraulic loadings (less than 3 cm/d). Sludge generation was less than at conventional primary plants and much less than at conventional secondary facilities. The economics of the hypothesized system appear promising.

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LIST OF ABBREVIATIONS AND SYMBOLS

AAFEB	Anaerobic Attached Film Expanded Bed
ADR	Acid Detergent Residue
B	Biodegradability (% of TVS)
B.ALK	Bicarbonate Alkalinity (g/l of Moisture Present)
Biogas	Quality Expressed in Terms of the Methane and Carbon Dioxide Content
BOLR	Biodegradable Total Volatile Solids Organic Loading Rate (g/l/d)
BV	AAFEB reactor Bed Volume, s, or m ³
BVSOLR	Biodegradable Volatile Solids Organic Loading Rate (g/l/d)
CE	Cellulose
CH ₄	Methane Concentration (% of Biogas Volume)
CH ₄ -D	Portion of Total Methane Production Dissolved in the Effluent
CH ₄ -PR	Methane Gas Mass Production Rate, g-CH ₄ /l-d Liquid
CH ₄ -VPR	Total Methane Volumetric Production Rate, l/l-d
CO ₂	Carbon Dioxide Concentration (% of Biogas Volume)
C.P.	Crude Protein
Cut	Cutin
DCW	Digestible Cell Wall
GRI	Gas Research Institute
HC	Hemi Cellulose
HRT	Hydraulic Retention Time, (days)
k _T	Methane Water Saturation Constant at Liquid Temperature T, mg/l
LR _A	AAFEB Reactor Organic or Inorganic Material Loading Rate, g/l-d
LR _N	NFT Reactor Organic or Inorganic Material Loading Rate, g/m ² -d
Ls	Lignin Content (% of TS)
MLR	Mass Loading Rate, mass/volume-t
NDR	Neutral Detergent Residue
NFT	Nutrient Film Technique
NFT _B	Expanded Bed Hydraulic Retention Time, Hours
NH ₄ -N	Ammonia Nitrogen
NYSERDA	New York State Energy Research Development Authority
OLR	Organic Loading Rate (g/l/d)
OR _w	Weir Overflow from NFT channels
Q	Influent Liquid Flow Rate, s/d, or m ³ /d
R	Ideal Gas Law Constant (0.0821 l-atm/-K-mole)
RE	Substrate Removal Efficiency, %
RR _A	AAFEB Reactor Removal Rate, g/l-d

RR _N	NFT Reactor Removal Rate, g/m ² -d
SA	NFT reactor Surface Area, m ²
S _e	Effluent Substrate Concentration, mg/l
S _o	Influent Substrate Concentration, mg/l
T.ALK	Total Alkalinity (g/l of moisture present)
T.COD	Total Chemical Oxygen Demand Concentration (g/l)
TDOM	Total Digestible Organic Matter
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen
TS	Total Solids Concentration (% of wet weight)
TVDS	Total Volatile Dissolved Solids
TVS	Total Volatile Solids
V	Volume (l)
Ve	Mass of Reactor Total Volatile Solids (g)
VFA	Volatile Fatty Acid Concentration (g/l)
V _H	Horizontal velocity of liquid in NFT channels
Vo	Initial Mass of Total Volatile Solids (g)
Vr	Volatile Solids Remaining in the Reactor (Decimal Fraction)
VS	Volatile Portion of the Total Solids Concentration (%)
VSd	Mass of Volatile Solids Removed as Biogas (grams)
VSe	Volatile Portion of the Reactor TS (Decimal Fraction)
VSo	Volatile Portion of the Initial Reactor TS (Decimal Fraction)
VSS	Volatile Portion of the Suspended Solids Concentration
WL	Mass of Water Vapor in Biogas (g)
WV	Volume of Water Vapor in Biogas (l)

Section 1

INTRODUCTION

Present wastewater treatment alternatives should emphasize maximum pollution control at minimum capital and energy costs. The value of substitute natural gas that could be generated from sewage by-products significantly exceeds the total costs of conventional treatment, but unit processes have not been available to cost-efficiently recover these by-products. It is proposed that new technologies capable of recovering energy from sewage on a small scale should be investigated using a pilot system to confirm their potential to produce energy from domestic sewage.

As much as \$300,000 worth of methane per year could be produced from sewage generated by 10,000 people, 20 percent from biochemical oxygen demand (BOD) conversion by an anaerobic wastewater treatment process, and 80 percent from biomass grown on the remaining nutrients in the effluent. This gross income may produce profitable sewage treatment systems if the capital costs and complexity of new technologies can be minimized.

Two new technologies have potential for energy and biomass recovery from sewage in treatment systems that cost less than present alternatives - the anaerobic-attached-film-expanded bed process (AAFEB), and the advanced hydroponic wastewater treatment system referred to as the nutrient film technique (NFT). The AAFEB unit produced secondary-quality effluent at retention times equal to aerobic systems without secondary biological sludge

production and without using aeration energy while producing methane in bench scale tests. The NFT can polish wastewaters while converting the nutrients into useful biomass that can be digested to yield methane. These two technologies are being tested in series at pilot scale, up to 10,000 gallons per day, to confirm the system's potential.

ANAEROBIC WASTEWATER TREATMENT

Treating sewage with an anaerobic process has been investigated for over a century (McCarty, 1985). Purifying wastewater to high quality using a simple process to produce useful clean energy without creating secondary biological sludge was believed impossible (Henze and Harremoës, 1983). The application of the slow-growing methanogens to cool and dilute wastewaters, such as domestic sewages, is one of the most difficult tasks in the microbial world.

The recent development of attached microbial film processes has drastically changed the capability of microbial processes. In one of the first developments, Jewell and his colleagues proposed the AAFEB as the optimum biological reactor using the simple hypothesis that maximum active microbial mass per unit reactor volume should result in maximum reaction rates, removal rates, and/or conversion efficiencies. The first anaerobic study using this process in 1974 challenged the long-held assumption that anaerobic processes cannot treat sewage (Jewell, 1980; Jewell, et al., 1982). The extraordinary capability of the process reflects the extreme density and large microbial populations that can be maintained in such reactors. Maximum microbial concentrations in

the AAFEB are 20 times more than those in conventional activated sludge.

High rate anaerobic processing of wastewater is an ideal pretreatment prior to systems where nutrient conversion to biomass is desirable. The macro pollutants such as biochemical oxygen demand (BOD) and suspended solids (SS) are removed; however, most of the plant nutrients will remain in the wastewater enabling maximum biomass production using the nutrients of the effluent liquid.

PLANTS, HYDROPONICS, AND THE NUTRIENT FILM TECHNIQUE (NFT)

The NFT is a unique modification of a hydroponic plant growth system that uses plants grown directly on an impermeable surface to which a thin film of water is continuously applied. This hydroponic alternative increases the availability of oxygen to the plant roots, compared to the conventional hydroponics system that requires extensive mechanical aeration. Plants on the impermeable surface produce a large root mass up to one foot deep. These large masses of self-generating root systems can filter, adsorb, absorb, and use the gross and trace inorganics and organics in wastewater.

A review of the NFT indicates that it can process wastewater at higher rates than any other plant-based system; control and conserve nutrients and other pollutants as efficiently or more efficiently; and provide complete control and access for all inputs and effluent constituents. The NFT system may therefore use much less land area than conventional land-based treatment

systems, while converting a difficult to control natural system into an easily monitored and managed self-generating treatment system.

Section 2

GOALS AND OBJECTIVES

The goal of this study is to document at pilot-scale the potential for resource recovery, ambient temperature domestic sewage treatment using AAFEB reactor treatment followed by hydroponic NFT reactor treatment. Specific objectives were to:

- Operate the pilot system at constant flows of 3,000 gal/d (11.4 m³/d) to 10,600 gal/d (40 m³/d) of raw domestic sewage and demonstrate its capability;
- Determine the efficiencies of removal of pollutants from each unit process and the production of biomass from the NFT system treating ambient temperature sewage and document the capabilities of the AAFEB and the NFT processes to remove; e.g., total and soluble chemical oxygen demand (COD), and biochemical oxygen demand (BOD₅), suspended solids (SS), and ammonia-nitrogen and soluble phosphorus;
- Determine the energy, operating, and maintenance requirements for the AAFEB/NFT components of the pilot system;
- Establish relevant design performance and operating parameters for each unit process of the resource recovery wastewater treatment system to base preliminary engineering designs of 0.1 to 1.0 million gallons per day system to

produce secondary and tertiary quality effluents year-round for rural New York State communities; and

- Estimate and compare the sizes and costs for a resource recovery wastewater facility to a conventional treatment facility to produce secondary and/or tertiary quality effluents from average-strength domestic wastewater.

Section 3

MATERIALS AND METHODS

INTRODUCTION

Cornell University, in cooperation with the Gas Research Institute (GRI), the Solar Energy Research Institute (SERI), and the New York State Energy Research and Development Authority (the Energy Authority), began research to document the potential for domestic sewage treatment for resource recovery October 1, 1986. This effort, administered through Walt Disney Imagineering, continued through December 31, 1989. During this 39-month research period an innovative, pilot-scale, domestic sewage treatment system was designed, constructed, operated, and analyzed. The treatment system consisted of a raw sewage delivery system, a coarse liquid solids separator, two AAFEB reactors enclosed within a greenhouse structure and operated in series to achieve organic removals, and two nutrient film hydroponic technique reactor systems also enclosed within a greenhouse structure and operated for organics polishing, nutrient uptake, and biomass production.

The Energy Authority provided a one-year continuation contract that was activated at Cornell University January 1, 1990 and continued through October 31, 1990. Experiments conducted during this ten-month contract are described in this section.

EXPERIMENTAL PROGRAM

To document the potential for ambient temperature resource recovery of domestic sewage treatment at pilot-scale, a six-task experimental program was developed as illustrated in Figure 3-1. and summarized in Table 3-1. This experimental program included system modification, a testing program for longer-term operation of the total system, and definition of unit pollutant removal capacities, data analysis of each unit process, and documentation of energy and maintenance requirements. The program also considered engineering designs and economic feasibility analysis for 0.1 MGD and 1.0 MGD flows, and project management with quarterly and final reports.

The pilot-scale wastewater treatment facility was constructed on the grounds of the City of Ithaca's Wastewater Treatment Facility in October, 1987 with funding from the Gas Research Institute and the Energy Authority. Operation of the pilot system began June 16, 1987 and continued through December 31, 1989. The system consisted of a raw sewage collection and delivery system, two custom-designed AAFEB reactors, and an NFT system composed of two deep- and two shallow-channel trough reactors.

Task 1. Start-up. Equipment, instrumentation and supplies - procurement, set-up, initial calibration, systems check-out, and personnel training

On January 4, 1990 funding from The New York State Energy Research and Development Authority arrived at Cornell University to support the documentation of the potential of the pilot system. The first

Figure 3-1. Task-time schedule of "Energy and Biomass Recovery from Wastewater
- Pilot Documentation."

Table 3-1

A SUMMARY OF WORK TASKS TO COMPLETE DOCUMENTATION OF THE PILOT-
SCALE, WASTEWATER, ENERGY AND BIOMASS RECOVERY SYSTEM.

Task	Description
1.	Start-up. A pilot scale wastewater treatment facility, originally constructed on the grounds of the City of Ithaca Wastewater Treatment Facility and capable of treating 3,000 to 10,000 gallons of sewage per day, will be modified to interpret gross pollution assimilation capabilities of the AAFEB reactor and NFT hydroponic system; specifically, COD, BOD, SS, Ammonia-Nitrogen, and Soluble Phosphorus. This phase of the study will include procurement of equipment, instrumentation, and supplies, set-up, initial calibration, systems check-out and personnel training.
2.	Testing Program. The goal of the test program will be to determine the efficiency of each unit process in removing gross wastewater pollutants and the production of biomass and biogas while treating ambient-temperature wastewater. In addition, records will be sufficient to estimate the energy and maintenance requirements for a full-scale system based on pilot-scale data and experience.
3.	Process/Data Analysis. A separate chronological tabulation of all process parameter data relevant to assessing removal of gross organic pollutants, as well as sludge and biomass accumulation and generation, will be prepared and projected into full-scale system applications.
4.	Preliminary Design and Economics of a Full-Scale System. Based on the accumulated data, unit designs and costs will be calculated for each unit process to achieve quality effluents for a community producing 100,000 gallons of sewage per day.
5.	Project Management, Plan and Schedule. A detailed experimental program, including routine evaluation of progress, will be prepared to meet the goals of the project.
6.	Reporting Activities. Three quarterly reports will be prepared to summarize activities throughout the twelve-month study and a final report summarizing all project activities will be prepared at the end of the study.

task was to remodel the pilot system to operate at raw sewage flow rates of 3,000 to 10,000 gallons per day. As part of this task, arrangements were made to use all the necessary equipment, work space, utilities, instrumentation, chemicals, and test devices to complete the documentation. Two research technicians were hired and trained to operate the pilot system and conduct the analytical program.

Tasks 2 and 3. Analytical Program and Data Evaluation

The second and third tasks focused on collecting and processing data to interpret the performance of each component of the pilot system. The components considered in this analysis included the raw sewage delivery system, gross particulate pretreatment, the two AAFEB reactors, the NFT reactors, and the greenhouse structure.

The rate of sewage flow through each component including measurement of the pH levels and temperature as well as the hydraulic flows was measured daily. From these flow rates theoretical hydraulic retention times were calculated; however, it was important to consider actual hydraulic retention times. Though not in the contract, tracer studies were conducted on each component of the pilot system. At points when the pilot system was operating under representative steady performance conditions, 24-hour composite samples were taken of the liquid influent and effluent of each component. These samples were characterized according to organic and nutrient concentrations including fecal coliform concentrations. These concentration values were used to

calculate the rates and efficiencies of conversion in each reactor.

Energy requirements were measured for each component of the system. Energy usages monitored included the raw sewage delivery pump; the liquid recycle pumps and the paddle mixers in the AAFEB reactor systems; the final effluent pump that conveyed final effluent from the pilot system back to the headworks of the Ithaca Wastewater Treatment Facility; the blower to maintain inflation of the double-film greenhouse; and annual heat and ventilation requirements in the greenhouse. In addition, average monthly climatological data records were maintained.

In a single-unit operation the AAFEB reactor system was designed to completely replace four unit operations conventionally found at sewage treatment facilities: primary clarification; biological degradation of organics; secondary clarification; and sludge digestion. Thus, measurements were taken to interpret performance within the AAFEB reactors. Several studies were conducted to interpret the settleability of particulates in the recycle liquid and effluent from the reactors. The mass of sludge produced from each reactor was monitored as well as rates of attrition of expanded bed attachment media and mass of attached and entrapped microbial masses within the beds. Though measurement of the volume of biogas produced by the AAFEB reactors was impossible, the mass of methane and carbon dioxide dissolved in the effluent liquid was measured. From these values and those of organic conversions it was possible to calculate biogas production potential.

Bench-scale AAFEB reactors using acclimated media were operated on sucrose to develop a standard to which the rates and efficiencies of organic conversion from the pilot-scale reactors were compared.

All NFT reactors were retained within a greenhouse structure. In a single unit operation these reactors were designed to replace conventional unit operations associated with achieving tertiary treatment of the effluent from the AAFEB reactor system throughout the year. They were also designed to produce biomass, a valuable resource derived from the nutrients in wastewater and photosynthesis. Thus, along with determining the removal of organics, nutrients, and fecal coliforms using the system, it was also important to measure the plant matter produced, including annual yields, stalk and root density, and plant composition. Since the greenhouse structure was essential for operating the NFT reactors throughout the year in a northern climate, the energy required to maintain acceptable temperatures within the greenhouse was also monitored, including energy for both heating and ventilation.

Task 4. Preliminary Design and Economics of a Full-Scale System

The fourth task focused on developing preliminary design parameters to estimate size and costs of full-scale wastewater energy and biomass recovery systems. These estimates were developed for both secondary and tertiary treatment schemes at both 0.1 million gallons per day (mgd) and 1.0 mgd and were compared to those of a conventional treatment facility.

Tasks 5 and 6. Project Management

These final tasks were designed to achieve the detailed experimental program and documentation to thoroughly evaluate the pilot system as an innovative new wastewater treatment and resource recovery technology. Included in these tasks was the preparation of a detailed experimental program including a range of operating conditions and complete analytical evaluation. Two quarterly reports were prepared as well as a report summarizing operation of the pilot system before the project started.

EXPERIMENTAL RESEARCH FACILITIES

The pilot-scale "Energy and Biomass Recovery from Wastewater" system was constructed at the Ithaca Wastewater Treatment Facility in Ithaca, New York. The Ithaca facility, which recently underwent major modifications (nearly \$40 million dollars) to increase capacity and improve treatment, began operation October 28, 1987. As illustrated in Figure 3-2, raw sewage from the city of Ithaca enters the influent building which contains a series of pumps to lift the sewage to the top of the settling tank through the domestic sewage forced main. Within the primary settling tank building the city tapped into the forced main to accommodate a refrigerated composite sampler to monitor the influent sewage characteristics. Cornell obtained permission to tap into this sample line to provide raw unsettled sewage to the research site.

The research site was approximately 100 yards north of the primary settling tank building, and centered around an abandoned structure, the recirculation building, 6.7 meters wide, 9.8 meters

Figure 3-2. Plan view of the pilot-scale and energy recovery system located at the Ithaca Sewage Treatment Plant in Ithaca, New York.

long, and 4.6 meters in height), which the City provided. Significant changes were made to the interior of the building including the removal of all the original contents, the addition of a fuel-oil heating system, and construction of a small sample preparation laboratory. On-site office space, a mobile trailer, was supplied by the Agricultural and Biological Engineering Department of Cornell University.

Most analytical testing was conducted by personnel in the Agricultural and Biological Engineering Department of Cornell University at the Agricultural Waste Management Laboratory in Ithaca, New York. This research facility has 74 square meters of wet-test laboratory space, 250 square meters of research space, 49 square meters of machine-shop space, and 24 square meters of office space. Among a conventional inventory of equipment and supplies, including balances, ovens, furnaces, pH meters, centrifuges, chemicals, and glassware, the wet-test laboratory also contains a spectrophotometer, a macro-kjeldahl unit, two gas chromatographs with recorders and integrators, an ion chromatograph, and an atomic adsorption machine.

As illustrated in the schematic of the pilot system, Figure 3-3, the raw sewage from the Ithaca Wastewater Treatment Facility forced main flowed by gravity to the recirculation building. The flow of raw sewage was more than 100 gallons per minute and flowed directly into the gross particulate removal system in the building. The pilot-system sewage delivery pump, also located in the building, transferred a small portion of this partially clarified sewage at a predetermined, constant flow rate to the first-stage AAFEB-1 reactor located adjacent to the southeast exterior wall of the building. The effluent from the AAFEB-1

Figure 3-3. A plan view of the pilot-scale wastewater energy and biomass recovery system.

reactor flowed by gravity to the second-stage AAFEB-2 reactor. To facilitate simultaneous analysis of both high- and low-flow conditions, an intermediate pump was positioned to by-pass a portion of the first-stage effluent directly to the headworks of the Ithaca Plant. Thus, the second-stage reactor was capable of operating at low-flow conditions while the first stage reactor was operated at high-flow conditions.

Both AAFEB reactors and the intermediate flow control pump were enclosed in a greenhouse structure (5 meters wide, 9.75 meters in length, and 6.7 meters high) that was fabricated with component parts purchased from X. S. Smith, Inc. This greenhouse was constructed to protect the reactors and pump from the weather and consisted of a double-film air-inflated structure with galvanized steel support members. As illustrated in Figure 3-4, this custom-designed greenhouse was attached directly to the exterior southeast wall of the recirculation building and included a platform (three meters above the floor) that provided direct access to the top of the expanded-bed reactors. The platform was accessible using a stairway that was constructed in the recirculation building and extended to the roof of the facility within the greenhouse structure.

The effluent from the second-stage expanded-bed reactor flowed by gravity in series through the NFT reactor system. The NFT system included two deep-channel reactors and two shallow-channel reactors enclosed in a single double-film air-inflated greenhouse structure (9.1 meters wide, 39.6 meters long, and 4.3 meters high, Figure 3-5). The liquid effluent from the NFT reactors was pumped to the headworks of the Ithaca Plant.

Figure 3-4. A cross section of the custom-fabricated greenhouse structure designed to protect the pilot-scale AAFEB reactor system.

The "STORMKING 30 Greenhouse" by X.S. Smith
 A prefabricated, free standing structure with air inflated double
 Nutri Gro 3 greenhouse film exterior envelope.

Figure 3-5.

A cross section of the prefabricated, free standing "STORM KING"
 greenhouse manufactured by X. S. Smith Inc. and designed to protect the
 NFT reactor system.

RAW SEWAGE PRETREATMENT AND DELIVERY SYSTEM

It was considered important to prevent large particulate matter in the raw sewage from plugging the small pumps, pipelines, and valves associated with the pilot-scale facility. Thus a simple particulate clarifier was constructed to achieve gross separation of the raw sewage particulates. This system, illustrated in Figure 3-6, consisted of a covered fiberglass tank (1.83 meters diameter, 0.91 meters deep, and effective volume 2 cubic meters) with a drain (7.6 cm diameter) in the bottom and a feed port (7.6 cm in diameter) in the sidewall of the tank, 38 cm from the top. Raw sewage from the headworks of the Ithaca Wastewater Treatment Facility flowed continuously at the rate of approximately 0.3 cubic meters per minute to the middle of the tank. This flow was directed to the bottom of the tank by a baffle consisting of a PVC pipe (15 cm diameter) vertically mounted in the center of the tank, five cm above the bottom. The major portion of the sewage flow passed through the drain, over an overflow tee, and back to the headworks of the Ithaca facility. The vertical positioning of this tee allowed the tank to be filled to any desired level. Removal of large particulate was accomplished by settling and/or flotation within the tank. Settled material was continuously removed automatically by the high volume of flow through the bottom drain. Floating material was allowed to accumulate and was periodically removed. A circular, float-particulate baffle (36 cm diameter and 40 cm high) was positioned vertically on the inside wall of the tank to provide an area from which the clarified sewage could be drawn. A float switch positioned within this baffled area controlled the operation of the pilot feed pump and prevented pump operation when the tank volume was too low.

Figure 3-6. A cross section of the pilot-scale particulate clarifier and system.

A variable rpm motor (Dayton 3/4 Hp DC motor with an AC converter for RPM control model 2Z846) was used to drive a rotary screw pump (Teel, model 1P898) that transferred the partially clarified sewage directly to the first-stage AAFEB reactor. This combination of drive motor, pump, and gross particulate removal was extremely successful. The desired sewage flow rate was attained by adjusting the RPM of the pump using the RPM dial on the DC motor.

Analytical Program

The analytical program associated with the raw sewage pretreatment and delivery system consisted of determining the organic and nutrient removals achieved by the pretreatment clarifier and characterization of the partially clarified sewage that was transferred to the pilot-scale treatment system. Twenty-four hour composite samples were taken of the raw and clarified sewage flows. The raw sewage samples were periodically taken; the clarified samples were taken on a weekly basis. Characterization of the samples included determining the total and soluble chemical oxygen and biochemical oxygen demands, total kjeldahl and ammonia nitrogen, total and ortho phosphate, and total suspended and volatile suspended solids concentrations. The flow rate of clarified sewage to the AAFEB-1 reactor was determined daily by measuring the volume transferred in a 30-second interval twice per day. The temperature and pH of the clarified sewage were measured using a grab sample once per day. From these values the mass of material removed by the clarifier and the efficiency of removal was calculated.

ANAEROBIC ATTACHED FILM EXPANDED BED REACTOR SYSTEM (AAFEB)

The first unit process in the total resource recovery treatment system was the anaerobic-attached-film reactor system referred to as the AAFEB reactor system. This system was designed to replace such conventional unit processes as primary clarification, biological degradation of organic material, secondary clarification and sludge stabilization all in a single unit operation. The pilot expanded-bed reactor system consisted of two AAFEB reactors operated in series and retained within a custom designed greenhouse structure.

First-Stage AAFEB

The partially clarified sewage from the gross particulate removal clarifier was pumped directly to the bottom of the first-stage AAFEB-1 reactor. This reactor, illustrated in Figure 3-7, consisted of a steel cylindrical tank (1.52 meter I.D., 3.2 meter height) with a steel cone (1.52 meter diameter, 1.27 meter height) welded inside the bottom of the cylinder. The total volume of the reactor was 4.3 cubic meters; the effective volume was 2.5 cubic meters.

The expanded bed consisted of 2.2 cubic meters of a diatomaceous earth filter aide (Celite 560 manufactured by Manville Products Corporation, Lampoc, CA) with a mean particle diameter of 100 microns and a specific gravity of 2.3. This material provided the surface area for the growth of anaerobic microorganisms capable of biodegrading the organic matter in sewage. This material with attached microorganisms was hydraulically expanded to

Figure 3-7. A cross section of the first-stage AAFEB-1 reactor.

approximately 15 percent of its static volume; thus the bed volume increased to 2.5 cubic meters. Hydraulic expansion of the media was achieved with the combined flows of influent wastewater and liquid recycle. These flows were combined so the upflow velocity in the reactor was approximately two meters per hour.

It was critical that the media and attached biomass was expanded so that even distribution of the influent sewage and particulate entrapment were simultaneously possible. Expansion of the bed was achieved hydraulically by combining the influent sewage flow with a specific volume of liquid recycled from above the media in the reactor. The combined flow entered the reactor flow distribution cone through a flow dispersion pipe (3.8 cm I.D., 15 cm long, and containing twelve one cm I.D. holes) in the bottom of the reactor. The upflow velocity of the liquid as it entered the cone was extremely high. However, as the flow moved vertically up the cone the resulting upflow velocity decreased to approximately two meters per hour. Above the bed, a portion of the liquid flowed by gravity through a steel recycle pipe (3.8 cm I.D.) to the recycle flow-measurement barrel (200 liter volume, 60 cm I.D., 70 cm height). This vessel, though not a functional part of the system, represented an analytical tool that was used to determine the flow of recycle liquid by timed displacement. A submersible pump (Little Giant, model 2P352, 1/6 horsepower) in the bottom of this barrel transferred the recycle liquid through a flow-control valve to the influent port in the bottom of the reactor.

To avoid short-circuiting the liquid flow through the reactor, a paddle-mixer system was designed to redistribute the bed within the cone area. The paddle mixer consisted of a steel shaft (2.5 cm diameter and 3.5 meters in length) to which steel plates (10 cm

wide and 1.22 meters in length) were welded. The shaft rotated on two sealed bearings; one mounted to the top of the flow distribution pipe in the bottom of the reactor and the other bolted to a channel iron catwalk at the top of the reactor. The mechanical mixer was driven by a gear motor (Dayton, 1/40 Hp, four rpm, 200 in-lbs, model 3M326) and controlled by a cycle timer (CSA minimum on 120 seconds maximum on 240 minutes), that was operated for two minutes every four hours at a speed of two rpm.

A biogas collection cone was placed within the top portion of the reactor and designed to funnel liquid from within the active zone of the reactor through a progressively increasing turbulent zone that separated the media from attached biogas bubbles. The biogas deflection cone consisted of a truncated sheet metal funnel (0.3 cm thick, 18 gauge steel, 1.45 meters O.D., 15 cm I.D, and 40 cm height). After the liquid passed through the narrow opening at the top of the cone, it moved horizontally to a quiescent zone in which the media settled by gravity into the active reactor zone while the clarified liquid flowed by gravity under a baffle and over V-notched weirs.

The effluent from the reactor overflowed V-notched weirs placed at the top circumference of the reactor and was collected in the effluent collection trough (5 cm x 5 cm angle iron welded to the inside top circumference of the reactor). The trough transferred the effluent liquid by gravity from the system through the effluent collection box. A baffle 15 cm in height was placed seven cm inside the weirs to prevent short-circuiting the liquid across the top of the reactor. To facilitate observation of media performance, two sight windows (1.3 cm thick plexiglass sheet,

30.5 cm wide, and 0.91 meters in height) were fabricated into the cylinder portion of the reactor.

Second-Stage AAFEB

The effluent from the first-stage expanded-bed reactor flowed by gravity to the bottom of the second-stage AAFEB-2 reactor. To interpret the performance of this reactor at low-flow conditions while the first-stage reactor was receiving a high-flow condition, a pump (Teel model 1P898, rotary screw pump driven by a Dayton 3/4 Hp DC motor with an AC converter for RPM control) was used to divert a portion of the AAFEB-1 effluent flow. The diverted liquid was transferred to the headworks of the Ithaca Wastewater Treatment Facility. The remainder of the effluent flowed by gravity to the second-stage reactor.

The second-stage AAFEB-2 reactor was similar in design to the first-stage AAFEB reactor, AAFEB-1. The main difference between the two reactors was the overall dimensions. The second-stage unit was 1.22 meters in diameter and three meters high. Like the first-stage unit, the bottom portion of the second stage unit consisted of a cone (1.52 meters high, and 1.22 meters in diameter) and the upper portion consisted of a cylinder (1.52 meters in height and 1.22 meters in diameter), as illustrated in Figure 3-8. The total volume of this reactor was 2.37 cubic meters with an effective volume of approximately 1.5 cubic meters. A static volume of 1.3 cubic meters of Celite 560 diatomaceous earth was used as the attachment media and like the first unit it was also hydraulically expanded to 15 percent of its static

Figure 3-8. A cross section of the second-stage AAFEB-2 reactor.

volume. The liquid recycle system used to expand the bed was an exact duplicate of that used in the first-stage reactor.

The paddle mixer and biogas collection cone were also designed as smaller versions of those used in the first-stage reactor. The outside diameter of both the paddles and the cone was 1.1 meters.

Effluent from the reactor overflowed V-notched weirs placed at the top circumference of the reactor and was collected in the effluent collection trough. The trough transferred the effluent liquid by gravity from the system through the effluent collection box. A baffle 15 cm high was placed seven cm inside the weirs to prevent short-circuiting the liquid across the top of the reactor. To facilitate observation of media performance, a sight window (1.3 cm thick plexiglass sheet, 30.5 cm wide, and 0.91 meters high) was fabricated into the cylinder portion of the reactor.

Experimental and Analytical Program

The experimental and analytical programs associated with interpretation of the performance of the expanded-bed reactor system consisted of determining the organic and nutrient removals achieved by each reactor, characterization of the microbial attached film, identification of the settling qualities of the recycle and effluent liquids, and documentation of sludge production at sewage flow rates from 3000 to 10000 gallons per day.

Hydraulic Flows and Organic and Nutrient Removals

As indicated in Table 3-2, a total of six flow conditions were examined using the two reactors. Twenty-four hour composite samples were taken of both the influent and effluent liquids from each reactor on a weekly basis; more often when documenting steady performance conditions. The characterization of the samples included determining the total and soluble chemical oxygen and biochemical oxygen demands, total kjeldahl and ammonia nitrogen, total and ortho phosphate, total suspended and volatile suspended solids, sulfate and sulfide, and fecal coliform concentrations.

Table 3-2

A SUMMARY OF CONDITIONS USING THE PILOT-SCALE FIRST- AND SECOND-STAGE AAFEB REACTOR SYSTEM

Operation Dates		Condition	Reactor	Flow	HRT	Temp.	Influent
From	To	Number	I.D.	(s/d)	(hr)	(°C)	Source
1/1/90	1/25/90	1	AAFEB-1&2	19.0	5.4	9	Settled Sewage
1/26/90	3/16/90	2	AAFEB-1&2	7.5	12.5	10	Settled Sewage
3/17/90	8/31/90	3	AAFEB-1	37.5	1.8	17	Settled Sewage
3/16/90	6/1/90	4	AAFEB-1&2	16.7	5.6	15	Settled Sewage
6/2/90	8/2/90	5	AAFEB-1&2	27.0	3.2	20	Settled Sewage
8/3/90	8/31/90	6	AAFEB-1&2	16.1	6.1	23	Settled Sewage

Note: Sewage had large particulate material removed in a tank with a three minute hydraulic retention time.

The influent flow rate to each reactor was calculated from volumetric measurement of the effluent liquid collected in a 30-

second interval twice per day. The recycle rate in both reactors was determined by displacement in the recycle flow measurement barrel. A valve in the pipeline leading to the barrel was closed, which caused a drop in the liquid level within the barrel. At the end of 30 seconds the displacement in the barrel was measured and the recycle rate expressed as the volume of liquid displaced from the barrel in a 30-second time interval. The temperature and pH in each reactor was measured using a grab sample from the recycle line once per day.

Recycle and Effluent Liquid Settling Characteristics

No secondary clarification unit process was used in the pilot-system design. Clarification within the reactors was accomplished by solids entrapment within the expanded bed and by a simple baffle system consisting of the biogas deflection cone, a settling zone, and a diversion baffle in the top of the reactor. It was considered important to document the clarification potential of the expanded bed as well as the simple baffle design alternative.

At six points during the operation of the system the settling characteristics of the effluent and recycle liquids was determined, as indicated in Table 3-3. The first two conditions examined the effluent liquid which was siphoned from the reactor at a point 12 cm below liquid level and 12 cm from the inside wall of the reactor using two rubber hoses (1.9 cm I.D.) to a settling chamber. The next four conditions examined the liquid above the expanded bed and below the diversion cone (the recycled liquid). The point from which the liquid was siphoned was 74 cm below the liquid surface and 80 cm from the reactor sidewall.

Table 3-3

A SUMMARY OF CONDITIONS TO INTERPRET EFFLUENT AND RECYCLE LIQUID
SETTLING CHARACTERISTICS OF THE FIRST-STAGE AAFEB REACTOR SYSTEM

Liquid Reactor								
	Test	Liquid	Temp.	SS	VSS	Influent	Recycle	Overflow
						Flow Rate	Flow Rate	Rate
Date	No.	I.D.	(°C)	(mg/l)	(mg/l)	(s/d)	(s/d)	(s/m ² -d)
3/2/90	1	Effluent	11	32	20	7.5	86.4	4.6
3/9/90	2	Effluent	11	28	17	8.2	89.1	5.1
4/19/90	3	Recycle	11	38	31	37.3	78.1	23.1
5/5/90	4	Recycle	15	36	29	38.0	66.8	23.5
6/29/90	5	Recycle	20	39	28	38.3	66.8	23.7
8/30/90	6	Recycle	26	29	21	39.2	66.5	23.6

The settling chamber consisted of a clear acrylic cylinder (20.3 cm I.D., with 0.6 cm wall thickness, and three meters high) which was sealed on the bottom with a plexiglass end plate (1.3 cm thickness and 30 cm in diameter). A ball valve (two cm diameter) was threaded into this end plate to drain the liquid from the chamber. At intervals of 15 cm, nineteen sampling ports were threaded into the side wall of the chamber. A 15 cm length of PVC pipe was threaded into the sampling port from the inside such that a sample of the liquid was obtained from the center of the chamber. The sampling pipes extended 10 cm into the chamber and five cm out from the chamber side wall. Ball valves were threaded onto the end of each sampling port to quickly collect liquid samples without disturbing the interior of the chamber. The

exterior surface of the chamber was insulated with nine cm of fiberglass insulation and a polystyrene cover (five cm thickness) was used to minimize heat transfer from the liquid to the atmosphere. A cross section of the chamber is shown in Figure 3-9.

Liquid from the reactor was siphoned into the chamber using two siphon hoses. As the chamber slowly filled, usually within approximately three minutes, the hoses were slowly raised to minimize turbulence until the chamber reached a depth of three meters. At that point the hoses were removed and the chamber contents were gently mixed with a plexiglass disk (1.3 cm thick, 20 cm diameter) attached to a PVC pipe (3.1 meters long and 2.5 cm in diameter). The mixer was plunged into the chamber five times at the beginning of each test. Liquid lost during the mixing operation was replaced after the mixing was complete.

The analytical program to interpret settling characteristics of the liquid consisted of removing samples from the sample ports immediately following mixing and at predetermined intervals thereafter (time 0.0, 0.5 , 1.0, 4.0, 6.5, and 24 hours) for analysis of the total suspended and volatile suspended solids concentrations. Samples from five sampling ports, located 15, 76, 152, 213, and 274 centimeters from the bottom of the chamber, were taken at each interval. The temperature of the samples was also determined immediately after they were withdrawn from the chamber.

Actual Expanded-Bed Hydraulic Retention Time

The theoretical hydraulic retention time (HRT) of liquid in each reactor was expressed in terms of the expanded bed volumes (HRT_B)

Figure 3-9.

A cross section of the settling chamber used to interpret the settling characteristics of the AAFEB-1 recycle and effluent liquids.

as well as the total reactor volumes (HRT_T). These theoretical values defined the actual hydraulic retention times only if there was no short-circuiting of liquid within the reactors. It was considered important to quantify the actual hydraulic retention time in each reactor for comparison to the theoretical values.

The actual hydraulic retention time was determined using the results of lithium chloride tracer studies conducted on each expanded-bed reactor in early January 1990. As summarized in Table 3-4, the studies consisted of the batch addition of a predetermined mass of lithium chloride (dissolved in water) directly to the influent flow to each reactor.

Table 3-4

A SUMMARY OF THE STUDIES TO EXAMINE THE ACTUAL HYDRAULIC RETENTION TIMES OF THE TWO PILOT-SCALE AAFEB REACTORS

		Reactor	Lithium	Influent	Recycle	Reactor	Total
		Temp.	Addition	Flow rate	Flow Rate	Bed	Reactor
Date	I.D.	(°C)	(g)	(s/d)	(s/d)	(s)	(s)
1/8/90	AAFEB-2	9	425	18.9	28.5	1.1	2.37
1/15/90	AAFEB-1	10	914	19.9	68.1	2.8	4.29

To minimize interference with reactors downstream of that being examined, the first reactor examined was the second-stage expanded-bed reactor on January 8, 1990. The first-stage reactor

was examined seven days later. Following the lithium chloride addition, grab samples of the effluent and recycle liquids were taken at six and ten minute intervals for the AAFEB-2 and AAFEB-1 reactors respectively over the next eight-hour period. Lithium concentration in each sample was determined using an atomic absorption spectrophotometer (Instrumentation Laboratories, model 451, with lithium hollow cathode lamp). The actual hydraulic retention time in each reactor was calculated as the time between the injection of the lithium and the centroid of the tracer response curve.

Sludge Production

Along with the capability of the expanded bed system to achieve biological stabilization and clarification of domestic sewage, thus replacing primary and secondary clarification unit processes, one of the most important reasons for considering the system was its potential to significantly reduce the production of secondary sludge, if not eliminating and simultaneously stabilizing primary and secondary sludge. Thus, it was important to document the actual mass and degree of stabilization of sludge removed from the system.

The pilot expanded-bed reactor system was designed to entrap particulate matter that entered the reactors in the influent wastewater stream. These particles were slowly biodegraded and migrated to the top of the beds, accumulating as a sludge layer. The depth of this sludge layer was monitored on a daily basis through the sight windows located on the side wall of the reactors.

The sludge layer was accumulated within the reactor until it reached a depth of approximately 10 centimeters. At this point it was siphoned from the reactors using a siphon hose (two cm I.D.) and transferred to a steel holding tank (90 cm diameter and 90 cm high). The volume of sludge removed was determined by measuring the depth in the collection vessel. The contents of the vessel was then thoroughly mixed and a large subsample was taken to analyze the total and total volatile solids concentrations.

Anaerobic Biomass Characteristics

The rate of biodegradation achieved by individual anaerobic microorganisms capable of biodegrading the organic material in domestic sewage, was known to be significantly less than that of aerobic microorganisms. However, it was assumed that if an anaerobic system could retain significant concentrations of anaerobic microorganisms, i.e., significantly above those of conventional aerobic systems, it was possible to achieve comparable net rates of biodegradation.

To achieve high concentrations of anaerobic microorganisms, the pilot-scale AAFEB reactors were designed with a bed of inert media. This media, a diatomaceous earth filter aid, Celite 560, manufactured by Manville Products Corporation, provided a large surface area to which the bacteria attached. This media, which had a mean particle diameter of 100 microns and specific gravity of 2.3, was chosen for its extremely large surface area and for its hydraulic characteristics that included a low energy input for achieving hydraulic expansion and a settling rate that retained the media within the reactor at the design sewage flow rates.

The success of the expanded-bed reactor system, in terms of biodegradation of the organic matter in domestic sewage, depended on retention of large concentrations of the anaerobic microorganisms in the reactors. Periodically, throughout the study, subsamples of the beds were removed from the reactors for analytical interpretation of both attached and entrapped total and total volatile solids concentrations in the reactors.

The technique used to interpret the mass of entrapped and attached solids consisted of thoroughly rinsing the entrapped material from the media with distilled water. The dry mass of both the entrapped material and the media was then analytically determined. This was followed by analytical interpretation of the fixed solids mass. The mass of entrapped and attached bacteria was assumed to be the difference between the dry and fixed solids mass, and was expressed in terms of the expanded bed volume.

Biogas Production

The anaerobic microorganisms in the expanded-bed reactors converted the organic material in the domestic sewage to biogas, a mixture of methane and carbon dioxide. Using the pilot-scale reactors, it was impossible to accurately measure the gaseous volume of biogas produced from each reactor, however, it was possible to estimate the total volume of methane produced from each reactor based on the removal of total chemical oxygen demand (TCOD).

The use of this analytical technique was based on a constant derived from the stoichiometric oxidation of methane which

predicted that 0.25 grams of methane were produced from the conversion of one gram of organic matter when the mass of the organic matter was expressed in terms of the chemical oxygen demand. This calculated mass of methane represented both gaseous methane and methane dissolved in the effluent from each reactor. By measuring the liquid temperature in each reactor and assuming that the effluent liquid was saturated with methane, it was possible to calculate the mass of methane dissolved in the liquid using solubility constants from "International Critical Tables" (Vol. 3, p. 260). The gaseous mass of methane from each reactor was calculated as the difference between the total produced and that in solution. The methane mass production values were converted to volumetric productions using the universal gas constant (22.317 liters of methane per mole of methane; each mole of methane has a mass of 16 grams).

The assumption that the effluent liquids were saturated with methane was verified by measuring the methane concentration of the effluent liquid using the headspace analysis technique, described in the Methane Production section.

Bench-Scale AAFEB Reactor

To determine the relative performance of the attached film on the support media of the pilot-scale reactors, laboratory studies were conducted consisting of parallel operation of two bench-scale AAFEB reactors. The control was a mature, attached film grown on a support media consisting of aluminum oxide (0.5 liters) particles and diatomaceous earth (0.5 liter). This unit had operated for six months using a sucrose feed with a concentration

of 1000 milligrams COD per liter. A mature biofilm was developed in the second laboratory-scaled reactor using one liter of bed from the pilot second-stage anaerobic reactor (AAFEB-2). The performance of the mature films on acetate were documented and then compared to the performance of subsamples from the second-stage AAFEB reactor as a means to interpret the performance of the methanogenic microorganisms of the pilot-scale system. Samples from the first-stage pilot AAFEB were not analyzed since the microorganisms in this reactor were primarily responsible for hydrolysis, solubilization, and acidification.

A one-liter subsample of the bed from the second-stage pilot AAFEB was placed in the two bench scale AAFEB reactors. Each of these reactors consisted of a sealed glass cylinder (seven cm I.D., 80 cm in height) that was specially fabricated with a tapered influent access port (0.6 cm I.D.) in the bottom, a recycle liquid outlet port (0.6 cm I.D.) located in the sidewall of the reactor above the expanded bed level, a biogas collection system and a gravity flow liquid effluent piping arrangement.

As illustrated in Figure 3-10, the influent liquid to the system was combined with the recycle liquid and entered the reactor through a tapered glass fitting in the bottom of the reactor. The influent liquid consisted of a nutrient solution containing a predetermined mass of sucrose that was pumped into the reactor at a constant rate using a peristaltic pump (Masterflex, six to 600 rpm pump with 7014 head and norprene tubing). Expansion of the bed was achieved hydraulically by recycling liquid from above the bed using a second peristaltic pump (Masterflex six to 600 pump with 7015 head and norprene tubing). Biogas produced in the reactor was collected from the top of the reactor in a flexible

Figure 3-10. A schematic of the bench-scale AAFEB reactor.

biogas collection and storage bag (Tedlar vessel). The liquid effluent flowed by gravity through the recycle outlet port and through a tee positioned above the recycle pipeline. This tee, which also controlled the liquid level within the reactor, was vented to the biogas collection system. A length of tubing (0.6 cm I.D Tygon tubing) directed the effluent from the tee to the bottom of a glass effluent collection bottle. The tubing discharge was maintained below the effluent liquid level within the bottle to prevent biogas from escaping the reactor system.

The laboratory-scale reactors were operated in a temperature chamber at both 10°C and 20°C using an acetic acid feed substrate. A summary of the conditions examined and the influent substrate characteristics are summarized in Table 3-5. Throughout the operation period, the influent and effluent chemical and biochemical oxygen demands were measured with the hydraulic flow rates, volatile fatty acid concentrations, pH, and temperature. These data were used to estimate removal rates and efficiencies.

NFT REACTOR SYSTEM

The effluent liquid from the AAFEB reactor system flowed by gravity to the second unit process of the pilot-scale system. This second unit process, the NFT reactor system, was designed to achieve polishing removal of pollutants and tertiary treatment of nutrients in the wastewater stream using a unique modification of a hydroponic plant growth system capable of self-generating a large root system to filter, adsorb, absorb, and use the gross and trace inorganics and organics in wastewater. This single, simple unit process was designed to replace all the complex, conventional

Table 3-5

A SUMMARY OF LABORATORY-SCALE AAFEB REACTOR CONDITIONS

Reactor ID	Acetic Acid Substrate (mg/l)	Temp. (°C)	HRT	BOD OLR (g/l-d)	Inf. BOD (mg/l)
Mature Bed	80	20	8.5	0.37	131
			5.1	0.57	122
			2.9	0.72	87
			0.9	2.64	99
		10	9.5	0.32	128
			4.7	0.41	81
			2.9	0.69	83
			1	2.35	98
			8.2	0.3	101
			5.3	0.45	99
AAFEB-2 Bed	80	20	3.3	0.75	103
			1.1	2.14	98
			9.3	0.26	102
			5.2	0.48	103
		10	3.2	0.78	104
			1.1	2.16	99
			10	2.03	845
			4.4	4.42	811
			2.1	9.41	823
			0.9	21.04	789
Mature Bed	800	20	10.8	1.89	850
			5.1	3.9	829
			3	7.02	877
			1.2	17.06	853
		10	10.3	1.99	853
			4.47	4.15	812
			3.1	6.54	845
			1.2	17.24	862
			10.2	1.86	789
			5.9	3.45	849
AAFEB-2 Bed	800	20	3.3	6.15	845
			0.8	24.36	812

processes associated with removing nitrogen and phosphorous from wastewater while producing a high-quality liquid effluent discharge to the receiving waters. The pilot-scale NFT system consisted of two deep channel reactors, an intermediate wet well, two shallow channel reactors, and a final effluent wet well to transfer the treated wastewater back to the head works of the Ithaca Wastewater Treatment Facility. The entire NFT treatment system was enclosed within the greenhouse structure illustrated in Figure 3-11.

Deep Channel Nutrient Film Technique Reactors

The second-stage expanded-bed effluent liquid flowed by gravity to the deep channel NFT reactors (NFT-D). This two-reactor system, designed to maximize interfacial surface area for rapid removal of remaining organic and inorganic pollutants, consisted of two baffled tanks (2.44 meters wide, 15.24 meters long, and 1.22 meters high). These tanks, illustrated in Figure 3-12, were fabricated at the Agricultural and Biological Engineering Department of Cornell University by project personnel using black plate steel sheets (18 gauge) with black steel angle iron (3.8 cm x 3.8 cm x 0.3 cm) support members. A baffle was fabricated into the middle of each tank, forming a long channel (1.22 meters wide, 30.5 meters long, with a maximum flooded depth of 1.2 meters). All interior and exterior surfaces were primed and spray-painted with a final coat of a polyurethane-based oil paint to prevent corrosion.

Figure 3-11. A schematic plan view of the pilot-scale, hydroponic, NFT wastewater treatment system.

DEEP CHANNEL NUTRIENT FILM TECHNIQUE REACTOR

Figure 3-12. An isometric illustration of one of the two pilot-scale, deep-channel NFT reactors.

The primary plant biomass in the NFT system was *typha glauca* cattails. Approximately 600 plants were donated by Dr Leland C. Marsh in Oswego, New York; 2000 were harvested by project personnel from the Montezuma National Wildlife Refuge; and another 3000 were harvested from a wild stand in Freeville, New York during 1987. Approximately 1500 plants were grown from seed supplied by Dr. Marsh. Approximately 3000 plants were evenly spread across the bottom of each deep channel reactor (approximately 40 plants per square meter). The seeds and root mass of a variety of other wetland plants, including reed canary grass, irises, and pickerel plants were added to the NFT system. The plant propagation biomasses were then covered with a layer, five to eight cm deep, of stone two to four cm diameter. This coarse stone was added to anchor the rhizomes to the bottom of the reactors. It also provided a stable mass from which the rhizomes could support the growth of the above-liquid biomass and minimize "lodging" (the laying over and flattening of the stalk biomass) as the height of the plants increased.

Wastewater from the expanded bed system flowed by gravity to the southernmost deep channel reactor (NFT-DS) and moved horizontally as a plug along the length of the reactor. The effluent liquid from this reactor moved by gravity through a semi-flexible pipe (five cm I.D.) into the northernmost deep-channel reactor (NFT-DN). Liquid flow through this reactor could be characterized as horizontal plug-flow that continued along the length of the reactor. The effluent discharged into an intermediate wet well through a steel pipe, five cm inside diameter.

The wet well (35 liter capacity), though not a necessary component of a full-scale facility, was required to transfer effluent liquid

from the deep-channel NFT reactors to the shallow-channel system. The liquid was transferred using a submersible sump pump (Little Giant model 2P352, 1/6 Hp) controlled by a pressure sensitive-switch placed in the bottom of the wet well.

Shallow Channel Nutrient Film Technique Reactor

The primary purpose of the two shallow-channel NFT reactors was cultivating plants using nutrients in the wastewater. Unlike the deep-channel reactors, there was no support media used in this reactor system; however, the shallow-channel reactors were designed as smaller versions of the deep-channel reactors. As illustrated in Figure 3-13, each shallow-channel reactor consisted of a steel tank (1.83 meters wide, 0.4 meters high, and 15.2 meters long) with a sealed baffle centered nearly its entire length that transformed each tank into a long trough 0.9 meters wide and 30.5 meters long.

After these troughs were painted, approximately 4100 *typha glauca* cattail rhizomes, more than 70 plants per square meter, were evenly spread across the bottom of the units. Other plants added to the system included napier grass, reed canary grass, bulrushes and willow boughs. To prevent the plants from lodging, a netting system was fabricated 75 centimeters above the bottom of the reactors. This netting consisted of a versatile plastic mesh material (Tenax Hotonova 12.5 cm x 12.5 cm, polypropylene) especially designed for plant cultivation. The netting was stretched horizontally above the reactor and firmly anchored to the reactor's side walls. The plants were supported as they grew through the netting.

SHALLOW CHANNEL NUTRIENT FILM TECHNIQUE REACTOR

Figure 3-13. An isometric illustration of one of the two, pilot-scale, shallow-channel NFT reactors.

The submersible pump in the intermediate wet well transferred the effluent liquid from the deep channel system to the northernmost shallow-channel reactor (NFT-SN). The wastewater trickled through the root mass of this hydroponic system horizontally as a plug. It flowed by gravity the length of this reactor, through a semi-flexible pipe (five cm I.D.) to the southernmost shallow-channel reactor (NFT-SS). The wastewater continued to flow horizontally through this reactor and emptied into an effluent transfer wet well.

This final effluent wet well (30 liter capacity), like the intermediate wet well contained a submersible pump (Little Giant) controlled by a pressure-sensitive switch. The pump transferred the effluent liquid to the head works of the Ithaca Wastewater Treatment Facility.

Experimental and Analytical Programs

The experimental and analytical programs associated with interpretation of the performance of the NFT reactor system consisted of determining the organic and nutrient removals and the hydraulic characteristics of each reactor, and included characterization of the biomass production.

Organic and Nutrient Removals

As indicated in Table 3-6 a total of fourteen flow conditions were examined using the two NFT reactor systems. Twenty-four hour composite samples were taken of the influent and effluent liquids

Table 3-6

A SUMMARY OF CONDITIONS TO INTERPRET PERFORMANCE
OF THE NFT REACTOR SYSTEM

Dates		Condition	Reactor	Temp.	Flow	Hydraulic
From	To	Number	I.D.*	(°C)	(s/d)	Loading (cm/d)
1/1/90	4/29/90	N-1	DS	10.0	3.8	10.2
1/1/90	4/29/90	N-2	D	10.0	3.8	5.1
1/1/90	4/29/90	N-3	D&SN	10.0	3.8	3.7
4/30/90	6/1/90	N-4	DS	11.0	6.4	17.2
4/30/90	6/1/90	N-5	D	11.0	6.4	8.6
4/30/90	6/1/90	N-6	D&SN	11.0	6.4	6.3
6/1/90	6/21/90	N-7	DS	11.0	6.4	17.2
6/1/90	6/21/90	N-8	D	11.0	6.4	8.6
6/1/90	6/21/90	N-9	D&S	13.0	15.0	11.5
6/22/90	8/3/90	N-10	DS	18.0	15.0	40.3
6/22/90	8/3/90	N-11	D	18.0	15.0	20.2
6/22/90	8/3/90	N-12	D&SN	18.0	15.0	14.7
8/3/90	8/31/90	N-13	D	22.0	7.6	10.2
8/3/90	8/31/90	N-14	D&SN	22.0	7.6	7.4

*DS - NFT southernmost deep-channel reactor

D - Both NFT deep-channel reactors

SN - NFT northernmost shallow channel reactor

S - Both shallow-channel reactors

from each reactor weekly. The characterization of the samples included determining the total and soluble chemical oxygen and biochemical oxygen demands, total kjeldahl and ammonia nitrogen, total and ortho phosphate, total suspended and volatile suspended solids, sulfate and sulfide ion, and fecal coliform concentrations. The loading and removal rates were expressed in terms of the mass loaded or removed per square meter of reactor surface area per day ($\text{g/m}^2\text{-d}$). The removal efficiency was calculated as the unit mass removed per unit mass loaded and was expressed as a percent.

The influent flow rate to each reactor was calculated from volumetric measurement of the influent liquid to the first deep-channel reactor collected in a 30-second interval twice each day. The wastewater flow rate to each reactor was expressed in steres per day and the hydraulic loading was expressed as the depth of wastewater loaded into the reactor per day (cm/d). The temperature and pH in the influent and effluent from each reactor was measured using a grab sample once each day.

Batch Nutrient Removal Studies

To examine the maximum rates of nutrient removal using the NFT reactor system, four batch nutrient uptake studies were conducted using the northernmost shallow-channel NFT reactor. The studies were designed to both interpret the rates of nutrient removal and also to interpret the volume of root mass within the reactor.

Immediately before beginning the study, the flow of wastewater to the reactor was interrupted and the average depth of liquid in the

reactor calculated from measurements taken at six points along the length of the channel. Following the depth measurements, the reactor liquid was gravity drained into a fiberglass collection tank (1.8 meters in diameter and 0.9 meters high) over twenty-four hours. The volume of liquid from the reactor was recorded and then tap water was added to adjust the total volume in the collection tank to a predetermined level. Specific masses (chosen to ensure excess nutrients throughout each test) of ammonium phosphate ($\text{NH}_4\text{H}_2\text{PO}_4$), potassium and ammonium nitrate (KNO_3 and NH_4NO_3), ammonium chloride (NH_4Cl), and lithium chloride (LiCl) were thoroughly mixed into the tank and then the entire volume was transferred using a Teel Centrifugal medium head pump into the reactor. A summary of the four conditions examined is presented in Table 3-7.

Table 3-7

A SUMMARY OF THE BATCH NUTRIENT UPTAKE STUDIES USING THE
NORTHERNMOST SHALLOW-CHANNEL NFT REACTOR

Tap													
		Init	Eff	H ₂ O	Nut	Final							
		Avg	Liq	Add	Sol	Avg (NH ₂)							
Dates		Cond	Temp	Depth	Vol	Vol	Vol	Depth	H ₂ PO ₄	NH ₄ Cl	KNO ₃	NH ₄ NO ₃	LiCl
From	To	No.	(°C)	(cm)	(l)	(l)	(l)	(cm)	(g)	(g)	(g)	(g)	(g)
2/20/90-2/26/90	1	12	9.2	0	0	0	9.2	43.9	0.0	148.6	0.0	0.0	0.0
3/6/90-3/14/90	2	14	7.9	412	1514	1514	7.1	238.8	214.8	391.1	0.0	0.0	0.0
5/16/90-5/24/90	3	19	8.6	315	1325	1325	7.1	296.3	295.5	310.8	0.0	170.0	0.0
10/17/90-1/23/91	4	18	8.6	315	1010	1325	12.1	396.3	0.0	175.0	166.4	184.3	0.0
11/29/90-12/6/90	5	10	10.8	570	0	0	3.2	0.0	0.0	0.0	0.0	0.0	0.0

The average depth of liquid in the reactor was recorded as soon as the liquid level equilibrated. After recording the depth, a liquid recycle system was activated to transfer liquid from the effluent end of the reactor back to the influent end. The recycle system, similar to the wet wells used as the intermediate and final effluent wet wells, consisted of a polyethylene tank (35 liter capacity) containing a submersible sump pump (Little Giant, model 2P352, 1/6 Hp) controlled by a pressure-sensitive switch. This wet well was designed to collect the gravity flow of liquid from the reactor and transfer this liquid to the influent end of the reactor at approximately 50 liters per minute.

Grab samples were taken from the recycle wet well two to four times each day for approximately two weeks. Analytical measurements of these samples included total kjeldahl nitrogen, total ammonia nitrogen, nitrate nitrogen, nitrite nitrogen, total, and ortho phosphorous, and lithium concentrations. The lithium chloride, added to the initial nutrient solution as a conservative substance, was used to correct the measured nutrient concentrations for evaporative losses. The nutrient uptake rate was calculated from the slope of the log plot of the nutrient concentration versus time and was expressed as mass removed per square meter per day ($\text{g/m}^2\text{-d}$).

The volume occupied by the reactor root mass was estimated as the calculated difference between the effluent liquid volume and the total reactor liquid volume which was calculated using the average depth measurement just prior to the start of each study. The root mass volume determined with this method was compared to that calculated from the volume of nutrient solution added and the

reactor total liquid volume, calculated from the average depth measurements just after the nutrient solution was added.

Hydraulic Characterization

The theoretical hydraulic retention time (HRT) of liquid in each NFT reactor was calculated as a function of the total liquid depth, surface area, and the wastewater flow rate to the reactor. Once each week, liquid depth measurements were recorded at six points along the length of each NFT reactor. From these values the average liquid depth was calculated and used to calculate the total liquid volume in each reactor. However, the actual hydraulic retention time was expected to be significantly shorter than the theoretical value due to the volume occupied by the root mass in the reactor system.

To interpret the actual hydraulic retention time of liquid within each NFT reactor, a lithium chloride tracer study was made in September, 1990. On September 17, 1990 a predetermined mass of lithium chloride (804.43 grams), dissolved in tap water (20 liters), was batch-added in the influent line to the southernmost deep-channel reactor. Following the lithium chloride addition, grab effluent liquid samples were taken hourly from each NFT reactor for four days. Throughout this period the wastewater flow rate through the system was maintained at 7.6 steres each day. Lithium concentration in each sample was determined using an atomic absorption spectrophotometer (Instrumentation Laboratories, model 451, with lithium hollow cathode lamp). The actual hydraulic retention time was calculated as the time between the

injection of the lithium and the centroid of the tracer response curve.

Biomass Production

The nutrients in the wastewater supplied to the plants in the NFT system represented the fertilizer source necessary to promote plant growth. Plant growth was interpreted in terms of the root and aerial mass yearly biomass productions (yields, wet and dry mass per unit area), root mass bulk density, aerial stalk density, fiber characteristics, and chemical composition.

Two harvesting techniques compared the net yield of plant biomass. The first technique consisted of periodic removal of aerial biomass from the reactor with a total harvest of all plant biomass at the end of the year. Four evenly spaced sections three meters long in the reactor were carefully measured and marked. On June 13, 1990 and again on July 13, 1990, all plant biomass 30 centimeters above the liquid level was harvested from the four designated areas. The total wet mass was recorded and the dry matter content analytically determined. At the end of the year, four representative areas (30.5 cm by 30.5 cm) of the biomass from the periodically harvested areas and two from the unharvested areas were carefully measured and partitioned on December 11, 1990. The number of stalks in the delineated areas was counted and then the above water biomass was harvested followed by the entire root mass. After the wet mass of each was measured, the dry mass yield of both root mass and above water biomass, including biomass from the earlier harvests, was calculated from these wet mass measurements and total solids analysis.

Since this total mass-production value represented the total growth over three years, the net yearly production was expressed as the difference between that of 1989 and 1990. The root mass bulk density was calculated using the unadjusted wet and dry mass values as a function of the root mass volume determined during the nutrient uptake studies and expressed as grams of wet or dry root mass per liter of root mass volume.

Representative samples of the root mass and above-water biomass were also taken to interpret the fiber and chemical composition. Fiber analysis of the samples was performed by the Department of Animal Science at Cornell University, according to the methods developed by Van Soest and Robertson. Elemental analysis of the biomass was performed by the Department of Fruit and Vegetable Crops, Cornell University, using ICP analysis. The mass of nutrients in the plant biomass was calculated from the biomass net yield and composition values.

Predator and Pest Management

An important part of the maintenance of the NFT system was managing predators and pests that might feed on the growing biomass. This study had initially included the examination of two NFT reactors to be operated outside the greenhouse structure. A muskrat moved into the outside reactors in November 1989 and destroyed most of the biomass in these systems, then moved into the greenhouse and destroyed the majority of the southernmost NFT shallow-channel reactor (NFT-SS). Though all undamaged biomass was consolidated into NFT-SS, experiments to interpret its

performance as well as the performance of the outside reactor systems were terminated. A chickenwire fence was placed around both shallow-channel reactors in the greenhouse to prevent these predators from doing further damage.

Insect pests that might consume the plant biomass were also a concern. It was important to control pests using natural techniques. Integrated Pest Management (IPM), president Ms. Carol Glenister, was hired to monitor the plants once a week and provide natural predators to control the pest population.

ANALYTICAL PROCEDURES

The analytical procedures provided the basis for mass balances of the following pollutants: suspended solids, total and soluble COD and BOD, nitrogen as organic and inorganic compounds, and phosphorus as total and ortho. Physical and biological parameters were measured throughout the pilot-system operation. Physical measurements for flow control of the AAFEB and NFT reactors were conducted daily while biological measurements to assess system performances were conducted weekly. A detailed summary of the analytical program is outlined in Table 3-8. The methods used to measure the organic and inorganic concentrations in the influent and effluent liquids of the pilot system are presented in Table 3-9.

Table 3-8

A SUMMARY OF THE PARAMETERS MEASURED AND FREQUENCIES TO INTERPRET
THE PERFORMANCE OF THE PILOT-SCALE ENERGY AND BIOMASS RECOVERY
DOMESTIC WASTEWATER TREATMENT FACILITY.

(D=DAILY; W=WEEKLY; AR=AS REQUIRED; P=PERIODICALLY; Y=YEARLY)

Parameter	Influent	Clarifier	AAFEB-1&2	NFT-D&S
I. Wastewater				
Flowrate	P	2/D	2/D	2/D
Temperature	P	D	D	D
pH	P	D	D	D
Recycle Rate			D	
Upflow Velocity		D		
Bed Height			D	
Liquid Depth				W
Power Required		D	D	D
Methane			4/Y	4/Y
Attached Biomass			4/Y	
Entrapped Biomass			4/Y	
Total COD	6/Y	W	W	W
Soluble COD	6/Y	W	W	W
Total BOD	6/Y	W	W	W
Soluble BOD	6/Y	W	W	W
SS	6/Y	W	W	W
VSS	6/Y	W	W	W
VFA	6/Y	W	W	W
TKN	6/Y	W	W	W
TAN	6/Y	W	W	W
NO ₃ -N	6/Y	W	W	W
NO ₂ -N	6/Y	W	W	W
Cl	6/Y	W	W	W
Total P	6/Y	W	W	W
Ortho P	6/Y	W	W	W
Sulfate S	6/Y	W	W	W
Sulfide S	AR	AR	AR	AR
Fecal Coliform	6/Y	W	W	W
II. AAFEB - 1&2 Sludge				
Height			D	
Volume			AR	
Total Solids			AR	
Total Volatile Solids			AR	
III. Plant Biomass				
Wet Mass				1-3/Y
Total Solids				1-3/Y
Total Volatile Solids				1-3/Y
Stalk Areal Density				4/Y
Root Mass Density				4/Y
Elemental Analysis				Y
Fiber Analysis				Y

Table 3-9

A SUMMARY OF THE ANALYTICAL TECHNIQUES USED TO MEASURE THE ORGANIC
AND INORGANIC CONCENTRATIONS OF THE PILOT SYSTEM

Concentration	Standard Methods Technique	Other Technique
Total COD		Knechtel ¹
Soluble COD		Knechtel
Total BOD	Azide Modification/Membrane Electrode Method	
Soluble BOD	Azide Modification/Membrane Electrode Method	
SS	Membrane Filter	
VSS	Membrane Filter	
TS	Total Solids Dried at 103 - 105°C	
TVS	Fixed and Volatile Solids Ignited at 550°C	
CH ₄		TCD Gas Chromatograph ²
VFA		FID Gas Chromatograph ³
TKN	Macro-Kjeldahl Method	
TAN	Ammonia Distillation/Titrimetric Method	Spec ⁴
NO ₃ -N		Ion Chromatograph ⁵
NO ₂ -N		Ion Chromatograph ⁵
Cl		Ion Chromatograph ⁵
Sulfate S		Ion Chromatograph
Sulfide S	Iodometric Method	
Total Phosphorus	Ascorbic Acid Method	
Ortho Phosphorus		Chromatograph
Fecal Coliforms		Private Laboratory ⁶
Elemental Analysis		ICP ⁷
Fiber Analysis		Van Soest ⁸
Dissolved Methane		Headspace

1. Method introduced by J. Ross Knechtel as described in: Knechtel, J. R., "A more Economical Method for Determination of Chemical Oxygen Demand." *Water & Pollution Control* (116) 5: 25-29, 1978.
2. GOW-MAC Series 580 Thermal Conductivity Detector with 6' by 1.4" stainless steel column packed with 80/100 mesh porapak Q.
3. GOW-MAC Series 740 P Flame Ionization Detector with 15 meter by 0.53 millimeter fused silica NukolTM (0.50 micrometer film thickness).
4. Soil and water technique
5. Dionex 2000i Ion Chromatograph with AS4A analytical column and Dionex Conductivity Detector.
6. BUCK Environmental Laboratories INC. Accredited Environmental Analysis, Cortland, NY.
7. Inductively Coupled Argon Plasma Technique conducted by the Spec Lab, Fruit and Vegetables Department, Cornell University, Ithaca, NY.
8. Sequential fiber and *in vitro* digestibility analyses using methods reported by Goering and Van Soest (1970) and Van Soest and Robertson (1985). Conducted by the Animal Science Department, Cornell University, Ithaca, NY.

Loading and Removal Rates and Removal Efficiency

The loading and removal rates and removal efficiencies of each reactor in the pilot system were calculated from average concentrations measured while the reactors were operated under steady-performance conditions. Steady performance was defined as a relative condition in which the influent and effluent substrate concentrations and flow rates were constant for at least five hydraulic retention periods.

The loading rate to each reactor of the pilot system was calculated in terms of the hydraulic flows and the influent and effluent liquid substrate organic and inorganic concentrations. The hydraulic flows to each reactor in the system were measured twice daily and were used to calculate the hydraulic loading rate in terms of the Hydraulic Retention Time (HRT) using Equation 3-1. The HRT of the AAFEB reactors (HRT_B) was expressed in terms of the volume of expanded bed media in each reactor. That of the NFT reactors was expressed in terms of the average liquid depth in each reactor.

$$HRT = BV/Q \qquad \text{Eq 3-1}$$

where,

HRT = Hydraulic Retention Time, hours

BV = Bed Volume (AAFEB), Total Liquid Volume
(NFT), steres

Q = Flow rate of liquid to the reactor,
steres per hour

The hydraulic loading rate to the NFT reactors was also calculated as the depth of liquid applied to the surface area of the reactor in a day and was expressed in centimeters per day (cm/d).

The organic and inorganic loading rates to each reactor of the pilot system were calculated as the mass of material loaded in grams per unit bed volume (AAFEB reactor system) or unit surface area (NFT reactor system) per day. The loading rates to the AAFEB reactor system were calculated using Equation 3-2 and those for the NFT reactor system using Equation 3-3.

$$LR_A = (Q \times S_O) / (BV \times 1000) \quad \text{Eq. 3-2}$$

$$LR_N = (Q \times S_O) / SA \quad \text{Eq. 3-3}$$

where,

LR_A = AAFEB Reactor Organic or Inorganic Material Loading Rate, g/l-d

LR_N = NFT Reactor Organic or Inorganic Material Loading Rate, g/m²-d

Q = Influent Liquid Flow Rate, s/d

S_O = Influent Substrate Concentration, mg/l

BV = AAFEB Reactor Bed Volume, s

SA = NFT Reactor Surface Area, m²

The substrate removal rates were calculated as the difference between the influent and effluent substrate concentrations and expressed similar to the loading rates using Equation 3-4 for the AAFEB reactors and Equation 3-5 for the NFT reactors.

$$RR_A = (Q \times (S_O - S_E)) / (BV \times 1000) \quad \text{Eq. 3-4}$$

$$RR_N = (Q \times (S_O - S_E)) / SA \quad \text{Eq. 3-5}$$

where,

RR_A = AAFEB Reactor Removal Rate, g/l-d

RR_N = NFT Reactor Removal Rate, g/m²-d

Q = Influent Liquid Flow Rate, s/d

S_O = Influent Substrate Concentration, mg/l

S_e = Effluent Substrate Concentration, mg/l

BV = AAFEB reactor Bed Volume, s

SA = NFT reactor Surface Area, m²

The removal of organic and inorganic substances in the reactor was also expressed as a removal efficiency. The removal efficiency (RE) was calculated from the calculated loading and removal rates and expressed as the percent of substance removed per unit substance loaded, using Equation 3-6.

$$RE = (RR_A \text{ or } RR_N) / (LR_A \text{ or } LR_N) \times 100 \quad \text{Eq. 3-6}$$

Methane Production

The stoichiometric oxidation of methane, illustrated in Equation 3-7, predicted that 64 grams of oxygen were required to oxidize 16 grams of methane (four grams oxygen per gram methane).

Using this relationship, the methane gas mass production rate ($\text{CH}_4\text{-PR}$) produced by each of the AAFEB reactors was calculated in terms of the methane equivalent of the mass of total COD removed from each reactor, using Equation 3-8.

$$\text{CH}_4\text{-PR} = \text{TCOD RR}_A/4$$

Eq. 3-8

where,

$\text{CH}_4\text{-PR}$ = Methane Gas Mass Production Rate, g- CH_4 /l-d

TCOD RR_A = Total COD Removal Rate, g-TCOD/l-d

The methane gas, mass production rate represented the total mass of methane produced by each AAFEB reactor. This total production included both methane dissolved in the effluent liquid and methane that escaped from each reactor as a gas. The equilibrium concentration of methane dissolved in the liquid effluent was a function of the methane partial pressure of the gas adjacent to the liquid. Thus, the dissolved methane concentration was dependent on the methane equilibrium mole fraction and the temperature dependent on Henry's Law Constant. The dissolved methane concentration was calculated using Equation 3-9, a specific application of Henry's Law.

$$\text{CH}_4\text{-D} = (x_g \times 8896)/H_T$$

Eq 3-9

where,

$\text{CH}_4\text{-D}$ = Dissolved methane concentration, mg/l

x_g = Equilibrium mole fraction of methane, %

H_T = Henry's Law Constant for methane at temperature
T, atm/mole fraction.

8896 = Conversion factor equal to the product of 55.6
moles- H_2O /l-water x 16 grams CH_4 /mole- CH_4 x 1000
mg/g divided by 100%

The methane equilibrium mole fraction was determined using a headspace analysis procedure. This technique consisted of placing a specific volume of the effluent liquid in a sealed vial. The

vial was placed in a gyrotory water-bath shaker (New Brunswick Scientific Co. Inc., Model G76D) maintained at 35°C for 24 hours. The methane concentration in the headspace of the vial was determined using a gas Chromatograph (GOW-MAC Series 580 thermal conductivity detector with a 0.25 inch by six-foot stainless steel column packed with 80/100 mesh, Por pak Q). The chromatograph determined the volumetric portion of methane in the headspace gas in percent. The methane concentration in the liquid was then calculated using Henry's Law. A summary of Henry's Law Constants for methane is presented in Table 3-10.

Table 3-10

HENRY'S LAW CONSTANTS FOR METHANE AT TEMPERATURES FROM 0°C TO 30°C

Temperature (°C)	Henry's Constant (atm/mole fraction)
0	22400
5	25900
10	29700
15	33700
20	37600
25	41300
30	44900
Regression Output:	
Constant	22264.3
Std. Err. of Y Est.	189.1
R Squared	0.9997
No. of Observations	7
Degrees of Freedom	5
X Coefficient (s)	758.6
Std. Err. of Coef.	5.75

$$H_T = 758.6(T) + 22264 \quad \text{Eq. 3-10}$$

where,

H_T = Henry's Law Constant at specific liquid temperature.

T = Liquid Temperature, °C

The mass of methane produced was converted to volumetric production values by using the universal gas constant that predicted that a mole of methane gas at standard temperature and pressure (273°K, and 1.0 atmosphere) occupied a volume of 22.413 liters. The volumetric methane production rates (CH₄-VPR) were expressed as liters of methane produced per liter of expanded bed volume per day (l/l-d) at standard temperature and pressure, using Equation 3-11.

$$\text{CH}_4\text{-VPR} = \text{CH}_4\text{-PR} \times 22.413/16 \quad \text{Eq. 3-11}$$

where,

$$\text{CH}_4\text{-VPR} = \text{Total Methane Volumetric Production Rate, l/l-d}$$

AAFEB Reactor Attached and Entrapped Biomass

The mass of attached and entrapped biomass within the first and second stage AAFEb reactor beds were measured monthly throughout the study. The technique used to interpret these masses consisted of careful measure of the total and total volatile solids concentrations in the reactor beds. Samples of support media particles and entrained solids were siphoned from the center of the beds. The sample was transferred to a wide-bore graduated cylinder using a wide-mouth 10 ml serological pipet. The cylinder was then tapped on the laboratory bench and spun to tamp and pack the sample. More sample was added or withdrawn from the cylinder until the the cylinder contained exactly five milliliters of packed-bed particles. The supernatant was decanted and the sample transferred to an ashed, preweighed evaporation dish. Distilled water was used to wash entrapped solids from the support media. The total and total volatile solids concentration of the entrapped

and attached solids were then analytically determined. Blanks of bare support media were simultaneously analyzed to adjust for hygroscopically bound water. Following the measure of the fixed solids mass, the support media was returned to the graduated cylinder and the final volume of sample was determined. The attached volatile solids concentration was calculated using Equation 3-12.

$$\text{Attached VS} = 1000 \times (W_s - W_b \times V_f) / V_i \quad \text{Eq. 3-12}$$

where,

Attached VS = Attached biomass concentration, g/l

W_s = Volatile mass of sample plus support media, g

W_b = Volatile mass of bare support media, g

V_i = Initial tamped sample volume, 5 ml

V_f = Final Tamped sample volume, ml

Section 4

PERFORMANCE RESULTS

INTRODUCTION

Performance results of the domestic sewage, pilot-scale energy and biomass recovery system, from January 1, 1990 through December 31, 1990 are summarized in this section. The research, conducted by personnel in the Department of Agricultural and Biological Engineering at Cornell University at the Ithaca Wastewater Treatment Facility in Ithaca, New York, focused on determining the feasibility of incorporating two innovative technologies to achieve high-quality treatment of domestic sewage: the anaerobic attached film expanded bed reactor wastewater treatment system followed by the hydroponic nutrient film technique. The research included a comprehensive analytical program designed to determine the key design parameters of each of the two unit processes. These design parameters were then used to obtain the sizes and economics of systems capable of high quality treatment at 100,000 and 1,000,000 gallons per day as discussed in Section 5.

PILOT SYSTEM PERFORMANCE

The influent wastewater to the pilot system was domestic wastewater taken from a forced main that transferred the total wastewater flow of Ithaca, New York from the headworks of their new wastewater treatment facility to the primary clarifiers. This forced main simultaneously transferred wastewater directly to the pilot system on a continuous basis, twenty-four hours a day so the

pilot system received exactly the same domestic wastewater concentrations as the Ithaca facility.

The temperature of the wastewater, illustrated in Figure 4-1, appeared to slowly increase over the test period from January 1, 1990 through August 31, 1990. It was as low as 9°C in early February and increased to approximately 23°C in August, 1990.

The composition of the Ithaca, New York domestic wastewater was strongly influenced by two factors. The Ithaca wastewater collection system is an old combined storm and sanitary system with significant inflow and infiltration flows. Though the average wastewater flow to the treatment facility was approximately six million gallons per day, rain often increased the flow to more than 15 million gallons a day for short periods. Transient residents (students) represent nearly 50 percent of the Ithaca population. When classes were not in session, many of the students left the area. These two variables strongly influenced the concentrations of organics, inorganics, and nutrients in the wastewater and contributed to classifying it as a weak sewage with total chemical oxygen demand (TCOD) less than 280 mg/l, total biochemical oxygen demand (TBOD) less than 120 mg/l, and suspended solids (SS) less than 110 mg/l, as indicated in Table 4-1. This was also true of the total nitrogen and phosphorous concentrations which were usually less than 30 mg/l and 6 mg/l, respectively.

The influent COD, BOD and SS concentrations were indeed variable; however, the concentrations in the effluent liquid from the pilot system were consistently low. The effluent COD concentration was always less than 50 mg/l, Figure 4-2, and the total BOD and total SS concentrations were less than 10 mg/l, Figures 4-3 and 4-4,

TEMPERATURE PILOT SYSTEM

Figure 4-1. An illustration of the influent wastewater temperatures during the study.

TCOD PILOT SYSTEM

Figure 4-2. Pilot system influent and effluent total chemical oxygen demand concentrations measured during the study.

Figure 4-3. Pilot system influent and effluent total five-day biochemical oxygen demand concentrations measured during the study.

Figure 4-4.

Pilot system influent and effluent total suspended solids concentrations measured during the study.

even when all data is lumped together covering a wide range of process and test variables.

Table 4-1

A SUMMARY OF THE ITHACA AREA WASTEWATER TREATMENT PLANT RAW SEWAGE CHARACTERISTICS

Parameter	High	LOW	Average
Study Period: 1/1/90 - 8/31/90			
Temperature (°C)	23	8	
Influent Flow (mgd)	10.00	5.00	
Chemical Oxygen Demand			
Total Chemical Oxygen Demand (mg/l)	278.46	111.03	210.17
Soluble Chemical Oxygen Demand (mg/l)	149.50	24.74	96.64
Biological Oxygen Demand			
Total Biological Oxygen Demand (mg/l)	120.50	43.40	87.60
Soluble biological Oxygen Demand (mg/l)	na	na	na
Volatile Fatty Acid (mg/l)	18.00	11.0	9.1
Nitrogen			
Total Kjeldahl Nitrogen (mg/l)	28.76	14.30	21.95
Ammonia Nitrogen (mg/l)	18.28	7.60	12.68
Phosphorus			
Total Phosphorus (mg/l)	5.13	1.35	3.34
Ortho Phosphorus (mg/l)	1.86	0.97	1.31
Solids			
Suspended Solids (mg/l)	108.13	42.24	67.50
Volatile Suspended Solids (mg/l)	93.40	27.48	52.94

RAW SEWAGE PRETREATMENT AND DELIVERY SYSTEM

The pilot system received a small portion of the Ithaca raw wastewater stream on a continuous basis twenty-four hours a day. To avoid problems associated with large particulate matter in the sewage plugging the small pumps and piping of the pilot system, a custom-designed gross particulate clarifier was installed prior to the pilot-system wastewater delivery pump. It is important to note that this clarifier was not designed to be a primary

clarification system but was required due to the scale of the research facility.

Total influent flow to the clarifier was approximately 200 gallons per minute. Thus, the hydraulic retention time in the clarifier (1.83 meters in diameter and 0.91 meters high) was approximately three minutes. A small portion of this partially clarified wastewater was used as the influent liquid to the pilot-scale biomass and energy recovery system. A positive displacement rotary screw pump was used to deliver the wastewater to the pilot system on a constant and continuous basis. The majority of the clarified liquid that entered the clarifier passed into a wastewater drainage pipeline that conveyed the liquid to the headworks of the Ithaca Wastewater Treatment Facility.

The clarifier successfully removed the gross particulates and minimal problems were encountered with delivery of wastewater to the pilot system. As presented in Appendix K and summarized in Table 4-2, the removal of chemical and biochemical oxygen demand was negligible; however, the removals of suspended and volatile suspended solids were 22 and 28 percent respectively. These values represented the average of seventeen composite samples of the wastewater influent flow to the clarifier and the partially clarified flow to the pilot system. Towards the end of the study, the pilot system was operated for several months without the use of the intermediate tank. The difference in operation was observed.

Table 4-2

A SUMMARY OF THE PERFORMANCE OF THE PILOT GROSS PARTICULATE
CLARIFIER WITH A 3.0 MINUTE HYDRAULIC RETENTION PERIOD

Parameter	Number Measurements	Influent (mg/l)	Effluent (mg/l)	Removal Efficiency (%)
Hydraulic Retention Time (hr)				
Chemical Oxygen Demand				
Total Chem. Oxygen Demand (mg/l)	17	178.12	173.12	2.8
Soluble Chem. Oxygen Demand (mg/l)	17	106.52	107.06	-0.5
Biological Oxygen Demand				
Total Biol. Oxygen Demand (mg/l)	17	84.47	82.04	2.9
Soluble Biol. Oxygen Demand (mg/l)		na	na	na
Solids				
Suspended Solids (mg/l)	17	81.22	63.68	21.6
Volatile Suspended Solids (mg/l)	17	69.67	50.13	28.0

AAFEB REACTOR SYSTEM

Partially clarified sewage was pumped continuously from the clarifier to the AAFEB reactor system. This system consisted of two AAFEB reactors operated in series. Throughout most of the studies, a portion of the effluent from the first-stage reactor was discarded so the second-stage reactor received a partially treated wastewater at a significantly reduced flow rate.

The AAFEB reactor system was designed to replace such conventional unit processes as primary clarification, biological degradation of organic material, secondary clarification and sludge stabilization in a single unit operation. A comprehensive analytical program was designed to interpret the system potential and determine organic and nutrient removals at each of the hydraulic loading conditions examined, and included interpretation of the effluent settling characteristics, actual bed hydraulic retention times, biogas and sludge production, and concentrations of anaerobic

biomass in the reactors. Performance of the two pilot-scale reactors was also compared to the results from bench-scale studies.

Hydraulic Flows

Design of the AAFEB reactor system focused on achieving maximum concentrations of anaerobic microorganisms in the two reactors. To prevent washout and achieve these maximum concentrations it was essential that the microorganisms attach themselves to a support media that would remain in the reactors over a wide range of hydraulic flow rates. Therefore, the choice of support media was critical in designing the reactors. The support media chosen was a diatomaceous earth filter aide (Celite 560 manufactured by Manville Products Corporation). This material, which was produced from diatoms, was composed of silica oxide and was completely inert to biological degradation. It had a mean particle diameter of 100 microns, a specific gravity of 2.3, and a surface area that was greater than 30 square meters per liter of expanded bed volume.

The tremendous surface area available for microbial attachment represented a major advantage of this media. The anaerobic microorganisms attached themselves to the surfaces of the media to produce reactor microbial concentrations that were 10 to 20 times those of conventional aerobic-activated sludge facilities. As summarized in Table 4-3, the microbial concentrations in the first-stage reactor (AAFEB-1) were between 20 and 30 grams of volatile solids per liter of expanded bed volume (g-VS/l) throughout this year of operation. Those in the second-stage reactor (AAFEB-2) were slightly less, between 13 and 20 g-VS/l.

Table 4-3

A SUMMARY OF THE BIOMASS CONCENTRATIONS ON THE DIATOMACEOUS EARTH
SUPPORT MEDIA IN THE TWO AAFEB BED REACTORS

Date	AAFEB-1 Biomass (g-VS/l)	AAFEB-2 Biomass (g-VS/l)
2/7/88	12.10	
3/25/88	19.78	
4/11/88	20.18	
5/17/88	23.34	
6/21/88	22.23	
7/15/88	23.90	13.42
8/5/88		15.34
10/12/88	28.91	13.32
7/2/90	27.40	20.00
12/5/90		19.60
12/18/90	28.20	

Note: The biomass concentrations are expressed in terms of the expanded bed volume (grams of VS per liter of expanded bed).

Another important consideration in the choice of support media focused on their hydraulic characteristics. It was important that the total population of anaerobic microorganisms attached on the media achieve maximum exposure to the influent wastewater. It was also important that the media should act as a self-cleaning filter to entrap particulate matter in the wastewater stream for long-term biodegradation. Thus, the reactors were designed for hydraulic expansion of the media approximately 15 percent above its static volume. At this expansion level, minimal short-circuiting problems were encountered and a high degree of particulate removal was achieved. Hydraulic expansion of the media was accomplished by combining the flow of influent wastewater with a recycle stream that consisted of liquid from above the bed of each reactor. The combination of the two flows was carefully matched to achieve a constant upflow velocity in the bed of approximately two meters per hour in each reactor.

The pumping systems associated with providing wastewater to the expanded bed reactors and including the recycle of liquid within the reactor systems required minimal attention. It was rare to encounter a problem that interrupted unit operations. The influent wastewater flow and recycle liquid flow rates were measured daily and occasionally adjusted slightly to maintain the desired conditions of operation. The flow of influent wastewater was provided by a simple rotary screw positive displacement pump that delivered a constant flow of wastewater twenty-four hours a day. The liquid recycle systems consisted of simple centrifugal pumps that delivered the recycled liquid through a simple ball valve that was used to adjust the recycle flow rate.

It is important to note that the head loss associated with the liquid recycle systems was extremely low, consisting of friction within the plumbing, and associated with movement through the expanded bed media. The total head loss in each system was less than six inches of water column. In fact, the second-stage reactor was gravity charged on a continuous basis with the effluent from the first-stage reactor using an elevation head of less than twelve inches of water column.

The combination of the influent wastewater and recycle liquid flows were the primary means to control expansion of the media within each expanded bed reactor system. However, a paddle mixer system was also incorporated into the design of each reactor. The paddle mixers, which operated at two revolutions per minute for two minutes every four hours, were designed to redistribute the bed and assist in preventing short-circuiting the influent wastewater.

The interpretation of the performance of the AAFEB reactor system during this study year included examining six operating conditions as summarized in Table 4-4. The sewage flow rates examined ranged from 7.5 steres per day (s/d) to 37.5 s/d (10,000 gallons per day). These flow rates produced theoretical hydraulic retention times (HRT) from less than two hours to greater than twelve hours at sewage temperatures from 9°C to 23°C. A detailed daily summary of the operation of each AAFEB reactor is presented in Appendix A.

Table 4-4

A SUMMARY OF CONDITIONS USING THE PILOT SCALE FIRST- AND SECOND-STAGE AAFEB REACTORS

Operation Dates From To	Condition Number	Reactor I.D.	Flow (s/d)	HRT (hr)	Temp. (°C)	Influent Source
1/1/90-1/25/90	1	AAFEB 1&2	19.0	5.4	9	Settled Sewage
1/26/90-3/16/90	2	AAFEB 1&2	7.5	12.5	10	Settled Sewage
3/17/90-8/31/90	3	AAFEB 1	37.5	1.8	17	Settled Sewage
3/16/90-6/1/90	4	AAFEB 1&2	16.7	5.6	15	Settled Sewage
6/2/90-8/2/90	5	AAFEB 1&2	27.0	3.2	20	Settled Sewage
8/3/90-8/31/90	6	AAFEB 1&2	16.1	6.1	23	Settled Sewage

Note: Sewage had large particles removed in a tank with a 3-minute hydraulic retention time.

The theoretical hydraulic retention time, as presented in Equation 3-1, was calculated by dividing the expanded bed reactor volume by the wastewater flow rate to the reactor. This theoretical value assumed that the reactor was a completely mixed vessel and that short circuiting did not exist in the reactor. It was important that the validity of this assumption be verified for both reactors using a lithium chloride tracer study. The studies, summarized in Table 4-5, consisted of adding a predetermined mass of lithium chloride to the influent streams of each reactor. The lithium concentration in the recycle and effluent liquid streams were

monitored for two days. A detailed summary of these two studies is presented in Appendix O.

Table 4-5

A SUMMARY OF THE LITHIUM CHLORIDE TRACER STUDIES TO EXAMINE THE ACTUAL HYDRAULIC RETENTION TIMES IN THE FIRST- AND SECOND-STAGE AAFEB REACTORS

Parameter	AAFEB-1	AAFEB-2
Dates of Operation	1/15/90	1/8/90
Influent Wastewater Temperature (°C)	10	9
Lithium Chloride Mass Addition (g)	914	425
Influent Wastewater Flow Rate (s/d)	19.9	18.9
Recycle Liquid Flow Rate (s/d)	68.1	28.5
Total Reactor Volume (s)	4.3	2.4
Recycled Zone Volume (s)	3.0	1.7
Clarifier Volume (s)	1.3	0.7
Expanded Bed Volume (s)	2.8	1.1
Total Reactor Theoretical HRT (hrs)	5.2	3.0
Total Reactor Actual HRT (hrs)	4.9	2.5
Recycled Zone Actual HRT (hrs)	3.7	2.0
Clarifier Zone Theoretical HRT (hrs)	1.6	0.8
Clarifier Zone Actual HRT (hrs)	1.3	0.5

As illustrated by the upper graphs in Figures 4-5 and 4-6, the slug addition of lithium chloride resulted in a brief mixing period that was followed by a steady decrease in the lithium concentration. Mixing within the reactors was achieved by the recycling of liquid from above the expanded bed to the bottom of the reactor. The time required to achieve complete mixing was the time from the initial addition of the lithium chloride until the onset of a uniform decrease to the lithium concentration. In both the first- and second-stage reactors this mixing period was approximately one hour. The time difference between the peak lithium concentration of the recycle stream and the effluent stream approximated the actual hydraulic retention time within the upper, clarifier, part of the reactors.

FIRST-STAGE AAFEB REACTOR

Figure 4-5.

A cartesian (top graph) and log plot (bottom graph) of the disappearance of lithium chloride from the first-stage AAFEB reactor during the lithium chloride studies to estimate the actual bed HRT.

SECOND-STAGE AAFEB REACTOR

Figure 4-6.

A cartesian (top graph) and log plot (bottom graph) of the disappearance of lithium chloride from the second-stage AAFEB reactor during the lithium chloride studies to estimate the actual bed HRT.

After the brief mixing period, the shape of these curves appeared similar to those of an ideal completely mixed vessel reacting to the slug addition of a tracer. Under ideal circumstances the decrease in the lithium concentration represented an exponential decay which would appear as a straight line when the log of the lithium concentration was plotted versus time. As illustrated in the lower graphs of Figures 4-5 and 4-6, this relationship appeared to be true. The actual hydraulic retention time of the lithium in the recycle and effluent streams was calculated as the centroid of the area beneath these curves. As indicated in Table 4-5, the theoretical and actual hydraulic retention times within the first-stage reactor bed were almost identical. There did appear to be slight short-circuiting in the first-stage reactor clarifier zone. The difference between the actual and theoretical HRT values was less than twenty minutes. The second-stage reactor appeared to have slight short-circuiting in the recycle and clarifier zones; however, the difference between theoretical and actual HRT values was approximately 10 minutes.

Removal of Chemical Oxygen Demand

Twenty-four hour composite liquid samples were collected of the influent to and the effluent from each expanded bed reactor a minimum of once each week throughout most of the operating period. A detailed summary of all COD measurements is presented in Appendix D. and is graphically illustrated in Figure 4-7. The top graph in this figure illustrates the measured total COD concentrations and the lower graph illustrates the reactor effluent soluble COD concentrations. The influent total COD concentration to the first-stage reactor, presented in both

Figure 4-7. An illustration of the first- and second-stage AAFEB reactor influent and effluent total (top graph) and soluble (bottom graph) chemical oxygen demand concentrations measured in the study.

graphs, varied from 200 mg/l to 250 mg/l. In these graphs there was a noticeable COD reduction achieved by the system.

These overview graphs did not consider the effects of temperature and the hydraulic flow rate of wastewater on reactor performance. Average values of the sewage flow rate, expanded bed volume, and the total and soluble COD concentrations were calculated for each of the six operating conditions. These values were used to calculate the theoretical hydraulic retention time (HRT), the total COD loading and removal rates and the removal efficiencies. The hydraulic retention time was expressed in hours, the COD loading and removal rates were expressed in grams per liter of expanded bed volume per day and the removal efficiency was expressed in percent. A summary of the results of these calculations is presented in Table 4-6.

The COD removal efficiency was calculated in terms of the total COD removed at each operating condition. As illustrated in Figure 4-8, the maximum COD removal was approximately 50 percent. This occurred at a hydraulic retention time of approximately six hours when the influent wastewater temperature was greater than 15°C. At wastewater temperatures below 15°C the HRT required to achieve 50 percent total COD removal appeared to be double that of the warmer conditions. To achieve this same removal efficiency the total COD organic loading rate required was approximately 0.4 g/l-d at wastewater temperatures below 15°C and 0.8 g/l-d at the higher temperatures. The total COD removal rates, Figure 4-9, were 0.2 g/l-d and 0.4 g/l-d respectively at the lower and higher temperatures, and the effluent total COD concentrations were approximately 120 mg/l, Figure 4-10.

Table 4-6

A SUMMARY OF THE TOTAL CHEMICAL OXYGEN DEMAND REMOVALS
BY THE PILOT-SCALE AAFEB REACTOR SYSTEM

TOTAL COD										METHANE				
CONDITION NUMBER	TEMP	FLOW	REACTOR VOLUME	HRT	INF	EFF	OLR	RR	RE	CH ₄ -PR MASS	CH ₄ -PR VOLUME	CH ₄ -D MASS	CH ₄ -E MASS	CH ₄ -E VOLUME
	(C)	(s/d)	(s)	(hr)	(mg/l)	(mg/l)	(g/l-d)	(g/l-d)	(%)	(mg/l-d)	(ml/l-d)	(mg/l-d)	(mg/l-d)	(ml/l-d)
1	9.0	19.0	4.3	5.4	210.1	149.1	0.93	0.27	29.0	67.38	94.4	108.09	0.00	0.00
2	10.0	7.5	3.9	12.5	207.1	116.1	0.40	0.18	43.9	43.75	61.3	45.85	0.00	0.00
3	17.0	37.5	2.8	1.8	210.9	166.4	2.82	0.60	21.1	149.00	208.7	271.08	0.00	0.00
4	15.0	16.7	3.9	5.6	206.5	107.0	0.88	0.43	48.2	106.52	149.2	90.58	15.93	22.32
5	19.7	27.0	3.6	3.2	217.9	133.4	1.63	0.63	38.8	158.44	221.9	143.45	14.99	20.99
6	22.8	16.1	4.1	6.1	221.9	132.4	0.87	0.35	40.3	88.03	123.3	70.77	17.25	24.17

Notes: Methane headspace partial pressure = 80 percent.

CH₄-PR is the total methane production rate.

CH₄-D is the portion of methane dissolved in the liquid.

CH₄-E is the methane liberated as a gas from the liquid.

Condition #3 interpreted performance of AAFEB-1 independent of AAFEB-2.

Figure 4-8. An illustration of the AAFEB reactor system total COD removal efficiency as a function of the HRT (top graph), COD organic loading rate (bottom graph), and temperature.

Figure 4-9.

An illustration of the AAFEB reactor system total COD removal rate as a function of the HRT (top graph), COD organic loading rate (bottom graph), and temperature.

Figure 4-10.

An illustration of the AAFEB reactor system effluent total COD concentration as a function of the HRT (top graph), COD organic loading rate (bottom graph), and temperature.

The volume of biogas produced by each expanded bed reactor could not be accurately measured directly during this study. However, using Equation 3-8., the total methane mass production rate ($\text{CH}_4\text{-PR}$) could be estimated. This equation predicted that the mass of methane produced, expressed in milligrams of methane produced per liter of expanded bed reactor volume per day (mg/l-d), was equal to one quarter of the total COD removal rate. By multiplying this value by the Universal Gas Constant (22.4136 liters of gas per mole) and dividing by the molecular weight of methane (16 grams per mole) the volumetric methane production rate was calculated and expressed as milliliters of methane produced per liter of expanded bed reactor volume per day (ml/l-d).

These production rates represented the total methane production rates that included both methane dissolved in the liquid ($\text{CH}_4\text{-D}$) and that which was evolved from the reactor as a gas ($\text{CH}_4\text{-E}$). It was assumed that Henry's Law predicted the amount of methane dissolved in the effluent liquid, thus the equilibrium methane concentration in the liquid was a function of the methane partial pressure in the gas adjacent to the liquid, the liquid temperature, and the Henry's Law constant, as illustrated by Equation 3-10.

These calculations revealed some interesting conclusions concerning the volume of methane that could be collected from each reactor. As illustrated in Figure 4-11, the maximum methane volumetric production rates possible with this dilute domestic wastewater increased as the total COD loading rate was increased. At loadings greater than 1.5 g/l-d , approximately 200 milliliters of methane were produced per liter of reactor volume per day. However, if a biogas collection cover were placed over the top of

the reactors, the concentration of methane in the gas within the cover (the headspace methane concentration) would be from 70 to 90 percent as determined by operation of the bench-scale AAFEB reactors. At these high methane partial pressures most of the methane remained in solution as seen in the top graph of Figure 4-11, and less than 25 milliliters of methane was collected per liter of reactor volume per day. This appeared to be even less when the wastewater temperature was less than 15°C. As soon as the effluent liquid flowed from the reactor, the methane partial pressure decreased to that of the atmosphere, approximately two percent. At this low partial pressure nearly all the methane in solution shifted to the gaseous state and was lost to the atmosphere as seen in the lower graph of Figure 4-11.

Removal of Biochemical Oxygen Demand and Volatile Fatty Acids

The total and soluble biochemical oxygen demand (BOD) concentrations were also measured using a portion of the weekly twenty-four hour composite samples. A detailed summary of all BOD measurements is presented in Appendix C. and is graphically illustrated in Figure 4-12. The top graph in this figure illustrates the measured total BOD concentrations and the lower graph illustrates the reactor effluent soluble BOD concentrations. The influent total BOD concentration to the first-stage reactor, presented in both graphs, was variable between 60 mg/l and 120 mg/l. In these overview graphs there was a noticeable BOD reduction in the effluent concentrations from each reactor.

Average values of the sewage flow rate, expanded bed volume, and the total and soluble BOD concentrations were calculated for each of the six operating conditions examined. These values were used

AAFEB METHANE PRODUCTION HEADSPACE 80% METHANE

HEADSPACE 2% METHANE

□ CH4-PR 20 C + CH4-E 20 C ⊠ CH4-PR 10 C × CH4-E 10 C

Figure 4-11.

An illustration of the total and gaseous methane production rate from the covered (top graph) and uncovered (bottom graph) AAFEB reactor system as a function of the total COD organic loading rate and temperature.

Figure 4-12. An illustration of the first- and second-stage AAFEB reactor influent and effluent total (top graph) and soluble (bottom graph) biochemical oxygen demand concentrations measured in the study.

to calculate the theoretical hydraulic retention time (HRT), the total BOD loading and removal rates and the removal efficiencies. The hydraulic retention time was expressed in hours, the BOD loading and removal rates were expressed in grams of total BOD per liter of expanded bed volume per day and the removal efficiency was expressed in percent. A summary of the results of these calculations is presented in Table 4-7.

The BOD removal efficiency was calculated in terms of the total BOD removed at each operating condition. As illustrated in Figure 4-13, the maximum BOD removal appeared to be approximately 70 percent. This occurred at a hydraulic retention time of approximately six hours when the influent wastewater temperature was greater than 15°C. At wastewater temperatures below 15°C the HRT appeared to be double that of the warmer conditions to achieve the same removal efficiency. To achieve this same removal efficiency the total BOD organic loading rate required was approximately 0.2 g/l-d at wastewater temperatures below 15°C and 0.4 g/l-d at the higher temperatures. Under these conditions the effluent total BOD concentrations were approximately 30 mg/l, Figure 4-14, and the soluble BOD was approximately 15 mg/l.

An intermediate by-product of anaerobic biodegradation is the production of volatile fatty acids (VFA) which represent the end product of a series of enzymatic biological reactions by several groups of anaerobic bacteria. This process is often referred to as hydrolysis or acidification. The final step in the complete reduction of the influent biodegradable material is the conversion of these acids to methane by an entirely different group of microorganisms referred to as methanogens. As illustrated in the overview graph in Figure 4-15, there was a measurable

Table 4-7

A SUMMARY OF THE TOTAL BIOCHEMICAL OXYGEN DEMAND
REMOVALS BY THE PILOT-SCALE AAFEB REACTOR SYSTEM

TOTAL BOD											
CONDITION NUMBER	TEMP. (C)	FLOW (s/d)	REACTOR VOLUME (s)	HRT (hr)	INF (mg/l)	EFF TBOD (mg/l)	EFF SBOD (mg/l)	EFF VFA (mg/l)	OLR (g/l-d)	RR (g/l-d)	RE (%)
1	9.0	19.0	4.3	5.4	97.9	65.3		21.0	0.43	0.14	33.4
2	10.0	7.5	3.9	12.5	100.8	32.5		9.8	0.19	0.13	67.8
3	17.0	37.5	2.8	1.8	83.5	64.6	46.8	37.7	1.12	0.25	22.6
4	15.0	16.7	3.9	5.6	78.8	33.7	13.8	7.4	0.34	0.19	57.2
5	19.7	27.0	3.6	3.2	86.5	36.8	24.4	11.3	0.65	0.37	54.2
6	22.8	16.1	4.1	6.1	89.5	28.4	14.5	4.5	0.35	0.24	68.3

Note: Condition #2 average effluent TBOD conditions taken over the last two weeks of this six week run as being steady operating conditions.
Condition #3 interpreted performance of AAFEB-1 independent of AAFEB-2.

Figure 4-13. An illustration of the AAFEB reactor system total five-day BOD removal efficiency as a function of the HRT (top graph), BOD organic loading rate (bottom graph), and temperature.

■ INFLUENT □ @ 10C × @ 20C

■ INFLUENT □ @ 10C × @ 20C

Figure 4-14. An illustration of the AAFEB reactor system total five-day BOD effluent concentration as a function of the HRT (top graph), BOD organic loading rate (bottom graph), and temperature.

Figure 4-15. An illustration of the first- and second-stage AAFEB reactor influent and effluent VFA concentrations measured in the study.

concentration of VFA in the effluent from both expanded bed reactors. It is interesting that the first-stage reactor, which was operated at much higher loading rates than the second stage, consistently had a higher effluent VFA concentration. This trend is more evident when the average effluent VFA concentration at each operating condition, summarized in Table 4-7, was plotted versus the reactor hydraulic retention time, Figure 4-16. The highest effluent VFA concentration occurred at a hydraulic retention time of less than two hours. This trend is extremely important since it indicates a rapid rate of hydrolysis that converts the total BOD into an easily biodegraded soluble form; a form which the plants and microorganisms of the NFT treatment system would rapidly eliminate.

Removal of Suspended and Volatile Suspended Solids

Beyond biological degradation of the organic material in the wastewater, the AAFEB reactors were also designed for primary and secondary clarification. Two mechanisms were incorporated in the design that could achieve suspended and volatile suspended solids removal. The first was entrapment by the hydraulically expanded support media and the second was a simple baffle system at the top of each reactor.

As illustrated in the overview graphs in Figure 4-17 and detailed in Appendix E, both reactors achieved significant removal of suspended and volatile suspended solids throughout the operating period. As illustrated by Figure 4-18, the wastewater temperature appeared to have a slight effect upon the suspended solids removal efficiency. At hydraulic retention times as low as two hours the SS removal efficiency was nearly 60 percent when the wastewater

Figure 4-16. An illustration of the AAFEB reactor system effluent VFA concentrations as a function of HRT and temperature.

SUSPENDED SOLIDS

—■— INFLUENT —□— AAFEB-1 —x— AAFEB-2

VOLATILE SUSPENDED SOLIDS

—■— INFLUENT —□— AAFEB-1 —x— AAFEB-2

Figure 4-17. An illustration of the first- and second-stage AAFEB reactor influent and effluent suspended (top graph) and volatile suspended (bottom graph) solids concentrations measured in the study.

Figure 4-18.

An illustration of the AAFEB reactor system SS (top graph) and VSS (bottom graph) removal efficiency as a function of HRT and temperature.

temperature was greater than 15°C. At lower temperatures the removal efficiency was greater than 50 percent at HRT values greater than five hours. The average SS and VSS effluent concentrations, summarized in Table 4-8 for each operating condition, were approximately 30 mg/l and 20 mg/l respectively at all six loading conditions examined, Figure 4-19. These effluent concentrations were achieved even when the hydraulic overflow rate, expressed in steres of liquid flow per square meter of reactor cross sectional area per day ($\text{s/m}^2\text{-d}$), was as high as 24 $\text{s/m}^2\text{-d}$ (600 gallons per square foot per day), Figure 4-20.

Since the AAFEB reactor system was designed to replace primary and secondary clarification unit processes, these low effluent suspended and volatile suspended solids concentrations represented a significant achievement. Though not in the contract, it was considered extremely important to further document the potential of the AAFEB reactor system with settling column tests. At six points during this one year study, representing wastewater temperatures from 11°C to 26°C, liquid from either the effluent stream or the recycled liquid stream was carefully removed from the first stage AAFEB reactor and transferred to an insulated settling column (20 cm diameter, 3 meter height). The suspended solids concentration was measured at five points along the height of the column at specific times over a twenty-four hour period. The detailed results of these tests are presented in Appendix H.

The suspended solids concentrations and removal efficiencies achieved at depths of one meter and three meters for each of the six tests are summarized in Table 4-9. In this table the initial effluent SS concentrations were significantly less than those of the recycle liquid. Upon observing the liquid above the expanded

Figure 4-19.

An illustration of the AAFEB reactor system effluent SS (top graph) and VSS (bottom graph) concentrations as a function of HRT and temperature.

SUSPENDED SOLIDS

VOLATILE SUSPENDED SOLIDS

Figure 4-20.

An illustration of the AAFEB reactor system effluent SS (top graph) and VSS (bottom graph) concentrations as a function of the hydraulic overflow rate and temperature.

Table 4-8

A SUMMARY OF THE SUSPENDED AND VOLATILE SUSPENDED SOLIDS REMOVALS
BY THE PILOT-SCALE AAFEB REACTOR SYSTEM

TOTAL SUSPENDED AND VOLATILE SUSPENDED SOLIDS											
CONDITION NUMBER	TEMP (C)	FLOW (s/d)	REACTOR VOLUME (s)	HRT (hr)	OVERFLOW RATE (s/m ² -d)	INF SS (mg/l)	EFF SS (mg/l)	INF VSS (mg/l)	EFF VSS (mg/l)	RE SS (%)	RE VSS (%)
1	9.0	19.0	4.3	5.4	16.0	70.7	34.8	53.5	24.2	50.8	54.8
2	10.0	7.5	3.9	12.5	6.4	51.4	23.7	36.0	15.3	53.9	57.4
3	17.0	37.5	2.8	1.8	23.6	71.4	34.6	57.3	25.4	51.6	55.7
4	15.0	16.7	3.9	5.6	14.3	72.6	28.4	58.3	17.4	60.9	70.2
5	19.7	27.0	3.6	3.2	23.1	68.4	26.9	55.7	21.4	60.7	61.6
6	22.8	16.1	4.1	6.1	13.8	71.9	29.3	54.9	20.7	59.2	62.3

Note: Condition #3 interpreted the performance of the AAFEB-1 independent of the AAFEB-2.

Table 4-9

A SUMMARY OF THE SETTLING TESTS TO EXAMINE THE SETTLEABILITY OF
THE EFFLUENT AND RECYCLE LIQUIDS OF THE AAFEB REACTOR SYSTEM
COLUMN DEPTH 3.03 METERS (10 FEET)

TEST NUMBER	1		1		3		4		5		6	
SAMPLE I.D.	EFFLUENT		EFFLUENT		RECYCLE		RECYCLE		RECYCLE		RECYCLE	
TEMPERATURE	20		11.5		13		15		20		26	
TIME	SS	RE	SS	RE	SS	RE	SS	RE	SS	RE	SS	RE
(hrs)	(mg/l)	(%)	(mg/l)	(%)	(mg/l)	(%)	(mg/l)	(%)	(mg/l)	(%)	(mg/l)	(%)
0.0	32.0	0.0	37.8	0.0	118.8	0.0	174.5	0.0	85.5	0.0	351.6	0.0
0.5	32.0	0.0	39.7	-5.0	115.0	3.2	146.5	16.0	62.9	26.4	138.2	60.7
1.5			43.5	-15.1	80.9	31.9	98.6	43.5	46.1	46.1	84.6	75.9
4.0	25.0	21.9	33.5	11.4	59.8	49.7	72.1	58.7	35.1	58.9	60.3	82.8
6.8	18.0	43.8	33.2	12.2	50.2	57.7	58.1	66.7	29.1	66.0	38.7	89.0
24.0	20.0	37.5	32.9	13.0	25.0	79.0	32.8	81.2	15.3	82.1	23.7	93.3

Column depth 0.90 meters (3 ft)

TEST NUMBER	1		1		3		4		5		6	
SAMPLE I.D.	EFFLUENT		EFFLUENT		RECYCLE		RECYCLE		RECYCLE		RECYCLE	
TEMPERATURE	20		11.5		13		15		20		26	
TIME	SS	RE	SS	RE	SS	RE	SS	RE	SS	RE	SS	RE
(hrs)	(mg/l)	(%)	(mg/l)	(%)	(mg/l)	(%)	(mg/l)	(%)	(mg/l)	(%)	(mg/l)	(%)
0.0	32.0	0.0	37.8	0.0	118.8	0.0	174.5	0.0	85.5	0.0	351.6	0.0
0.5	26.0	18.8	35.3	6.6	102.6	13.6	128.6	26.3	53.8	37.1	112.6	68.0
1.5	24.0	25.0	36.7	2.9	78.5	33.9	95.7	45.2	46.8	45.3	73.2	79.2
4.0	18.0	43.8	33.6	11.1	56.0	52.9	65.1	62.7	29.4	65.6	43.3	87.7
6.8	19.5	39.1	25.9	31.5	44.1	62.9	52.0	70.2	22.5	73.7	45.9	86.9
24.0	18.7	41.6	28.5	24.6	20.5	82.7	33.2	81.0	15.4	82.0	27.0	92.3

bed through the sight windows in the sidewall of the reactors, it was apparent that the biogas production was the major cause of these high concentrations. The tiny biogas bubbles appeared to adhere to the particulate matter in the reactor bed and buoy the particles out of the bed. The particles continued to ascend until they contacted the cone-shaped baffle directly above the bed. At that point the bubble broke away from the particle. The particle settled back into the bed while the bubble continued to rise out of the reactor. The liquid above the bed was always turbid with particles rising and falling. The liquid passed through the nose of the cone or around the outside perimeter and entered the clarification zone. It was from this zone that effluent liquid was removed to examine the long-term settleability in the settling column.

The wastewater temperature appeared to have a slight effect on the suspended solids settleability. As illustrated in Figure 4-21, the suspended solids removal efficiency was highest at the higher wastewater temperatures. When the wastewater temperatures were below 15°C, the suspended solids concentrations after twenty-four hours of settling to a depth of three meters was approximately 30 mg/l and when the temperature was greater than 15°C, the concentrations were less than 25 mg/l, as seen in Figure 4-22. This appeared to be true of both the effluent and recycled liquid streams. At all temperatures the major portion of the removals were achieved in less than five hours.

The AAFEB reactor system was also designed to achieve primary and secondary sludge digestion. Organic and inorganic matter in the wastewater from the gross particulate clarifier were entrapped in the first-stage AAFEB reactor. By observing the height of the bed

SETTLING COLUMN RESULTS

AT 3 m DEPTH

SETTLING COLUMN RESULTS

AT 1 m DEPTH

Figure 4-21. An illustration of the settling column SS removal efficiencies at a three meter depth (top graph) and one meter depth (bottom graph) as a function of time, temperature, and the liquid examined (recycle or effluent).

SETTLING COLUMN RESULTS

AT 3 m DEPTH

SETTLING COLUMN RESULTS

AT 1 m DEPTH

Figure 4-22. An illustration of the settling column effluent SS concentration at a three meter depth (top graph) and one meter depth (bottom graph) as a function of time, temperature, and the liquid examined (recycle or effluent).

through the sight window in the side of the reactor, it was apparent that a sludge layer slowly accumulated on the top of the bed. This sludge layer increased until the expanded bed volume increased from its normal operating level of 2.6 steres to approximately 2.8 steres. The accumulated sludge was then siphoned from the top of the bed and transferred to a sludge storage tank. As summarized in Appendix P, sludge was siphoned from the reactor 52 times during the period from January 1, 1990 through August 21, 1990. As illustrated in Figure 4-23, the volume of sludge wasted was less than 10 liters per thousand liters of wastewater treated most of the time.

It is important to note that the Ithaca Wastewater Treatment Facility provides services for the treatment of both landfill leachate and septage. These additions are made directly to the headworks of the facility and therefore became a portion of the wastewater flow to the pilot facility. This fact made for a highly variable volume of sludge accumulation within the first-stage reactor. The average sludge accumulation, summarized in Table 4-10, was approximately six liters per 1000 liters of wastewater treated. The dry mass of sludge produced was approximately 50 grams per 1000 liters of wastewater treated. The average total solids concentration of the sludge was approximately eight grams per liter which meant that a large volume of treated liquid was siphoned with the accumulated sludge.

As summarized in Table 4-11, a settling test was conducted using the sludge siphoned from the first-stage AAFEB reactor. The initial total solids concentration (TS) of the sludge was 0.57 percent (5.68 g/l). When this siphoned sludge was allowed to settle, as illustrated in Figure 4-24, for 1.5 hours, the solids

AAFEB-1 SLUDGE ACCUMLATION

Figure 4-23.

An illustration of the volume of sludge wasted from the first-stage AAFEB reactor during the study period.

Table 4-10

A SUMMARY OF THE SLUDGE ACCUMULATION REMOVED FROM THE FIRST-STAGE
AAFEB-1 REACTOR

Parameter	Units *	Average Value	Maximum Value	Minimum Value
Sludge Volume	l/s	6.4	18.9	1.0
TS Concentration	% of wet	0.8	2.5	0.3
VS Concentration	% of TS	46.1	59.4	21.0
Dry Sludge Mass	g/s	50.6	468.7	2.6
Volatile Sludge Mass	g/s	23.3	278.4	0.5

*l/s is liters of sludge per 1000 liters of wastewater treated
g/s is grams of sludge per 1000 liters of wastewater treated

Table 4-11

A SUMMARY OF THE SETTLEABILITY OF THE SLUDGE SIPHONED FROM THE
FIRST-STAGE AAFEB REACTOR

Time (min)	Sludge Level (ml)	Sludge TS (%)	Sludge TS (g)	Supernatant TS (g/l)
0	2000	0.57	11.36	5.68
10	330			
16	280			
23	220			
37	216			
53	195			
65	185			
88	180			
96	175	6.02	10.53	0.45

SLUDGE SETTLING

Figure 4-24. An illustration of the first-stage AAFEB reactor wasted sludge settling characteristics (as sludge interface level in a two liter graduated cylinder) as a function of time.

concentration of the settled material was greater than six percent and the supernatant solids concentration was 0.45 g/l. In fact, the majority of the settling occurred within 15 minutes. Thus, by using a sludge-thickening vessel, the volume of sludge that needed to be handled could be reduced by a factor of six, and the actual sludge production would be approximately one liter of sludge per cubic meter of wastewater treated (1000 gallons per million gallons treated). The volatile portion of the sludge was approximately 46 percent of the dry mass.

It is also important to note that sludge was never wasted from the second-stage reactor. The total volume of accumulated sludge was removed from the first-stage AAFEB reactor.

Fate of Sulfur

An important competing reaction within the AAFEB reactors was the biological reduction of sulfate (SO_4^{--}) to sulfide (primarily H_2S and HS^-). In this reaction two grams of ultimate BOD were consumed in the reduction of one gram of sulfate-sulfur to sulfide-sulfur. However, the oxygen demand was not removed from solution; it merely changed from organic material to sulfide. Although sulfides could be lost to the gas phase, the high solubility ($K_H = 1.15$ mole/l-atm at 20°C) and acid/base equilibrium ($\text{pK}_a = 7$ at 28°C) kept the large majority of sulfides in solution so each gram of sulfide-sulfur in the liquid effluent from the reactors exerted an oxygen demand of two grams.

As detailed in Appendix Q, the Ithaca domestic wastewater usually contained a sulfate-sulfur concentration of approximately 13 mg/l and a sulfide sulfur concentration of approximately four mg/l, Figure 4-25. Consistently, the sulfate reduction in the first-

Figure 4-25. An illustration of the first- and second-stage AAFEB reactor influent and effluent sulfate (top graph) and sulfide (bottom graph) concentrations measured in the study.

stage AAFEB reactor resulted in effluent sulfate-sulfur concentrations of less than four mg/l and sulfide-sulfur concentrations of approximately 15 mg/l. Complete reduction of all the sulfate present in the wastewater was not observed. The second-stage AAFEB reactor did not appear to support additional sulfate reduction, though the influent sulfate-sulfur concentrations were three to four mg/l.

Components of Effluent Total COD

The total COD concentration of the effluent liquid from the AAFEB reactors, though similar in magnitude to that of aerobic systems, was slightly different. To compare this difference and illustrate the impact of each of the components, a comprehensive analytical procedure was developed, as illustrated in Figure 4-26. The procedure consisted of a three-step process in which the components of the total oxygen demand Figure 4-26 were determined before and after each step. Using a subsample from the second-stage AAFEB reactor, the first step consisted of filtration of the subsample that isolated the impact of the volatile suspended solids concentration. In the second step a portion of the filtered subsample was aerated with nitrogen gas for one hour that isolated the impact of dissolved methane and volatile fatty acid concentrations. The third step consisted of chemical precipitation using ferric chloride that isolated the impact of the dissolved hydrogen sulfide concentrations. As summarized in Table 4-12, subsamples were withdrawn from the initial sample (Total), the filtered sample, (Soluble), the nitrogen purged sample (Purged), and the supernatant from the chemically treated sample (Precipitated) for determination of the

- total BOD (TBOD);
- total COD (TCOD);

Figure 4-26. An illustration of the three-step analytical procedure to interpret the components of the AAFEB reactor effluent total oxygen demand.

Table 4-12

A SUMMARY OF THE SOURCES OF OXYGEN DEMAND IN THE EFFLUENT FROM THE
AAFEF REACTORS

SAMPLE DESCRIPTION	EFFLUENT MEASURED CONCENTRATIONS						
	Table A						
	TBOD	TCOD	SULFIDE	VFA	CH4	VSS	
	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	
TOTAL	31.47	135.46	12.23	20.00	0.57	28.00	
SOLUBLE	23.17	78.42	8.13	17.00	0.29	0.00	
PURGED	22.07	69.41	4.38	14.00	0.00	0.00	
PRECIPITATED	21.37	62.51	2.55	15.00	0.23	0.00	
OXYGEN DEMANDS CONSTANTS							
Table B							
SULFIDE =	1.88	g-O2/g-S H2S + 2O2 --> H2SO4					
VOLATILE ACID =	1.07	g-O2/g-VF CH3COOH + 2O2 --> 2CO2 + 2H2O					
METHANE =	4.00	g-O2/g-CH CH4 + 2O2 --> CO2 + 2H2O					
VOLAITLE SOLIDS =	1.42	g-O2/g-VS C5H7O2N + 5O2 --> 5CO2 + 2H2O • NH3					
EFFLUENT OXYGEN DEMAND							
Table C							
SAMPLE DESCRIPTION	TBOD (mg/l)	TCOD (mg/l)	SULFIDE (mg/l)	VFA (mg/l)	CH4 (mg/l)	VSS (mg/l)	REMAINING ORGANICS (mg/l)
TOTAL	31.47	135.46	23.02	21.33	2.28	39.65	+ 49.18
SOLUBLE	23.17	78.42	15.30	18.13	1.16	0.00	+ 43.82
PURGED	22.07	69.41	8.24	14.93	0.00	0.00	+ 46.23
PRECIPITATED	21.37	62.51	4.80	16.00	0.92	0.00	+ 40.79
OXYGEN DEMAND BALANCE							
Table D							
PARAMETER	TCOD (mg/l)	SULFIDE (mg/l)	VFA (mg/l)	CH4 (mg/l)	VSS (mg/l)	SUMMMATION (mg/l)	TBOD (mg/l)
TOTAL - SOLUBLE	57.04	7.72	3.20	1.12	39.65	51.68	8.30
SOLUBLE - PURGED	9.01	7.06	3.20	1.16	0.00	11.42	1.10
SOLUBLE - PRECIPITATED	15.91	10.50	2.13	0.24	0.00	12.88	1.80

- sulfide (H_2S and HS^-);
- volatile fatty acid (VFA);
- methane (CH_4); and
- volatile suspended (VSS) solids concentrations.

The total BOD and COD represented measured oxygen demands. The actual oxygen demand exerted by H_2S (1.88 g- O_2 /g-S), VFA (1.07 g- O_2 /g-VFA), CH_4 (4.00 g- O_2 /g- CH_4), and VSS (1.42 g- O_2 /g-VSS) was calculated by multiplying the respective concentrations by the stoichiometric oxidation constants of each parameter. Thus, the total oxygen demand, which was measured as the total COD, of the effluent from the AAFEB reactors was equal to the oxygen demands of sulfide, VFA, methane, VSS, and the biodegradable and refractory oxygen demand dissolved in the liquid (Remaining Organics). Table 4-12 summarizes these calculations for a single sample taken from the second-stage AAFEB reactor. The top Table (A) summarizes the measured concentrations of each of the parameters. Table (B) summarizes the oxidation constants that were used to calculate the oxygen demand of each of the parameters, Table (C). It is important to realize that these values were measured for a single effluent sample and do not represent the performance of the reactor under all loading conditions examined. These values illustrate the general distribution of the total oxygen demand of the AAFEB reactor effluents.

The primary difference between the effluents from the AAFEB reactors and conventional aerobic processes was the presence of sulfides, VFA, and methane. These three sources of oxygen demand would not normally exist in an aerobic effluent, though the VFA

oxygen demand does represent a biodegradable oxygen demand that may be present in a different form in an aerobic effluent.

As illustrated in Figure 4-27, the measured total oxygen demand (as TCOD) was 135.46; however, more than 25 mg/l was in the form of sulfides and methane. The oxygen demand of the VSS was nearly 40 mg/l and represented a significant portion of the total oxygen demand. Purging the filtered sample with nitrogen eliminated the methane oxygen demand; however, this proved to be an insignificant portion of the total oxygen demand under the mode of operation practiced. The nitrogen purge, as expected, also reduced the sulfide oxygen demand. The sulfide concentration appears to have a much greater impact on the total oxygen demand than that of methane. Precipitation of the sulfides with ferric chloride was more effective than nitrogen aeration in reducing the oxygen demand of the sulfides.

The refractory organics were unaffected by filtration, nitrogen aeration, or chemical precipitation. These non-biodegradable soluble organics represented the total oxygen demand of the AAFEB reactors when the oxygen demands of sulfides, VFA, methane, and VSS were removed. This was especially important in designing the NFT reactor system which was naturally capable of rapid removal of nearly 100 percent of the non-refractory oxygen demands.

The measurement of COD appeared to be an accurate measure of the true oxygen demand of the effluent liquid. As indicated in the bottom table of Table 4-12 (D), the summation of the oxygen demands removed by filtration (Total minus Soluble), nitrogen aeration (Filtered minus Purged), and chemical treatment (Filtered

Figure 4-27. An illustration of the oxygen demand components of the effluent from the AAFEB reactor system.

minus Precipitated) of sulfides, VFA, methane, and VSS were equal to the change in the COD concentration.

Removal of Nitrogen and Phosphorus

The AAFEB reactors were not expected to have a large impact on the removal of nitrogen and phosphorous from the wastewater stream as indicated by the magnitude of the influent and effluent total concentrations in Table 4-13 and Table 4-14. These values represent the average nitrogen and phosphorous concentrations measured at each of the six loading conditions examined. A detailed summary of the nitrogen measurements is presented in Appendix F. and those for phosphorous in Appendix G. It was interesting that a portion of the total nitrogen and phosphorous concentrations were converted from the organic forms into the soluble forms. In both cases approximately one third of the organic nitrogen and phosphorous were converted into their respective soluble products; total ammonia nitrogen (TAN) and orthophosphorus (OP), Figure 4-28 and Figure 4-29.

Bench Scale AAFEB Reactor

Development of the pilot anaerobic-attached films on the Celite 560 diatomaceous earth filter aid particles began in January, 1988. The feed substrate to the reactors was the dilute, partially settled Ithaca, New York sewage. It was important to compare the performance of this attached film to a mature film developed using a sucrose feed substrate.

In the spring of 1990 a parallel bench-scale study was conducted using one liter of bed from the second-stage AAFEB reactor and a mature film that had been in operation with sucrose as the feed

Table 4-13

A SUMMARY OF THE AAFEB REACTOR SYSTEM INFLUENT AND EFFLUENT
NITROGEN CONCENTRATIONS

NITROGEN								
CONDITION NUMBER	TEMP. (C)	FLOW (s/d)	REACTOR VOLUME (s)	HRT (hr)	INF TKN (mg/l)	EFF TKN (mg/l)	INF TAN (mg/l)	EFF TAN (mg/l)
1	9.0	19.0	4.3	5.4	27.1	26.2	16.1	19.7
2	10.0	7.5	3.9	12.5	23.9	23.0	13.2	17.8
3	17.0	37.5	2.8	1.8	20.9	21.2	12.3	15.3
4	15.0	16.7	3.9	5.6	21.1	22.4	12.3	16.8
5	19.7	27.0	3.6	3.2	20.5	21.0	12.1	16.5
6	22.8	16.1	4.1	6.1	21.3	23.9	14.1	20.0

Note: Condition #3 interpreted the performance of the AAFEB-1 independent of the AAFEB-2.

Table 4-14

A SUMMARY OF THE AAFEB REACTOR SYSTEM INFLUENT AND EFFLUENT
PHOSPHOROUS CONCENTRATIONS

PHOSPHOROUS								
CONDITION NUMBER	TEMP. (C)	FLOW (s/d)	REACTOR VOLUME (s)	HRT (hr)	INF TP (mg/l)	EFF TP (mg/l)	INF OP (mg/l)	EFF OP (mg/l)
1	9.0	19.0	4.3	5.4	3.8	3.5	1.5	2.0
2	10.0	7.5	3.9	12.5	3.6	3.4	1.5	2.8
3	17.0	37.5	2.8	1.8	3.3	3.8	1.2	2.2
4	15.0	16.7	3.9	5.6	3.0	3.0	1.3	2.1
5	19.7	27.0	3.6	3.2	3.5	4.7	1.0	2.9
6	22.8	16.1	4.1	6.1	4.5	4.7	1.7	1.7

Note: Condition #3 interpreted the performance of the AAFEB-1 independent of the AAFEB-2.

NITROGEN

Figure 4-28.

An illustration of the AAFEB reactor system effluent TKN (top graph) and TAN (bottom graph) concentrations as a function of HRT and temperature.

PHOSPHATE

Figure 4-29. An illustration of the AAFEB reactor system effluent TP (top graph) and OP (bottom graph) concentrations as a function of HRT and temperature.

substrate for more than six months. The pilot media volatile solids concentration was 15 g-VS/l and that of the mature film was 20 g-VS/l. Acetic acid was used as the feed substrate to both bench-scale reactors. The performance of the reactors was compared at 10°C and 20°C at acetic acid concentrations of 80 mg/l and 800 mg/l over hydraulic retention times ranging from 0.9 hours to 9.5 hours.

The results of the bench scale parallel study, detailed in Appendix M, revealed that acclimation of the anaerobic-attached film to the influent substrate concentration and temperature was extremely important. As illustrated in Figure 4-30, when the influent substrate concentration was low (80 mg-BOD/l), the pilot bed was more efficient than the mature bed. The pilot film, which was acclimated to the dilute Ithaca sewage, was also less affected by temperature than the mature film. When the influent substrate concentration was increased to 800 mg-BOD/l, the conditions favored the mature bed that had been acclimated to an influent substrate concentration of 1000 mg-BOD/l as seen in Figure 4-31.

NFT REACTOR SYSTEM

The effluent from the second-stage AAFEB reactor was directed by gravity to the NFT reactor system. This system, which consisted of two deep-channel reactors and two shallow-channel reactors operated in series, was designed to interpret the potential of the system to achieve polishing removal of organic material including fecal coliform concentrations, while removing nutrients including nitrogen and phosphorous, and producing plant biomass, a valuable resource. The system was designed to replace all conventional unit processes associated with tertiary treatment of wastewater.

Figure 4-30. An illustration of the bench-scale reactor BOD removal efficiency at low influent substrate concentrations as a function of temperature, the BOD organic loading rate (top graph), and the hydraulic retention time (bottom graph).

BENCH SCALE AAFEB REACTORS
800 mg/l ACETIC ACID

BENCH SCALE AAFEB REACTORS
800 mg/l ACETIC ACID

MATURE @ 10

 ANA-2 @ 10C

 MATURE @ 20

 ANA-2 @ 20C

Figure 4-31. An illustration of the bench-scale reactor BOD removal efficiency at high influent substrate concentrations as a function of temperature, the BOD organic loading rate (top graph), and the hydraulic retention time (bottom graph).

A comprehensive analytical program was designed to quantify the removal of organic and inorganic matter including nutrients as nitrogen and phosphorous in terms of the required reactor area and hydraulic flows. A total of fourteen conditions, summarized in Table 4-15, were examined to quantify these parameters. The studies also included interpretation of batch nutrient uptake rates, rates of biomass production, and pest management.

Table 4-15

A SUMMARY OF CONDITIONS TO INTERPRET PERFORMANCE OF THE NFT REACTOR SYSTEM

Dates		Condition Number	Reactor I.D.*	Temp. (°C)	Flow (s/d)	Hydraulic
From	To					Loading (cm/d)
1/1/90-4/29/90		N-1	DS	10.0	3.8	10.2
1/1/90-4/29/90		N-2	D	10.0	3.8	5.1
1/1/90-4/29/90		N-3	D&SN	10.0	3.8	3.7
4/30/90-6/1/90		N-4	DS	11.0	6.4	17.2
4/30/90-6/1/90		N-5	D	11.0	6.4	8.6
4/30/90-6/1/90		N-6	D&SN	11.0	6.4	6.3
6/1/90-6/21/90		N-7	DS	11.0	6.4	17.2
6/1/90-6/21/90		N-8	D	11.0	6.4	8.6
6/1/90-6/21/90		N-9	D&S	13.0	15.0	11.5
6/22/90-8/3/90		N-10	DS	18.0	15.0	40.3
6/22/90-8/3/90		N-11	D	18.0	15.0	20.2
6/22/90-8/3/90		N-12	D&SN	18.0	15.0	14.7
8/3/90-8/31/90		N-13	D	22.0	7.6	10.2
8/3/90-8/31/90		N-14	D&SN	22.0	7.6	7.4

DS - southernmost deep channel NFT reactor.

D - deep channel NFT reactors.

SS - southernmost shallow channel NFT reactor.

SN - northernmost shallow channel NFT reactor.

S - shallow channel NFT reactors.

Hydraulic Characterization

Wastewater from the second-stage AAFEB reactor flowed by gravity to the southernmost deep-channel NFT reactor (NFT-DS) and

continued through the northernmost deep-channel reactor (NFT-DN). As illustrated in Figure 4-32, the liquid effluent from NFT-DN flowed into a wet well containing a submersible pump that transferred this liquid to the northernmost shallow-channel NFT reactor NFT-SN. The wastewater then flowed by gravity through both the northern and southern (NFT-SS) shallow-channel reactors.

Earlier research had proven that the plants in the pilot system required some means of support as they were growing, to avoid "lodging" themselves, or falling against each other preventing light from penetrating to smaller plants, that decreased yield and increased pest problems. The support mechanism in the deep channel reactors consisted of adding stone (2.5 centimeter diameter; 10 centimeter depth in the southern unit and five centimeter depth in the northern unit) on top of the root mass. This stone, which had a bulk density of 1.6 kilograms per liter, a bulk volume of 0.6 liters per liter, and a porosity of 0.4 liters per liter, provided stability to the growing root biomass which was then capable of maintaining a vertical aspect to the stalks. This support successfully prevented "lodging" of the stalk biomass as the height of the plants increased. It also anchored the root mass to the bottom of the reactors preventing root mass floatation.

Stone was not used in the shallow channel reactors to support the root biomass. The support mechanism in these reactors consisted of netting (12.5 cm by 12.5 cm openings) positioned horizontally 75 centimeters above the bottom of the reactors. The stalks grew through the netting and were supported vertically.

NFT SYSTEM CROSS SECTION

Figure 4-32. An illustration of the hydraulic profile through the pilot-scale NFT reactor system.

The wastewater from the AAFEB reactor system trickled through the root mass of the pilot NFT system as a plug. The depth of liquid in each reactor, presented in Appendix B, was slightly dependent on the wastewater flow rate; however, the maximum depth; 22 centimeters, was measured at the influent end of NFT-DS. The depth decreased to five cm at the effluent end of this reactor. A similar profile was apparent in NFT-DN which decreased from approximately eight cm at the influent end to four cm at the effluent end. The depth profile in the shallow channels ranged from a maximum of 20 cm at the influent end of NFT-SN to one cm at the effluent end of NFT-SS. These depths were used to calculate the theoretical hydraulic retention time at each flow rate examined.

It was anticipated that the actual hydraulic retention time in each NFT reactor would be significantly different than the theoretical value. To estimate the actual HRT, lithium chloride was introduced into the wastewater flow to the pilot NFT system September 10, 1990. As presented in Appendix O and illustrated in Figure 4-33, the effluent lithium concentration was measured from each reactor over the following 65 hours. When the natural log of the lithium concentration was plotted versus time, the resulting curves appeared as straight lines as seen in Figures 4-34 and 4-35. The area beneath these curves was mathematically determined and the actual HRT was assumed to be the centroid of this area. As summarized in Table 4-16, the actual HRT values were significantly less than the theoretical values ranging from 4.4 hours in NFT-DS to 8.6 hours in NFT-DN with a total HRT through the NFT system of 24.8 hours. Though these actual HRT values were specific to the wastewater flowrate used during the tracer study, the study also provided information about the actual volume of

LITHIUM TRACER STUDY

Figure 4-33.

A cartesian (top graph) and log plot (bottom graph) of the disappearance of lithium chloride from the NFT reactor system during the lithium chloride studies to estimate the actual NFT system HRT.

NFT-DS

NFT-DN

Figure 4-34. An illustration of effluent NFT-DS (top graph) and NFT-DN (bottom graph) centroid of the lithium chloride response curve which estimates the actual liquid retention in the system.

NFT-SN

NFT-SS

Figure 4-35.

An illustration of effluent NFT-SN (top graph) and NFT-SS (bottom graph) centroid of the lithium chloride response curve which estimates the actual liquid retention in the system.

liquid in each reactor as well as the volume of root mass present. With these values it was possible to estimate the actual HRT at any flow rate from a measure of the liquid depth in each reactor,

Table 4-16

A SUMMARY OF THE RESULTS OF THE LITHIUM CHLORIDE TRACER STUDY TO ESTIMATE THE ACTUAL HYDRAULIC RETENTION TIME IN NFT REACTORS

Parameter	Units	NFT-DS	NFT-DN	NFT-SN	NFT-SS
Lithium Chloride Mass	(g)	804.4	0.0	0.0	0.0
Temperature	(°C)	15	13	12	10
Dimensions					
Length	(m)	30.5	30.5	30.5	30.5
Width	(m)	1.2	1.2	0.9	0.9
Height	(m)	1.2	1.2	0.4	0.4
Depth					
Influent End	(cm)	21.5	14.5	20.0	8.25
Effluent End	(cm)	13.5	5	8.5	1
Surface Area	(m ²)	37.2	37.2	27.9	27.9
Wastewater Flow Rate	(s/d)	7.63	7.32	7.00	6.87
Theoretical HRT	(hrs)	20.4	11.9	13.6	4.5
Actual HRT	(hrs)	6.9	3.56	6.8	4.16
Total Volume	(s)	6.5	3.6	4.0	1.3
Actual Liquid Volume	(s)	2.2	1.1	2.0	1.2
Support Media Volume	(s)	2.3	1.7	0.0	0.0
Root Mass Volume	(s)	2.0	0.8	2.0	0.1
	(l/m ²)	53.9	21.5	70.9	3.5
Theoretical Horizontal Velocity	(m/hr)	1.5	2.6	2.2	6.8
Actual Horizontal Velocity	(m/hr)	4.4	8.6	4.5	7.3

The total volume in each reactor was determined as the product of the liquid depth and the reactor surface area. The actual liquid volume was calculated as the product of the actual HRT and the wastewater flow rate. The volume of support media was measured before it was placed within the reactor system. Thus, the root mass volume was calculated as the difference between the total volume and the sum of the liquid and support media volumes. To

estimate the actual HRT at a different wastewater flow rate, the total volume was calculated by measuring the total liquid depth in the reactor. From this value the root mass and support media volumes were subtracted to give the actual liquid volume which when divided by the wastewater flow rate gave an estimate of the actual HRT.

By visual inspection, it was possible to deduce that the root mass volumes in each of the reactors was quite different. This visual observation was confirmed by the tracer study. The reactor with the highest root mass volume per unit area (70.9 liters per square meter) was NFT-SN. Due mainly to availability and manpower requirements, the initial root mass additions to this reactor in 1987 were far greater than any of the other reactors. As a result the entire surface area of this reactor was covered with root mass. It is important to note that the NFT-SN was the only NFT reactor that developed a complete root mass covering over the entire surface area of the reactor. The other three reactors have continued to develop by growing into empty areas.

Organic Removals

In the design of this pilot-scale domestic wastewater treatment facility the NFT system was responsible for polishing removal of organic material. To interpret the potential of the NFT system to accomplish this goal, 24-hour composite samples of the effluent from each NFT reactor were gathered once per week. The influent and effluent total and soluble COD (Appendix D), total BOD (Appendix C), and suspended and volatile suspended solids (Appendix E) concentrations of these samples were then determined and the average calculated at each loading condition examined.

The wastewater flow rates examined ranged from 3.8 s/d to 15 s/d at wastewater temperatures from 10°C to 22°C. By considering each NFT reactor as a part of the series treatment system it was possible to examine hydraulic loading rates from 3.7 centimeters per day (cm/d) to 40.3 cm/d (16 inches per acre).

The NFT system was extremely successful in achieving removal of organic material from the wastewater. As illustrated in Figure 4-36 and summarized in Table 4-17, the effluent total five-day BOD was less than 18 mg/l under all conditions examined and less than 10 mg/l when the hydraulic loading rate was less than 20 cm/d (equivalent to 4.7 acres per million gallons treated). At a hydraulic loading rate of 20 cm/d the effluent total and soluble COD concentrations were less than 50 mg/l, Table 4-18 and Figure 4-37. At double this loading rate (to 40 cm/d) the effluent total COD concentration was approximately 60 mg/l and the soluble COD remained less than 50 mg/l. The removal of suspended and volatile suspended solids by the NFT system appeared to be quite exceptional, Table 4-19 and Figure 4-38. At all conditions examined the SS concentration was less than 10 mg/l and the VSS less than five mg/l.

Wastewater temperature did apparently influence the rate and removal of organic material. As illustrated in Figure 4-39, the maximum total five day BOD removal rate of 120 kilograms per hectare per day (kg/ha-d) observed in the study occurred when the wastewater was approximately 20°C. This represented a removal efficiency of greater than 70 percent of the influent BOD. When the waste water temperature was approximately 10°C the removal rate was 60 kg/ha-d; a removal efficiency of 50 percent. At hydraulic loading rates less than 20 cm/d the influence of

Figure 4-36. An illustration of the total NFT reactor system total five-day BOD effluent concentration as a function of the hydraulic loading rate and temperature.

Table 4-17

A SUMMARY OF THE BOD REMOVALS ACHIEVED IN THE NFT REACTORS

BIOCHEMICAL OXYGEN DEMAND													
CONDITION NUMBER	TEMP (C)	FLOW (s/d)	REACTOR S.A. (sq. m.)	REACTOR DEPTH (cm)	REACTOR VOLUME (s)	FLOW (cm/d)	SURFACE LOADING (m ² /s-d)	HRT (hr)	INF TBOD (mg/l)	EFF TBOD (mg/l)	LR (kg/ha-d)	RR (kg/ha-d)	RE (%)
1	10	3.8	37.2	13	474.3	10.2	9.8	30.0	38.3	14.8	39.1	24.0	61.3
2	10	3.8	74.4	9	669.6	5.1	19.6	42.3	38.3	8.9	19.6	15.0	76.8
3	10	3.8	102.3	7	731.4	3.7	26.9	46.2	38.3	6.6	14.2	11.8	82.8
4	11	6.4	37.2	11	412.9	17.2	5.8	15.5	24.6	10.1	42.3	24.9	58.9
5	11	6.4	74.4	8	569.2	8.6	11.6	21.3	24.6	6.4	21.2	15.7	74.1
6	11	6.4	102.3	6	629.1	6.3	16.0	23.6	24.6	5.3	15.4	12.1	78.6
7	13	15.0	37.2	15	565.4	40.3	2.5	9.0	34.0	17.8	137.3	65.4	47.7
8	13	15.0	74.4	12	874.2	20.2	5.0	14.0	34.0	11.8	68.6	44.9	65.5
9	13	15.0	130.1	10	1236.0	11.5	8.7	19.8	34.0	10.8	39.2	26.7	68.2
10	18	15.0	37.2	18	653.2	40.3	2.5	10.5	36.5	15.9	147.2	83.1	56.4
11	18	15.0	74.4	13	964.2	20.2	5.0	15.4	36.5	10.6	73.6	52.2	71.0
12	18	15.0	102.3	11	1146.8	14.7	6.8	18.3	36.5	10.0	53.5	38.9	72.6
13	22	7.6	74.4	13	974.6	10.2	9.8	30.8	28.4	7.1	29.0	21.8	75.0
14	22	7.6	102.3	12	1242.9	7.4	13.5	39.3	28.4	3.9	21.1	18.2	86.3

Table 4-18

A SUMMARY OF THE COD REMOVALS IN THE NFT REACTORS

CHEMICAL OXYGEN DEMAND															
CONDITION NUMBER	TEMP (C)	FLOW (s/d)	REACTOR S.A. (sq. m.)	REACTOR DEPTH (cm)	REACTOR VOLUME (s)	FLOW (cm/d)	SURFACE LOADING (m ² /s-d)	HRT (hr)	TCOD INF (mg/l)	SCOD INF (mg/l)	TCOD EFF (mg/l)	SCOD EFF (mg/l)	LR (kg/ha-d)	RR (kg/ha-d)	RE (%)
1	10	3.8	37.2	13	474.3	10.2	9.8	30.0	118.9	73.0	52.4	41.8	121.5	67.9	55.9
2	10	3.8	74.4	9	669.6	5.1	19.6	42.3	118.9	73.0	42.2	37.6	60.7	39.2	64.5
3	10	3.8	102.3	7	731.4	3.7	26.9	46.2	118.9	73.0	26.3	23.3	44.2	34.4	77.9
4	11	6.4	37.2	11	412.9	17.2	5.8	15.5	89.5	50.5	51.9	44.2	154.0	64.7	42.0
5	11	6.4	74.4	8	569.2	8.6	11.6	21.3	89.5	50.5	29.3	23.8	77.0	51.8	67.3
6	11	6.4	102.3	6	629.1	6.3	16.0	23.6	89.5	50.5	28.1	23.3	56.0	38.4	68.6
7	13	15.0	37.2	15	565.4	40.3	2.5	9.0	117.7	64.4	72.8	54.3	474.6	180.9	38.1
8	13	15.0	74.4	12	874.2	20.2	5.0	14.0	117.7	64.4	40.2	33.9	237.3	156.3	65.8
9	13	15.0	130.1	10	1236.0	11.5	8.7	19.8	117.7	64.4	36.5	22.4	135.7	93.6	69.0
10	18	15.0	37.2	18	653.2	40.3	2.5	10.5	145.3	100.0	51.1	44.2	585.8	379.8	64.8
11	18	15.0	74.4	13	964.2	20.2	5.0	15.4	145.3	100.0	39.5	38.8	292.9	213.2	72.8
12	18	15.0	102.3	11	1146.8	14.7	6.8	18.3	145.3	100.0	25.3	21.6	213.0	175.9	82.6
13	22	7.6	74.4	13	974.6	10.2	9.8	30.8	132.4	70.0	74.6	69.6	135.3	59.1	43.7
14	22	7.6	102.3	12	1242.9	7.4	13.5	39.3	132.4	70.0	41.2	36.5	98.4	67.8	68.9

Figure 4-37.

An illustration of the NFT reactor system total (top graph) and soluble (bottom graph) effluent COD concentration as a function of the hydraulic loading rate and temperature.

Table 4-19

A SUMMARY OF THE SS AND VSS REMOVALS IN THE NFT REACTORS

SUSPENDED AND VOLATILE SUSPENDED SOLIDS															
CONDITION NUMBER	TEMP	FLOW	REACTOR S.A.	REACTOR DEPTH	REACTOR VOLUME	FLOW	SURFACE LOADING	HRT	INF SS	INF VSS	EFF SS	EFF VSS	LR	RR	RE
	(C)	(s/d)	(m ²)	(cm)	(s)	(cm/d)	m ² /s-d	(hr)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(kg/ha-d)	(kg/ha-d)	(%)
1	10	3.8	37.2	13	474.3	10.2	9.8	30.0	28.1	17.8	9.0	5.5	28.7	19.5	68.1
2	10	3.8	74.4	9	669.6	5.1	19.6	42.3	28.1	17.8	5.4	2.8	14.3	11.6	80.7
3	10	3.8	102.3	7	731.4	3.7	26.9	46.2	28.1	17.8	4.4	3.2	10.4	8.8	84.3
4	11	6.4	37.2	11	412.9	17.2	5.8	15.5	29.0	16.0	9.8	7.8	49.9	33.0	66.2
5	11	6.4	74.4	8	569.2	8.6	11.6	21.3	29.0	16.0	5.5	2.7	25.0	20.2	80.9
6	11	6.4	102.3	6	629.1	6.3	16.0	23.6	29.0	16.0	5.2	3.5	18.2	14.9	82.0
7	13	15.0	37.2	15	565.4	40.3	2.5	9.0	30.9	21.2	6.9	5.1	124.6	96.6	77.5
8	13	15.0	74.4	12	874.2	20.2	5.0	14.0	30.9	21.2	8.0	4.8	62.3	46.2	74.1
9	13	15.0	130.1	10	1236.0	11.5	8.7	19.8	30.9	21.2	9.0	4.1	35.6	25.2	70.9
10	18	15.0	37.2	18	653.2	40.3	2.5	10.5	23.9	21.5	3.2	2.0	96.4	83.6	86.8
11	18	15.0	74.4	13	964.2	20.2	5.0	15.4	43.7	21.5	2.4	1.9	88.1	83.4	94.6
12	18	15.0	102.3	11	1146.8	14.7	6.8	18.3	43.7	21.5	5.5	2.9	64.1	56.0	87.4
13	22	7.6	74.4	13	974.6	10.2	9.8	30.8	29.3	20.7	3.6	2.1	29.9	26.3	87.9
14	22	7.6	102.3	12	1242.9	7.4	13.5	39.3	29.3	20.7	3.9	1.5	21.8	18.9	86.7

Figure 4-38. An illustration of the NFT reactor system suspended (top graph) and volatile suspended (bottom graph) solids concentration as a function of the hydraulic loading rate and temperature.

Figure 4-39. An illustration of the NFT reactor system total five-day BOD removal rate (top graph) and removal efficiency (bottom graph) as a function of the hydraulic loading rate and temperature.

temperature was less significant. The temperature influence on the total COD removal rates and efficiencies appeared to be less pronounced especially at hydraulic loading rates less than 20 cm/d, Figure 4-40. The NFT system appeared capable of removing nearly 400 kg/ha-d of total COD at a removal efficiency of approximately 70 percent. Temperature also had little influence on the removal of suspended solids. Greater than 80 percent removal of SS was measured at most conditions examined with removal rates as great as 160 kg/ha-d, Figure 4-41.

Nutrient Removal

A primary function of the NFT system was achieving removal of nutrients; specifically nitrogen and phosphorous from the wastewater. From the weekly twenty-four hour composite subsamples taken of the effluents from each NFT reactor, total kjeldahl nitrogen (TKN) and total ammonia nitrogen (TAN) (Appendix F) concentrations as well as total (TP) and ortho phosphate (OP) (Appendix G) concentrations were determined. The average influent and effluent concentrations at each loading condition were calculated and summarized in Tables 4-20 and 4-21.

The TKN concentration in the wastewater entering the NFT system was consistently between 20 mg/l and 25 mg/l throughout the study with the TAN concentration between 16 mg/l and 21 mg/l. The nitrogen loading and removal rates as well as the removal efficiencies were expressed in terms of TKN. As illustrated in Figure 4-42, the effluent TKN and TAN concentrations were only slightly less than the influent concentrations at hydraulic loading rates in excess of 10 cm/d. Below this loading rate the effluent concentrations decreased rapidly to 12 mg-TKN/l and six

Figure 4-40.

An illustration of the NFT reactor system total COD removal rate (top graph) and removal efficiency (bottom graph) as a function of the hydraulic loading rate and temperature.

Figure 4-41. An illustration of the NFT reactor system suspended solids removal rate (top graph) and removal efficiency (bottom graph) as a function of the hydraulic loading rate and temperature.

Table 4-20

A SUMMARY OF THE NITROGEN REMOVALS BY THE REACTORS

TOTAL TKN															
CONDITION NUMBER	TEMP (C)	FLOW (s/d)	REACTOR S.A. (sq. m.)	REACTOR DEPTH (cm)	REACTOR VOLUME (s)	FLOW (cm/d)	SURFACE LOADING (m ² /s-d)	HRT (hr)	INF TKN (mg/l)	INF TAN (mg/l)	EFF TKN (mg/l)	EFF TAN (mg/l)	LR (kg/ha-d)	RR (kg/ha-d)	RE (%)
1	10	3.8	37.2	13	474.3	10.2	9.8	30.0	22.5	17.4	19.9	16.2	23.0	2.7	11.6
2	10	3.8	74.4	9	669.6	5.1	19.6	42.3	22.5	17.4	17.7	14.5	11.5	2.5	21.3
3	10	3.8	102.3	7	731.4	3.7	26.9	46.2	22.5	17.4	11.9	9.2	8.4	3.9	47.1
4	11	6.4	37.2	11	412.9	17.2	5.8	15.5	23.9	16.9	21.9	15.8	41.1	3.4	8.4
5	11	6.4	74.4	8	569.2	8.6	11.6	21.3	23.9	16.9	17.4	14.6	20.6	5.6	27.2
6	11	6.4	102.3	6	629.1	6.3	16.0	23.6	23.9	16.9	12.8	10.1	15.0	6.9	46.4
7	13	15.0	37.2	15	565.4	40.3	2.5	9.0	21.0	15.9	18.8	15.3	84.7	8.9	10.5
8	13	15.0	74.4	12	874.2	20.2	5.0	14.0	21.0	15.9	17.6	15.1	42.3	6.9	16.2
9	13	15.0	130.1	10	1236.0	11.5	8.7	19.8	21.0	15.9	15.7	14.4	24.2	6.1	25.2
10	18	15.0	37.2	18	653.2	40.3	2.5	10.5	20.9	16.9	18.3	16	84.3	10.5	12.4
11	18	15.0	74.4	13	964.2	20.2	5.0	15.4	20.9	16.9	18.3	16.5	42.1	5.2	12.4
12	18	15.0	102.3	11	1146.8	14.7	6.8	18.3	20.9	16.5	18.0	16.1	30.6	4.3	13.9
13	22	7.6	74.4	13	974.6	10.2	9.8	30.8	23.9	20.0	20.6	19.2	24.4	3.4	13.8
14	22	7.6	102.3	12	1242.9	7.4	13.5	39.3	23.9	20.0	19.7	17.9	17.8	3.1	17.6

Table 4-21

A SUMMARY OF THE PHOSPHOROUS REMOVALS BY THE REACTORS

TOTAL TP															
CONDITION NUMBER	TEMP (C)	FLOW (s/d)	REACTOR S.A. (sq. m.)	REACTOR DEPTH (cm)	REACTOR VOLUME (s)	FLOW (cm/d)	SURFACE LOADING (m ² /s-d)	HRT (hr)	INF TP (mg/l)	INF OP (mg/l)	EFF TP (mg/l)	EFF OP (mg/l)	LR (kg/ha-d)	RR (kg/ha-d)	RE (%)
1	10	3.8	37.2	13	474.3	10.2	9.8	30.0	3.3	2.4	2.3	1.7	3.3	0.9	28.2
2	10	3.8	74.4	9	669.6	5.1	19.6	42.3	3.3	2.4	1.6	1.3	1.7	0.9	51.2
3	10	3.8	102.3	7	731.4	3.7	26.9	46.2	3.3	2.4	0.5	0.3	1.2	1.0	84.7
4	11	6.4	37.2	11	412.9	17.2	5.8	15.5	2.8	2.3	2.0	2.1	4.8	1.4	28.6
5	11	6.4	74.4	8	569.2	8.6	11.6	21.3	2.8	2.3	1.6	1.0	2.4	1.0	42.9
6	11	6.4	102.3	6	629.1	6.3	16.0	23.6	2.8	2.3	1.1	0.0	1.8	1.1	60.7
7	13	15.0	37.2	15	565.4	40.3	2.5	9.0	3.4	1.9	3.5	1.7	13.7	-0.3	-2.1
8	13	15.0	74.4	12	874.2	20.2	5.0	14.0	3.4	1.9	3.8	2.3	6.9	-0.8	-11.8
9	13	15.0	130.1	10	1236.0	11.5	8.7	19.8	3.4	1.9	2.5	1.3	3.9	1.0	26.5
10	18	15.0	37.2	18	653.2	40.3	2.5	10.5	6.0	3.5	5.5	3.4	24.2	2.0	8.3
11	18	15.0	74.4	13	964.2	20.2	5.0	15.4	6.0	3.5	5.4	3.6	12.1	1.2	10.0
12	18	15.0	102.3	11	1146.8	14.7	6.8	18.3	6.0	3.5	6.0	3.3	8.8	0.0	0.0
13	22	7.6	74.4	13	974.6	10.2	9.8	30.8	4.7	1.7	3.8	2.0	4.8	0.9	18.2
14	22	7.6	102.3	12	1242.9	7.4	13.5	39.3	4.7	1.7	3.7	2.5	3.5	0.7	20.1

Figure 4-42.

An illustration of the NFT reactor system TKN (top graph) and TAN (bottom graph) effluent concentrations as a function of the hydraulic loading rate and temperature.

mg-TAN/l at a hydraulic loading rate of five cm/d. This represented a 50 percent removal of the influent TKN at a rate of approximately five kg-N/ha-d (0.5 grams per square meter per day, g/m²-d), Figure 4-43.

The TP concentration in the wastewater entering the NFT system was consistently from three mg/l to five mg/l throughout the study with the OP concentration from 1.5 mg/l to three mg/l. The phosphorous loading and removal rates as well as the removal efficiencies were expressed in terms of total phosphorous. As illustrated in Figure 4-44, the effluent TP and OP concentrations were only slightly less than the influent concentrations at hydraulic loading rates in excess of 20 cm/d. Below this loading rate the effluent concentrations decreased rapidly to 0.3 mg-TP/l and 0.0 mg-OP/l at a hydraulic loading rate of five cm/d. This represented a 90 percent removal of the influent TP at a rate of approximately one kg-N/ha-d (0.1 grams per square meter per day, g/m²-d), Figure 4-45.

The NFT system appeared to be quite capable of removing phosphorous to extremely low concentrations; however, with the phosphorous gone there did appear to be a significant concentration of nitrogen remaining in the effluent wastewater under the conditions examined.

Batch Nutrient Uptake Studies

To better interpret upper values of nutrient removal by the NFT system four batch studies were conducted; one in February 1990, another in March 1990, the third in May 1990, and the last in October 1990. Since the northernmost shallow-channel NFT-SN root

Figure 4-43.

An illustration of the NFT reactor system TKN removal rate (top graph) and removal efficiency (bottom graph) as a function of the hydraulic loading rate and temperature.

Figure 4-44.

An illustration of the NFT reactor system TP (top graph) and OP (bottom graph) effluent concentrations as a function of the hydraulic loading rate and temperature.

Figure 4-45.

An illustration of the NFT reactor system TP removal rate (top graph) and removal efficiency (bottom graph) as a function of the hydraulic loading rate and temperature.

mass covered the entire surface area of the reactor, this reactor was used as the most representative of a mature reactor that could interpret the maximum nutrient uptake rates. In each of these studies the average depth of liquid in the reactor was first measured then the majority of the liquid content was removed and the volume determined. Excess nitrogen (as ammonia and nitrate) and phosphorous (as ortho phosphate) was added. The liquid was then returned to the reactor and the average depth was again measured. The liquid in the reactor was recycled from the effluent end to the influent end of the reactor. The TKN, TAN, $\text{NO}_3\text{-N}$, and OP concentrations were measured periodically throughout the following 180 hours. A detailed presentation of the results of these four studies is given in Appendix L. In each of the studies the log of the concentration was calculated and plotted versus the operation time. This plot produced a straight line over the period of uninhibited nutrient uptake. The slope of this line was assumed to be the nutrient uptake rate.

The results, summarized in Table 4-22, were extremely consistent. The uptake rate, when expressed as milligrams of a nutrient removed per liter of liquid in the reactor per hour (mg/l-hr), was slightly greater than one mg/l-hr. This was true for all four studies including wastewater wastewater temperatures from 10°C to 15°C. Since the volume of liquid used in each study was different, the uptake rate when expressed in grams of nutrient removed per square meter of reactor surface area per day, ranged from 0.90 g/m²-d in February to 1.35 g/m²-d in March with values for May and October at approximately 1.2 g/m²-d. These rates applied to each of the four nutrient parameters measured. From these results it appeared that maximum nitrogen uptake rates by the NFT system were as high as 2.7 g/m²-d (summation of nitrate uptake and TKN

uptake). The ortho phosphate uptake rate appeared to be approximately half that of nitrogen. As illustrated in Figure 4-46, these uptake rates appeared to be quite constant at the four points during the year the batch studies were conducted.

Table 4-22

A SUMMARY OF THE NUTRIENT UPTAKE STUDIES CONDUCTED USING THE
NORTHERNMOST SHALLOW NFT REACTOR

Parameter	2/20/90	3/6/90	5/16/90	10/17/90
Test Number	1	2	3	4
Temperature (°C)	10	10	15	15
Time (days)	50	64	135	289
Uptake Concentration (mg/l-hr)				
TKN		1.040	1.020	
TAN	1.017	1.040	1.020	1.021
NO ₃ -N	1.024	2.042	1.022	1.082
PO ₄ -P	1.011	1.015	1.054	1.134
Uptake Rate (gm/m ² -d)				
TKN		1.354	1.163	
TAN	0.900	1.354	1.163	1.163
NO ₃ -N	0.906	1.357	1.165	1.232
PO ₄ -P	0.895	1.322	1.201	1.292
Regression Time Period (hours)				
Start	3.3	21.8	11.7	2.0
Stop	67.3	76.1	90.1	26.0

By measuring the liquid depth/volume relationship before and after the liquid was removed from the reactor, it was possible to calculate the volume of root mass in the reactor by difference. As summarized in Table 4-23, the total volume was calculated as the product of the initial liquid depth in the reactor and the reactor surface area. The displaced volume was the product of the liquid depth after the liquid was removed from the reactor and the reactor surface area. The liquid volume removed from the reactor was measured directly and the displaced root mass volume was the difference between the total volume and the displaced volume. It was assumed that the relationship of root mass volume to liquid

Figure 4-46

An illustration of the nitrogen and phosphorous removal rates measured during the four batch nutrient uptake studies.

Table 4-23

A SUMMARY OF THE ROOT MASS VOLUME AND DENSITY

Surface Area Harvested For Analysis = 0.093 square meters.
 Reactor Surface Area = 27.9 meters.

DATE	TEMP	INITIAL DEPTH (cm)	TOTAL VOLUME (l)	FINAL DEPTH (cm)	DISPLACED VOLUME (l)	LIQUID REMOVED (l)	DISPLACED ROOT VOLUME (l)	TOTAL ROOT VOLUME (l)	TOTAL ROOT VOLUME (l/m ²)
10-Feb-90	10	9.2	2564	3.3	1644	300	1344	2096	75
06-Mar-90	10	7.9	2202	3.0	1366	250	1116	1799	65
16-May-90	15	8.6	2397	3.1	1533	315	1218	1904	68
17-Oct-90	15	8.6	2397	3.0	1561	315	1246	1913	69
03-Dec-90	11	10.8	3010	3.2	2118	600	1518	2157	77
Averages									71

TOTAL VOLUME.....Initial depth x reactor surface area.

DISPLACED VOLUME.....Final depth x reactor surface area.

LIQUID VOLUME.....Measured directly.

DISPLACED ROOT VOLUME.....Displaced volume - liquid volume.

TOTAL ROOT MASS VOLUME.....A proportion of the total volume based on the
 assumption that the relationship of liquid volume
 to root mass volume was the same before and after
 the liquid was removed.

volume was the same after the liquid was removed from the reactor as it was before the liquid was removed. Thus, by proportion the total root mass volume was estimated as a portion of the total volume. These measurements were taken at the start of each of the four batch nutrient studies and a fifth measurement was taken in December 1990. The average root mass volume in the reactor was two cubic meters (1.8 m^3 to 2.2 m^3); 71 liters per square meter (l/m^2). These values were consistent with those calculated in the Hydraulic Characterization section using the approach of actual hydraulic retention time.

Biomass Production

Nutrient removal in the pilot NFT system was accomplished by mechanisms within the plant root zone. Nitrogen and phosphorous as well as all other nutrients required for plant growth were derived from the wastewater passed through the system and all the plants in the system, including cattails, reed canary grass, napier grass, willow, irises, and others appeared to thrive in the wastewater environment. Thus, biomass, a useful product and possible revenue source, was produced from the wastewater and in the process contaminants in the water were removed leaving a much higher quality water as the effluent from the system. It was therefore important to quantify the biomass yield and characterize the plant rheology and composition.

Determining the biomass yield was accomplished by harvesting the plants to analyze the dry mass and composition. This means of analysis was a destructive procedure since, once harvested, the plants could not be returned to the system. To gather as much yield information as possible two forms of harvesting were

attempted. Alternate sections of each reactor were selected to examine the two harvesting techniques. The first technique consisted of removing the plant stalks approximately 40 centimeters high three times during the year, and the second consisted of a single harvest in which all the stalks approximately 10 centimeters high and small representative samples of the root mass were removed for analysis. A detailed summary of the biomass harvest information is presented in Appendix J.

Harvest of the plant stalks at three points during the year (June 13, 1990, July 13, 1990, and January 11, 1991) apparently did not affect the net annual stalk dry yield when compared to the single annual harvest. As summarized in Table 4-24, the maximum dry mass yield of stalk material was 1.9 kilograms of dry material per square meter of reactor surface area per year ($\text{kg-m}^2\text{-yr}$) (19 metric tons per hectare year, mt/ha-yr) for both the tri-harvest and single harvest techniques. The northernmost shallow-channel reactor (NFT-SN), with a root mass that appeared to cover the entire reactor surface area, in fact had the highest yield. The NFT-DS reactor yield was 15 mt/ha-yr , followed by NFT-DN at 12.5 mt/ha-yr and NFT-SS at 7 mt/ha-yr .

The tri-harvest technique revealed several interesting facts about the stalk biomass. Over half the annual stalk dry yield was accumulated at the point of the first harvest on June 13, 1990. The change in the stalk dry matter content was also of interest. Both the first and second harvest stalk dry matter contents were approximately 16 percent of the wet weight while the annual harvest on January 11, 1991 was more than 34 percent; the stalk biomass apparently die late in the fall of the year and lose their green color.

Table 4-24

A SUMMARY OF THE STALK BIOMASS YIELD FROM THE NFT REACTOR SYSTEM

Parameter	DS	DN	SN	SS
I. Stalk Biomass Yield				
A. Surface Area (m ²)	37.16	37.16	27.87	27.87
B. Wet Mass (kg/m ²)				
1. Three Times per year				
a. First harvest (kg/m ²)	5.08	3.43	6.67	--
b. Second harvest (kg/m ²)	1.52	0.96	3.97	2.98
c. Third harvest (kg/m ²)	1.11	1.17	1.06	3.19
d. Total (kg/m ²)	7.72	5.56	11.70	6.17
2. Once per year (kg/m ²)	4.42	3.15	4.80	1.83
C. Total Solids Concentration (%)				
1. Three times per year				
a. First harvest (%)	16.42	16.07	16.40	--
b. Second harvest (%)	16.12	16.12	10.61	14.08
c. Third harvest (%)	34.49	39.67	39.67	39.70
D. Dry Matter Yield (kg/m ²)				
1. Three times per year				
a. First harvest (kg/m ²)	0.83	0.55	1.09	0.00
b. Second harvest (kg/m ²)	0.25	0.15	0.42	0.42
c. Third harvest (kg/m ²)	0.38	0.46	0.42	1.26
d. Total (kg/m ²)	1.46	1.17	1.94	1.68
2. Once per year (kg/m ²)	1.53	1.25	1.90	0.73
3. Average (mt/ha-yr)	15.2	12.5	19.0	7.3
II. Stalk Density, number per m ²				
A. First harvest	45	24	86	NA
Second harvest				
Third harvest			65	
B. Once per year harvest			151	

Stalk density, expressed as the number of stalks per square meter of reactor surface area, ranged from 24 to more than 150. The sum of stalks from the tri-harvested areas was equal to single-harvested zones. The first harvest stalk density was a little more than half the total. After the the first and second harvests it was apparent that many of the cut stalks appeared to die and new shoots began growing from the rhizomes; however, some of the cut stalks continued to grow. It appeared that new shoots were produced throughout the summer and into the fall. Following the final harvest of the stalks in January 1991, it was apparent that the rhizomes had produced a multitude of tiny shoots that did not appear to grow until the middle of March.

The method used to estimate the net yearly dry mass yield of root mass consisted of removing representative predetermined areas (0.093 square meters) of root mass, including everything within the root zone, from several points within the northernmost shallow-channel reactor (NFT-SN). Samples were taken November 15, 1989, after all the stalk material in the reactor had been removed and again one year later December 11, 1990. The results were compared and the difference between the 1989 and the 1990 yield was assumed to be the net yearly root mass dry yield. As summarized in Table 4-25, there did not appear to be a significant increase in the dry mass present at each sampling point. The dry mass of root material present in each year was approximately 4.8 kilograms per square meter (48 metric tons per hectare) and the dry matter content of the root mass was approximately nine percent of the wet weight in each case. It is noteworthy that minimal samples were taken for analysis since each sampling removed valuable root material from the reactor; however, the results

Table 4-25

A SUMMARY OF THE ROOT MASS YIELD FROM THE NFT REACTOR SYSTEM.

PARAMETER	NFT-SN
RHYZOME BIOMASS YIELD	
A. Wet Mass Present (kg/m ²)	
1. NFT-SN-2&7 1990	52.64
2. NFT-SN-3&6 1990	55.43
3. NFT-SN-3 1989	57.01
4. NFT-SN-7 1989	51.95
B. Total Solids Concentration (%)	
1. NFT-SN-2&7 1990	7.00
2. NFT-SN-3&6 1990	10.79
3. NFT-SN-3 1989	8.89
4. NFT-SN-7 1989	8.89
C. Dry Mass Present 1990 (kg/m ²)	
1. NFT-SN-2&7 1990	3.68
2. NFT-SN-7 1989	4.62
3. NFT-SN-3&6 1990	5.98
4. NFT-SN-3 1989	5.07
5. 1990 Average Mass	4.83
6. 1989 Average Mass	4.84
D. Rhizome Bulk Density (kg/m ³)	
1. Area Sampled (m ²)	0.093
2. Root Mass Volume (m ³ /m ²)	0.071
3. Wet Mass Sampled (kg)	5.0
4. Rhizome Wet Bulk Density (kg/m ³)	757
5. Total Solids Concentration (%)	8.9
6. Rhizome Dry Bulk Density (kg/m ³)	67
7. Total Volatile Solids (%)	86
8. Rhizome Volatile Bulk Density (kg/m ³)	58

indicated a negligible net increase in dry mass within the root zone.

As mentioned in the Batch Nutrient Uptake Studies section, the root mass volume was calculated to be 71 liters per square meter of reactor surface area; 0.071 cubic meters per square meter (m^3/m^2). Using the results of the root mass harvest, it was possible to calculate the root mass bulk density. As summarized in Table 4-25 and detailed in Appendix J., the average wet mass harvested was five kilograms from a sample area of 0.093 square meters. Thus, the wet bulk density was approximately 750 kilograms per cubic meter (kg/m^3) with a dry density of 70 kg/m^3 and a volatile density of 60 kg/m^3 .

The mass of nitrogen (N) and phosphorous (P) removed from the system as stalk biomass was determined at each harvest. As summarized in Table 4-26 and 4-27, the accumulation of N and P, as expected, appeared to increase during the growing season and decrease after the growing season. The N and P content of the stalks following the first harvest on June 13, 1990 was greater than two percent and 0.3 percent of the dry weight. Following the second harvest in July 1990 these concentrations had increased to greater than three percent and 0.4 percent respectively. Then in December the N and P concentrations had dropped to just over one percent and 0.3 percent respectively.

The mass of N and P removed from the reactor was significantly greater from the tri-harvested areas than from the annually harvested zones. The nitrogen removed as stalk biomass from the tri-harvested areas was 0.12 grams nitrogen per square meter of reactor surface area per day ($\text{g-N}/\text{m}^2\text{-d}$), while that of the

Table 4-26

A SUMMARY OF NITROGEN REMOVAL AS BIOMASS BY THE NFT REACTOR SYSTEM

PARAMETER	DS	DN	SN
BIOMASS NITROGEN (% of TS)			
A. Biomass Nitrogen Content			
1. Stalk Nitrogen Content			
a. First Harvest	2.30	2.48	2.21
b. Second Harvest	3.15	3.15	2.35
c. Third Harvest			1.71
2. Once per Year			1.23
3. Rhizome Nitrogen Content			
a. Frequent Stalk Harvest			2.42
b. Once per Year Stalk Harvest			2.82
B. Biomass Nitrogen Yield (g-N/m ²)			
1. Stalk Nitrogen Removed			
a. First Harvest	19.17	13.68	24.19
b. Second Harvest	7.74	4.85	14.10
c. Third Harvest			7.18
d. Total (g-N/m ² -yr)			45.47
2. Once per Year (g-N/m ² -yr)			23.37
3. Rhizome Nitrogen Content (g-N/m ²)			
a. Frequent Stalk Harvest			89.10
b. Once per Year Stalk Harvest			168.30

Table 4-27

A SUMMARY OF PHOSPHORUS REMOVAL AS BIOMASS
BY THE NFT REACTOR SYSTEM

PARAMETER	DS	DN	SN
BIOMASS PHOSPHORUS (% of TS)			
A. Biomass Phosphorus Content			
1. Stalk Phosphorus Content (%)			
a. First Harvest	0.30	0.36	0.27
b. Second Harvest	0.43	0.43	0.50
c. Third Harvest			0.39
2. Once per Year			0.27
3. Rhizome Phosphorus Content (%)			
a. Frequent Stalk Harvest			0.57
b. Once per Year Stalk Harvest			0.52
B. Biomass Phosphorus Yield (g-P/m ²)			
1. Stalk Phosphorus Removed			
a. First Harvest	2.52	1.99	2.99
b. Second Harvest	1.06	0.66	2.09
c. Third Harvest			1.65
d. Total (g-P/m ² -yr)			6.73
2. Once per Year (g-P/m ² -yr)			5.13
3. Rhizome Phosphorus Content (g-P/m ²)			
a. Frequent Stalk Harvest			21.10
b. Once per Year Stalk Harvest			31.27

annually harvested zones was approximately $0.064 \text{ g-N/m}^2\text{-d}$. That of phosphorous was $0.018 \text{ g-P/m}^2\text{-d}$ and $0.014 \text{ g-P/m}^2\text{-d}$, respectively. All these stalk biomass nitrogen and phosphorous removals were significantly below those calculated from actually measuring the influent and effluent wastewater nitrogen and phosphorous concentrations. Accumulation of N and P in the upper plant stems is only one mechanism capable of removing nutrients in the hydroponic plant systems.

Most of the plant biomass in the NFT system was *Typha glauca* cattails, many of which were donated to the project by Dr. Leland Marsh of Oswego College in Oswego, New York. Upon receipt of the cattails from Dr. Marsh in the early spring of 1987, samples of the combined stalk and rhizome were submitted to Dr. James Robertson in the Animal Science Department of Cornell University for analysis of the fiber content and the *in vitro* digestibility. Samples of the December 1990 harvest of stalks and rhizomes from the northern most shallow channel NFT reactor were also sent to Dr. Robertson. From this analysis, summarized in Table 4-28, and detailed in Appendix J, it appeared that the NFT cattails were much more digestible than those from Dr. Marsh. The total digestible organic matter (TDOM), which is also an estimate of the plant biodegradability, was 63 percent of the volatile matter (both stalks and rhizomes) in the NFT system and 45 percent in the original samples. The digestible cell wall (DCW) of the pilot cattails were also significantly higher than those of Marsh. The rhizomes appeared to be the most digestible portion of the plant with a TDOM of nearly 70 percent. The nitrogen content of the samples was also quite different. The NFT biomass nitrogen content was four times that of the original biomass; 2.4 percent of the dry mass. The NFT samples appeared to contain more cell

soluble (CS) organics than the original biomass and less fiber as cell wall (CW), which was assumed to be the summation of cellulose (CE), hemi-cellulose (HC), lignin (Ls & Lsk), and Cutin).

Table 4-28

A SUMMARY OF THE PILOT CATTAIL FIBER ANALYSIS COMPARED TO THOSE OF DR. LELAND C. MARSH

Sample ID	Pilot Cattail Stalks	Pilot Cattail Rhizomes	Total Pilot Cattails	Dr. Marsh Fertile Cattails
Yield (kg/m ² -d)	1.9	4.8		
Percent of TS				
VS	84.5	86.9	86.3	88.5
ASH	15.5	13.1	13.7	11.5
TKN	1.5	2.8	2.4	0.8
CP	9.3	17.3	15.0	5.1
Percent of VS				
CS-Cell Soluble	34.7	47.7	44.0	32.3
HC-Hemi-cellulose	18.6	20.2	19.8	17.0
CE-Cellulose	36.2	20.7	25.1	35.9
Ls-Lignin	9.3	11.5	10.8	11.5
Lsk-lignin	6.3	8.7	8.0	9.5
Cutin	3.0	2.4	2.6	2.1
CW-Cell Wall	65.5	44.3	50.3	67.7
TDOM	52.1	67.3	63.0	44.9
DCW	38.5	49.0	46.0	24.5

TDOM - Total Digestible Organic Matter
DCW - Digestible Cell Wall

The original cattail biomass samples and those from the NFT system were submitted to the Fruit and Vegetable Crops Department of Cornell University to determine the elemental compositions. As summarized in Table 4-29 and detailed in Appendix J., the ash content of the NFT samples was slightly higher than the ash content of the original plants. In the nutrient-rich environment of the NFT system the concentration of several elements appeared to be significantly higher than those of the original plants. The

Table 4-29

A SUMMARY OF THE NFT CATTAIL ELEMENTAL COMPOSITION AS COMPARED TO
THE ORIGINAL CATTAILS SUPPLIED BY DR. LELAND C. MARSH

ELEMENT	NFT CATTAIL STALK	NFT CATTAIL RHYZOME	TOTAL NFT CATTAIL	ORIGINAL CATTAIL
ASH CONTENT	15.5	13.1	13.7	11.5

Percent of the dry matter.

N	1.5	2.6	2.3	0.8
K	2.4	1.0	1.4	0.5
P	0.3	0.7	0.6	0.1
Ca	2.1	1.5	1.7	0.9
Mg	0.3	0.3	0.3	0.1
S	0.4	0.8	0.7	0.1

Parts per Million of the dry matter.

Mn	329	368	357	772
Fe	3461	15308	11968	2950
Cu	14.0	57.7	45.4	7.1
B	24.6	32.9	30.6	4.7
Zn	231	276	263	19.5
Mo	0.8	3.2	2.5	0.0
Al	289	1434	1111	1033
Na	7737	4534	5437	3243
Co	0.0	0.0	0.0	0.3
Cd	0.2	0.1	0.1	0.1
Cr	2.3	5.0	4.2	3.1
Ni	0.1	3.4	2.5	1.8
Pb	7.5	4.1	5.1	1.9
Si	267	1861	1412	433
V	0.0	0.0	0.0	0.0
As	0.0	0.0	0.0	0.4
Se	8.1	17.4	14.8	0.0

NFT cattail nitrogen content was four times greater, phosphorous six times greater, and sulfur seven times greater than the original plant concentrations. However, the concentrations of heavy metals including cadmium (Cd), chromium (Cr), nickle (Ni), and lead (pb) did not appear to significantly increase in the plant biomass. Other elemental concentrations were notabably higher in the pilot cattails including Fe, Cu, B, Zn, Na, Si, and Se. It is important to point out that the NFT channels were constructed of steel which may have contributed to the accumulation of iron in the plant biomass.

Fecal Coliform Concentrations

The pilot reactor system appeared to have a significant potential for removal of fecal coliforms. Samples of the influent wastewater and the effluents from the AAFEB reactor system, deep-channel NFT reactor system and the shallow-channel system were taken periodically throughout the summer and fall of 1990. As summarized in Table 4-30 and Appendix I, the influent fecal coliform concentrations were from 0.5 to two million colonies per 100 milliliters (col/100 ml) of sample. The AAFEB reactor system reduced these concentrations by a factor of 10 at both wastewater flow rates examined; 15 s/d and 7 s/d. The major coliform reductions occurred in the NFT system. As illustrated in Figure 4-47 the coliform concentration was less than 10,000 col/100 ml when the flow was 15 s/d (10 cm/d). When the flow was reduced to 7 s/d (five cm/d), the fecal coliform concentrations in the NFT effluent was less than 100 col/100 ml. At hydraulic loading rates less than five cm/d the NFT system appeared capable of achieving effluent quality removals of fecal coliforms without chlorination.

Figure 4-47

An illustration of the fecal coliform concentrations in the influent and effluent from each of the reactors of the pilot system.

Table 4-30

A SUMMARY OF THE PILOT SYSTEM FECAL COLIFORM CONCENTRATIONS

	Wastewater		AAFEB-2	NFT-DN	NFT-SS
	Flow	Inf.	Eff.	Eff.	Eff.
Date	(s/d)	(col/100 ml)	(col/100 ml)	(col/100 ml)	(col/100 ml)
6/19/90	16.1	1,000,000	260,000	160,000	146,000
6/26/90	14.2	470,000	420,000		4,400
7/3/90	14.8	700,000	61,800		45
7/10/90	15.4	434,000	131,000		4,800
7/17/90	14.4	740,000	178,000		14,200
7/24/90	15.4	1,100,000	326,000		1,700
7/31/90	15.2	846,000	192,000	23,100	3,750
8/7/90	7.1	1,200,000	240,000		9,300
8/22/90	6.9	640,000	84,000	9,900	4,600
8/28/90	7.9	682,000	250,000		120
8/30/90	7.1	406,000	133,000		40
9/27/90	7.1	156,000	124,000	4,000	30
12/10/90	5.3	280,000	35,000	180	1
12/31/90	5.3	200,000	170,000	910	20

Pest Management

The NFT treatment system represented an entire ecosystem. Birds were noticed nesting among the biomass. The earthworm population threatened to plug the outlet pipe from the NFT-SN reactor. There were insects of all varieties including bees, wasps, and spiders. There was visible evidence of protozoa in the liquid of the NFT system; for most of the year goldfish were maintained in the effluent wastewater.

Late in 1989 the southernmost shallow-channel NFT reactor was victim to one form of pest. In a matter of a few days what once was a dense cattail stand was totally destroyed by a muskrat that loved to eat the growing buds of the cattails. Immediately

following the incident, a chickenwire fence was built around the outside circumference of both shallow channels to prevent these pests from entering the system. This preserved the northernmost shallow-channel reactor; however, the southernmost unit was destroyed and not used further for research.

Mosquitos became a problem early in the spring of 1990; however, they were quickly and easily controlled by introducing lemna (duck weed) to the exposed liquid surfaces. The lemna prevented the larva from reaching the liquid surface to breathe eliminating the problem at its source.

Some predators required professional help to control. These included spider mites, which attacked the cattails, as well as aphids and thrips, which attached the reed canary grass. Control of these pests was accomplished by the introduction of predator organisms by IPM Laboratories, Inc. (Ms. Carol S. Glenister, President). Ms. Glenister made visual inspections of the system once per week from late March through the middle of June. As pest problems began to develop she introduced predators to control the pest population. In a written summary of her activities she mentioned that a person with keen eyesight and enough patience to carefully look for pests and keep careful records would be required at a treatment facility. The "pest scout" would be required to spend approximately two hours per week in March, four hours per week in April, three hours per week in May, and two hours per week throughout the remainder of the year. She mentioned that a pest scout could be adequately trained with a four hour training session in April followed by monthly two-hour training sessions throughout the growing season; a total of fourteen hours.

After a one time addition of Aphidoletes (two releases of 1,000 per facility) at a cost of \$60 per acre, the annual cost of pest control was also estimated by IPM Laboratories to be \$50 per hour for training sessions (\$700), and \$544 dollars per acre per year for release of predator organisms, including:

Initial Pest Control Costs

Pest Scout Training	\$700
Aphidoletes 2 releases of 1000 per facility	\$60/acre

Annual Pest Control Costs

Lady bugs, 1 gallon per acre @ \$60/gallon	\$60/acre/year
Lacewings, 2 releases of 44,000/acre @ \$2.50/1000	\$220/acre/year
Predatory mites, 1 release 22,000/acre @ \$12/1000	\$264/acre/year
Total	\$544/acre/year

PILOT SYSTEM ENERGY REQUIREMENTS

The pilot system was operated with electricity and kerosene as its sources of energy. All electricity used at the facility was monitored by a kilowatt meter supplied by the New York State Electric and Gas Corporation which supplied monthly usage records as part of the invoice. Kerosene was used to operate two forced-hot-air furnaces that supplied heat to the AAFEB and NFT system greenhouses.

From the monthly electrical usage records, presented in Appendix R, the pilot system electrical requirements were sub-divided into four categories, as summarized in Table 4-31. The first category consisted of electricity required to operate the wastewater transfer pumps. This included the wastewater feed pump and the intermediate transfer pump, both of which operated continuously. It also included the intermediate NFT transfer pump and the effluent pump which both operated daily on an intermediate basis.

Table 4-31

A SUMMARY OF THE PILOT SYSTEM ELECTRICAL USAGES

ELECTRICAL USAGE	Quantity	Hp	Voltage	Amperage	wattage	Average Operation Time (hrs/d)	Operation Months	ENERGY USAGE (kwh/d)
Wastewater Transfer Pump								
Feed	1	0.75	115	9.3	560	24	All	13.4
AAFEB Intermediate	1	0.75	115	9.3	560	24	All	13.4
NFT Intermediate	1	0.17	115	5.0	124	9	All	1.1
Effluent	1	0.33	115	7.0	249	4	All	1.0
TOTAL								29.0
AAFEB Reactor System								
Recycle Pumps	2	0.17	115	5.0	124	24	All	6.0
Paddle Mixers	2	0.03	115	1.4	19	0.20	All	0.01
TOTAL								6.0
AAFEB and NFT Greenhouse								
Inflation Fans	2	0.04	115	1.5	30	24	All	1.4
NFT Ventilation Fan	1	1.00	115	12.8	746	4	All	3.0
AAFEBR Ventilation F	1	0.33	115	5.0	249	4	6, 7, 8	1.0
Heating Furnaces	2	0.33	115	13.0	249	4	1, 2, 3, 11, 12	2.0
TOTAL								4.4 TO 7.4
Other Highly Variable Energy Useages								
Sample Prep Room								
pH Meter	1		115	1.0	58			
Balance	1		115	2.0	115			
Hot Water Heater	1		208	19.0	3952			
Lights	6		115	0.7	75			
Office								
Baseboard Heater	1		208	14.4	3000			
Portable Heater	1		115	13.0	1500			
Air Conditioner	1		115	5.5	600			
Small Refrigerator	1		115	1.5	30			
Large Refrigerator	1		115	6.8	136			
Lights	6		115	0.7	75			

The second category consisted of energy required to operate the AAFEB reactor system. This included the liquid recycle pumps that operated continuously and the paddle-mixer motors that operated for two minutes every four hours. The third category consisted of electrical energy required for the two greenhouse structures and included the two film inflation fans that ran continuously; furnaces, that operated intermittently during the months of November, December, January, February, and March, and the ventilation fans. The NFT ventilation fan was used both to circulate hot air during the cooler months and to evacuate hot air during the warmer months and therefore operated intermediately throughout the year. The AAFEB ventilation fan operated intermittently only during the months of June, July, and August. The final category consisted of a variety of miscellaneous electrical usages associated with the sample preparation room and office.

The most significant electrical energy usage in the pilot system was associated with the transfer of wastewater, summarized in Table 4-32, and illustrated in the upper curve of Figure 4-48. This systems specific energy use represented a continuous electrical requirement of approximately 30 kilowatt-hours per day (kw-hr/d). The AAFEB system usage for recycle was approximately 6 kw-hr/d and represented the least energy usage in the system. The energy usage associated with maintaining the greenhouse environments was variable throughout the year from a high of 7.4 kw-hr/d in the winter to 4.4 kw-hr/d in the late spring.

Both greenhouse structures were heated using forced hot air kerosene furnaces that were controlled using thermostats. The furnaces, that operated intermittently November through March,

Table 4-32

A SUMMARY OF THE PILOT SYSTEM MONTHLY ELECTRICAL USAGES

DATE	METER READING	TOTAL	WASTEWATER			
		ENERGY	AAFEB	TRANSFER	GREENHOUSE	OTHER
		USAGE (kwh/d)	USAGE (kwh/d)	USAGE (kwh/d)	USAGE (kwh/d)	USAGE (kwh/d)
22-Dec-89	6587	114.00	6.0	29.0	6.4	72.7
24-Jan-90	6603	87.27	6.0	29.0	6.4	45.9
23-Feb-90	6620	102.00	6.0	29.0	6.4	60.7
26-Mar-90	6631	63.87	6.0	29.0	6.4	22.5
25-Apr-90	6644	78.00	6.0	29.0	6.4	36.7
24-May-90	6655	68.28	6.0	29.0	6.4	26.9
25-Jun-90	6668	73.13	6.0	29.0	5.4	32.8
25-Jul-90	6676	48.00	6.0	29.0	5.4	7.7
23-Aug-90	6686	62.07	6.0	29.0	5.4	21.7
24-Sep-90	6696	56.25	6.0	29.0	4.4	16.9
24-Oct-90	6706	60.00	6.0	29.0	4.4	20.7
26-Nov-90	6717	60.00	6.0	29.0	6.4	18.7
24-Dec-90	6727	64.29	6.0	29.0	6.4	22.9
24-Jan-91	6742	87.10	6.0	29.0	6.4	45.8
25-Feb-91	6755	73.13	6.0	29.0	6.4	31.8

* - Readings supplied by NYSEG Corporation from a kilowatt meter with a conversion factor of 180.

PILOT ELECTRICAL USEAGE 1990

GREENHOUSE FUEL CONSUMPTION 1990

Figure 4-48. An illustration of the electrical (top graph) and kerosene (bottom graph) energy requirements of the pilot wastewater treatment system.

maintained temperatures above 40°F throughout the night and on most days; however, there were occasions when the temperature was increased to produce a warmer environment in which project personnel could work. The total surface area enclosed by the two greenhouse structures was nearly 400 square meters; 360 m² (NFT greenhouse) and 35 m² (AAFEF greenhouse). As summarized in Table 4-33 and illustrated in lower curve of Figure 4-48, the maximum volume of kerosene required to maintain the temperature in the two greenhouse structures was less than 20 gallons per day for a brief period in January 1990. The average yearly kerosene requirement for the system in 1990 was approximately 7.2 liters per square meter of greenhouse surface area per year (l/m²-yr).

Table 4-33

A SUMMARY OF KEROSENE USED TO MAINTAIN 40°F
IN THE TWO GREENHOUSE STRUCTURES

NFT reactor area = 362.3 sq.m.
AAFEF Greenhouse area = 35.3 sq.m.
Total Greenhouse area = 397.6 sq.m.

DELIVERY DATE	DELIVERED VOLUME (gal)	KEROSENE USAGE (gal/d)	KEROSENE USAGE (l/d)
22-Dec-89	221.8	16.5	62.6
03-Jan-90	198.4	7.3	27.5
22-Jan-90	137.8	8.5	32.1
08-Feb-90	144.1	7.1	26.8
02-Mar-90	155.9	0.9	3.2
30-Aug-90	154.8	1.0	4.0
31-Dec-90	128.8	11.9	45.0
10-Jan-91	118.9	14.2	53.6

Fuel consumption during 1990 = 7.2 l/sq.m.-yr

Section 5

SYSTEM REQUIREMENTS AND ECONOMICS

INTRODUCTION

This section synthesizes data from this pilot study. Requirements for systems using 0.1 and 1.0 million gallons per day of domestic sewage are given. To provide a comparison, the cost of each system is estimated and compared to conventional alternatives.

It should also be noted that producing tertiary-quality effluents at low flows is costly and difficult using conventional unit processes. For many small applications the septic tank combined with a leach field is often the only satisfactory alternative to discharge a near-drinking water quality effluent to the groundwater. The use of this alternative depends on the availability of sufficient field area and the appropriate soil for long-term effectiveness. This treatment system uses physical, biological, and chemical reactions to filter wastewater and remove pollutants. This contrasts to the resource recovery concept that focuses on use of pollutants to produce useful products and is not limited by field area, appropriate soil, or groundwater location.

The goal of this resource recovery wastewater treatment system is to minimize the resource requirements for treatment while maximizing potential revenue generation through energy production or plant by-product. Since conventional wastewater treatment systems produce limited revenue, it is difficult to compare them to the concept proposed in this study. Another shortcoming is

that the system was intended to have no ultimate disposal problem; however, all conventional facilities tend to export unwanted by-products, such as sludge, from the treatment area to land application or to landfills. The value of producing significant revenue and/or eliminating ultimate disposal problems is difficult to incorporate in this analysis.

DESIGN PROCEDURE - EMPIRICAL APPROACH

This pilot-plant demonstration was not intended to define pollutant removal phenomena so rational equations could be developed for all pollutants and processes. There is enough information available to design the anaerobic expanded bed for the system's first stage. There is relatively little information available to design these units when applied to a raw domestic sewage feed under real-world conditions as demonstrated in the pilot. In addition, the accumulation of a sludge blanket in the AAFEB system complicates the design procedure. Therefore the design values for the anaerobic expanded bed must be related to the operational conditions as tested in this program. To be conservative, winter temperatures were assumed as the rate-limiting conditions and two-stage AAFEB reactors were assumed to be required, with the first stage acting as a solids-controlling system as well as a BOD conversion unit.

Since much less is known about the parametric sensitivity and design requirements for the NFT system, the design should be guided by empirical limits from testing conducted in the 1970's (Jewell et al. 1982) along with the pilot-testing program.

The overall design procedure for the hydroponic NFT system is illustrated in Figure 5-1. The removal efficiency of all pollutants is related to the hydraulic retention time in the system and the velocities that occur in continuous flowing units. Both these parameters can be varied over a wide range using varying depth of flooding and intermittent loadings. Neither of these options was defined in the demonstration program and will not be included in these designs. Both these alternatives could lead to significant efficiency changes and system size effects.

There are generally two parameters that must be fixed in a nutrient film channel design. The first is the aerial loading rate and the second is the cross-sectional loading rate or flow-through velocity. Both these variables affect the availability of oxygen and suspended solids removal, and ultimately the soluble pollutant interaction proprieties.

The design of the NFT is an iterative empirical procedure in which the total area requirements are first defined by the surface area hydraulic loading rates. These hydraulic loading rates are derived from the required efficiency as determined from data shown in the Results Section presented earlier. The width of the channels can be estimated based on the limitations used in the demonstration program. The length of each channel is related to the area and the width loading rates. This then leads directly to the number of individual channels, which is determined by fixing the channel width. It is assumed that a length-to-width ratio much greater than 30 to 40 is unnecessary and that 1:1 would be the minimum required.

Areal Loading Rate = Surface Area Requirements

NFT CHANNEL

A. System Definition for Biodegradable Organics Removal

BOD removal/conversion = f (HRT, Temp)

HRT = f (O₂ diffusion rate, O₂ demanding reactions)

O₂ demand = f (BOD, nitrification, sulfide oxidation, accumulated sludge and plant mass oxidation)

Empirical definition BOD removal = f (HRT, MLR)

B. System Definition for Removals of SS, Turbidity, Coliform Organisms

SS removal = f (V_H, HRT) = f (SS sedimentation rate, microorganism filtration rate)

Empirical definition = f (HLR, MLR) for fixed channel depths, and width to length ratios

Loading Rates

1) Areal Hydraulic Loading Rate, HLR

$$HLR = \frac{\text{Flow Rate}}{\text{NFT Surface Area}} = \frac{Q}{A} = \frac{\text{m}^3/\text{d}}{\text{m}^2} = \frac{\text{m}}{\text{d}} \text{ or } \frac{\text{cm}}{\text{d}}$$

Figure 5-1a. Overview of the hydroponic design considerations and procedure to size individual nutrient film channels.

Figure 5.1a continued

2) Mass Loading Rate, MLR

$$\text{MLR} = \frac{\text{Pollutant Mass Addition Rate}}{\text{NFT Surface Area}} = \frac{Q S_0}{A} = \frac{\text{kg/d}}{\text{m}^2}$$

Retention Time, T

$$T = \frac{\text{Reactor Volume}}{\text{Flow Rate}} = \frac{\text{Channel Width} \times \text{Length} \times \text{Depth}}{Q} =$$

= days or hours

Horizontal Velocity and Weir Loading Rates

$$V_H = \frac{\text{Flow Rate}}{\text{Cross Sectional Area}} = \frac{Q}{\text{Width} \times \text{Length}} = \frac{\text{m}}{\text{hr}}$$

$$R_w = \frac{\text{Flow Rate}}{\text{Width}} = \frac{Q}{W} = \frac{\text{m}^3}{\text{m-hr}}$$

NFT Channel Dimension Estimate Procedure

A number of pollutants depend primarily on the retention time and the availability of oxygen for this conversion and removal implant root area. (BOD, NH_3 , NO_3 , etc.), whereas other pollutant removals, namely SS, are controlled by the velocities in the system. Until the processes are more explicitly defined, the process design will be more empirical and will be guided by long-term test results using similar water quality. The removal rate curves developed in this study may be used to estimate system needs. If the waste is significantly different in concentration or character, the procedure should be used with caution.

Define NFT Channel Dimensions

1. Using relationship between hydraulic loading rate, total flow and effluent quality shown in relationship defined here.

$$A. \text{ Total NFT Area, } A_T = \frac{\text{Total Flow Rate } Q_T}{\text{Design HLR}_{SS}}$$

= total area in m^2

B. Estimate the total width assuming that the system operates at a given maximum initial depth (15 to 20 cm), and V_H .

$$V_H = \frac{Q_T}{\text{Cross Sectional Area}} = \frac{Q_T}{\text{Total Width} \times \text{Depth}}$$

C. Knowing total width and total surface area, the length of the channels can be estimated:

$$L_{\text{channels}} = \frac{\text{Area}}{\text{Total Width}}$$

D. Number of individual NFT channels: The number of channels specified will depend on specific lengths-to-widths ratios and convenience for construction.

$$\text{Number Channels} = \frac{\text{Total Width}}{\text{Individual Channel Width}}$$

Values would be corrected by root volume where this is known.

E. If possible, compare theoretical HRT with literature values for reaction rates and required retention times to achieve required effluent quality. Long and narrow channels should conform to the first order plug flow equation:

$$S_e = S_0 e^{-kt}$$

when plug flow or batch reaction kinetics describe the pollutant removal (S_0 = influent concentration, S_e = effluent concentration, k is the first-order removal rate constant, and t is the time period).

Figure 5-1b. Overview of the hydroponic design considerations and procedure to size individual nutrient film channels.

A wide range of design parameters was tested in the pilot NFT program (Table 5-1) that represent the acceptable range for these variables. Although it is possible to calculate the resulting depth of the liquid in an NFT channel based on the frictional factor of liquid flowing in the channel, this was not done in this design procedure. Instead, all depths were assumed. It was felt that all of the assumptions lead to highly conservative estimates for the NFT channels and that the exact depth estimates are not justified at this level of analysis. The detailed design procedures for the resource recovery treatment system are included in Appendix S.

Table 5-1

RANGE OF DESIGN PARAMETERS TESTED WITH THE NFT SYSTEM FOR THE
TOTAL PILOT SYSTEM

	Minimum	Maximum
A. Surface Area or Areal Loading Rates		
gpd/ft ²	0.60	25
l/m ² -d	24.4	1020
ft ³ /ft ² -d	0.080	3.34
m ³ /m ² -d	0.024	1.02
Hydraulic Loading Rates		
cm/d	2.44	102
inches/d	0.96	40
B. Weir Loading Rates		
gpd/ft width	250	2,500
m ³ /d-m width	3.1	310
C. Horizontal Velocity		
1) At Initial Depth of 6 inches (0.15 m)		
ft/d	66.8	668
m/d	20.4	204
2) At Initial Depth of 3 inches (0.075 m)		
ft/d	132	1320
m/d	40.2	402

RESOURCE RECOVERY SYSTEM DESIGN

The generic system layout for the resource recovery wastewater treatment plant is illustrated in Figure 5-2. This shows a total of approximately eight unit processes that would be included with all but two common to both the secondary and tertiary treatment systems. Adding a second-stage hydroponic system for further removal of dissolved pollutants for a tertiary-quality application represents the difference between the two levels of treatment. The first unit process is preliminary treatment and includes, for costing purposes in this report, a primary sedimentation unit. As emphasized in this demonstration, sedimentation upstream from the AAFEB units is unnecessary. However, this is a low-cost unit process and if separate digestion is used it is a recommended addition for the system. This would minimize solids handling problems within the small-particle moving-bed reactors.

The second treatment unit is the heavily loaded nutrient film unit designed to produce secondary-quality effluent. The effluent quality is always less than 30 mg/l for suspended solids and BOD₅. The second-stage NFT unit is added for further nutrient removal to achieve nitrogen and phosphorus concentrations of less than one mg/l and fecal coliforms at less than 40 colonies per 100 milliliters without chemical disinfection. The plant biomass, as well as the primary sludge, is diverted to a digester that generates energy as biogas. The effluent from the digester is taken to another NFT system or a turf production operation. For the secondary-quality effluent it would appear that the using a secondary NFT unit is not the most economical option. Accumulation of the solids for long periods of time, more than ten years in a turf production operation is the lowest cost option.

Figure 5-2. Overview of resource recovery wastewater treatment for a 3800 m³/d domestic sewage facility.

However, the larger quantity of biomass in the tertiary treatment system may also use a turf operation instead of the off-line non-discharging NFT system. The resulting dimensions and sizes of the anaerobic system and the hydroponic NFT channels are summarized in Tables 5-2 and 5-3. Comparing these values to Table 5-1 indicates that all of the loading rates in the hydroponic system are in the lower range of those tested for secondary and tertiary-quality effluents, producing relatively conservative designs.

The total area requirements for a secondary-quality resource recovery wastewater treatment system would be less than two hectares; the tertiary quality would be less than 15 hectares. Additional area is required in the hydroponic system to provide access which has been part of the cost estimates.

ECONOMICS OF RESOURCE RECOVERY AND CONVENTIONAL WASTEWATER TREATMENT

The cost for the resource recovery and conventional wastewater treatment system is based on the estimated costs of materials including liner materials to construct channels, and other components such as pumps and greenhouses, and some cost estimating references prepared for EPA. The unit cost basis for resource recovery treatment system are given in Table 5-4.

The costs for conventional processes were derived from construction costs that provided detailed capital and operation and maintenance costs for unit processes. These cost estimates were derived from the contracted costs for the various unit processes for several hundred treatment plants and were expressed in values given in 1973 and 1977, and these were updated to 1992 by using the ratio of capital cost estimates and construction

Table 5-2

SUMMARY OF NFT CHANNEL DIMENSIONS AND DESIGN PARAMETERS FOR TWO DIFFERENT DESIGN FLOWS.

	Channel Dimensions m		Total Number	Channel Loading Conditions		
	Width	Length		Areal $\text{m}^3/\text{m}^2\text{-d}$	Weir $\text{m}^3/\text{m-d}$	Horizontal Vel., * m/d
Example #1 For Q=1 MGD, Secondary Quality effluent or better	6	50	41	0.312	15	101
Example #2 For Q=0.1 MGD, Secondary Quality Effluent or better	3	50	9	0.28	14	92
Example #3 For Q=1 MGD, Tertiary Quality Effluent	15	100	54	0.0469	4.69	31
Example #4 For Q=0.1 MGD, Tertiary Quality Effluent	6	100	15	0.422	42.2	280.4

*Assume initial depth of 0.15 m

Table 5-3. Summary of resource recovery wastewater treatment system size for various flows and quality of effluent.

Example							(SECONDARY TREATMENT)					(TERTIARY TREATMENT)				
	Anaerobic Treatment AAFEB						Hydroponic Treatment-NFT Channels First Stage					Hydroponic Treatment-NFT Channels Second Stage				
Q, Effluent m ³ /d Quality	Num- ber of Units in Series	Column dia- meter, m	Reac- tor Height , m	Volume per Unit	Total Volume		Channel Size					Channel Dimension				
							Total Area, m ²	Area per Chan- nel, m ²	Num- ber of Chan- nels	Width, m	Length , m	Total Area m ²	Area per Chan- nel, m ²	No. of Chan- nels	Width , m	Length , m
1. 3800 Secondary	5	6	17	475	2375		12,300	300	41	6	41	-	-	-	-	-
2. 3800 Tertiary	5	6	17	475	2375		12,300	300	41	6	41	81,000	1,500	54	15	100
3. 380 Secondary	5	3	6.7	47.5	238		1,350	150	9	3	50	-	-	-	-	-
4. 380 Tertiary	5	3	6.7	47.5	238		1,350	150	9	3	50	9,000	600	15	6	100

Table 5-4

SUMMARY OF ASSUMPTIONS USED TO ESTIMATE COSTS OF RESOURCE RECOVERY
WASTEWATER TREATMENT SYSTEM

<u>Treatment Process</u>	<u>Costing Basis</u>
Preliminary Treatment - Bar screen, grit chamber, flow control	EPA Costing Manuals
Expanded Bed Reactors	\$900/m ³ (\$26/ft ³)
Sludge and Biomass Digester	\$175/m ³ (\$5/ft ³)
NFT - channels & greenhouse and access areas and turf system.	\$37.66/m ² (\$3.5/ft ²) (including land costs @ \$1000 per ac)
Operation and Maintenance	Similar to primary treatment facility with additional plant management tasks.
Energy Consumption	Similar to primary facility modified by estimates of pumping needs.
Energy Production	Biogas valued at \$5 per million Btu's.
Turf Production Sludge Management	\$30 per m ²

Note: All capital costs and O&M costs adjusted to mid 1992 \$ by using ENR estimated Capital Cost Construction Index for June, 1992 of 5,000.

*Typical rigid greenhouse structure costs with plastic lined NFT channels; inflated plastic greenhouse costs are expected to be less. Greenhouse construction costs can range from less than \$10/m² to more than \$1000/m² (Wahba and Kosut 1986, Albright 1992).

indices as estimated from the *Engineering News Record's* values. The effect of size on the economics was determined by using the relationship between contracted cost for sewage treatment plants at one mgd and 0.1 mgd by applying a factor of 0.13 times the cost at one mgd for capital cost estimates at the lower flow rates. This was the actual ratio of construction bids on hundreds of sewage treatment plants at varying sizes as given in the USEPA cost documents. It was assumed that the operation and maintenance costs on a unit basis remain constant. This may not be true; however, a detailed estimate for the increased operation and maintenance costs for lower treatment systems is beyond the scope of this study.

The cost estimates for the secondary-quality resource recovery wastewater treatment system are given in Table 5-5, and tertiary quality in Table 5-6. The capital cost is estimated at \$1.6 and \$6.7 million, respectively, with operations and maintenance costs at 37¢ and 48¢ per thousand gallons treated, respectively. These are relatively low values for modern treatment systems.

In reviewing the cost-effectiveness of the system it is necessary to estimate the total cost of the system including the operations and maintenance cost and the energy requirements of the system. A comprehensive analysis of the total life-time cost would provide the basis for the most cost-effective decision. By estimating the present value cost of the operation and maintenance and adding this to the capital cost this gives an overview of the total cost of the system. In an NFT system, the energy value can be subtracted from this value. For secondary-quality systems the total energy production is relatively insignificant, and so it was assumed to be zero, whereas this could be a significant lifetime revenue in the tertiary treatment systems. Since energy is not available to decrease the smaller unit flow costs, a total present cost of the secondary system is nearly double the capital cost or \$3.2 million. Because of the reduction of cost relating to energy production in the tertiary-quality system, the total 20-year value was \$6.87 million, with a turf operation that consumed the final sludge production.

Costs for conventional alternatives that can be used to compare both secondary and tertiary quality at 0.1 mgd and one mgd are given in Tables 5-7, 5-8, and 5-9. These values are also summarized in Table 5-10 and compared to the resource recovery alternative treatment system. In all cases, the resource recovery

Table 5-5

RESOURCE RECOVERY WASTEWATER TREATMENT SYSTEM SIZE AND COST
ESTIMATE SUMMARY FOR A DESIGN FLOW OF ONE MILLION GALLONS
PER DAY AND SECONDARY QUALITY EFFLUENT (LESS THAN 30 MG/L SS
AND 30 MG/LBOD₅). OPERATION AND MAINTENANCE COSTS IN ¢ PER
1,000 GALLONS TREATED AND CAPITAL IN MILLIONS OF \$1992

Treatment Process	Size	O&M	Capital Costs
1. Preliminary treatment	(common to all)	5	0.102
2. Primary Sedimentation	(common to all)	11	0.36
3. Anaerobic AFEB	2375 m ³	11	0.417
4. NFT - First Stage	12,300 m ² +	5	0.508
	access area of 1200 m ² , total area 13,500 m ²		
5. Sludge Assimilation with			
a. NFT - Off Line	5500 m ²	2	0.207
b. (Alternative Turf Area)	(2100 m ²)	(2)	(0.063)
6. Anaerobic Digester	293 m ³	3	<u>0.051</u>
7. Cost Subtotals			
a. With Off-Line NFT		37	1.645
b. With Alternative Turf Area		37	1.489
8. Life Cycle Cost Analysis			
a. With Off-Line NFT Sludge Management			
O&M = \$135,000/yr			
O&M present cost worth = $135,000 \times (11.83)$			
= $\$1.60 \times 10^6$			
Energy Value = insignificant			
Total Life Cycle Cost = $\$1.645 \times 10^6 + 1.60 \times 10^6$			
= $\$3.245 \times 10^6$			
b. With Turf Assimilation of Sludge			
All values same as in "a." except capital			
Total Life Cycle Costs = $1.60 \times 10^6 + 1.489 \times 10^6$			
= $\$3.1 \times 10^6$			

Note: Present cost worth assumptions were:

20-year life, interest rate of 5.6%.

Present worth factor (PWF) of 11.83.

Land costs included at \$1000 per acre.

Table 5-6

RESOURCE RECOVERY WASTEWATER TREATMENT SYSTEM SIZE AND COST
ESTIMATE SUMMARY FOR Q=1 MGD AND TERTIARY QUALITY EFFLUENT.
VALUES IN 1992 \$. O&M IN ¢/1000 GAL TREATED, CAPITAL IN MILLION \$

Treatment Process	Size	O&M	Capital Costs
1. Preliminary treatment	(common to all)	5	0.102
2. Primary Sedimentation	(common to all)	11	0.360
3. Anaerobic AFEB	2375 m ³	11	0.417
4. NFT - First Stage	12,300 m ² + access area of 1200 m ² , total area 13,500 m ²	5	0.508
5. NFT - Second Stage	81,000 m ² + access area of 8000 m ² total of 89,000 m ²	11	3.350
6. Sludge Assimilation with			
a. NFT - Off Line	42,000 m ²	5	1.580
b. (Turf Area)	(8450 m ²)	(2)	(0.250)
6. Anaerobic Digester	2250 m ³	3	<u>0.394</u>
7. Cost Subtotals			
a. With Off-Line NFT		51	6.711
b. With Alternative Turf Area		48	5.381
8. Life Cycle Cost Analysis			
a. With Off-Line NFT Sludge Management			
O&M cost = \$186,000/yr			
O&M present cost worth = $186,000 \times (11.83) = \2.2×10^6			
Energy value = $\$73,000 \times (11.83) = \0.86×10^6 (credit)			
Total life cycle cost = $\$8.05 \times 10^6$			
b. With Turf Assimilation of Sludge			
O & M cost = \$175,000/yr			
O & M present cost worth = $175,000 \times (11.83) = \2.07×10^6			
Energy value = $\$73,000 \times (11.83) = \0.86×10^6 (credit)			
Total life cycle cost = $\$5.381 \times 10^6 + 2.07 \times 10^6 - 0.86 \times 10^6 = \6.59×10^6			
c. NFT Plant Nursery By-Products. Using half the NFT area for production with gross annual income equal to \$10/m ² per year. Value = $81,000 \text{ m}^2 / 2 (\$10) = \$405,000$ per year. Present Value Plant By-Products = \$4,790,000. Total Life Cycle Costs = \$1,800,000 to \$3,260,000.			

Note: Present cost worth assumptions were:
20-year life, interest rate of 5.6%.
Present worth factor (PWF) of 11.83.
Land costs included at \$1,000 per acre.

Table 5-7

SUMMARY CONVENTIONAL PROCESSES REQUIRED TO ACHIEVE EQUIVALENT
EFFLUENT QUALITY TO A SECONDARY QUALITY RESOURCE RECOVERY
WASTEWATER TREATMENT SYSTEM AND ESTIMATED COSTS. Q = 1 MGD

Unit Process	Feb. 1973 costs cents/10 ³ gal treatment			Capital Costs (\$)	Annual O&M (\$)
	Cap.	O&M	Total		
1. Preliminary Treatment	0.9	1.8	2.7	36,660	6570
2. Primary Sedimentation	3.2	3.8	7.0	130,000	13,870
3. Activated Sludge	8.4	9.5	17.9	341,000	34,675
4. Anaerobic Digestion	1.3	2.8	4.1	56,100	10,200
5. Dewatering	3.5	5.4	8.9	151,100	19,700
6. Disinfection	<u>1.3</u>	<u>1.7</u>	<u>3.0</u>	<u>53,800</u>	<u>6,200</u>
7. Total costs without sludge disposal.					
Σ 1973 \$	18.6	25	43.6	768,660	91,200
1992 \$	51.7	69.5	121	2,140,000	254,000
8. Total costs including turf farm for Ultimate Sludge Disposal	--	71.5	123	2,203,000	261,000
O&M cost = \$261,000/yr					
O&M present cost worth = \$261,000 (11.83) = \$3.088 x 10 ⁶					
Energy value (insignificant)					
Total life cycle cost = \$5.145 x 10 ⁶ w/o sludge disposal, \$5.29x10 ⁶ with ultimate sludge disposal.					

Table 5-8

SUMMARY CONVENTIONAL PROCESSES REQUIRED TO ACHIEVE EQUIVALENT
EFFLUENT QUALITY TO A TERTIARY QUALITY RESOURCE RECOVERY
WASTEWATER TREATMENT SYSTEM AND ESTIMATED COSTS IN 1973 \$.
Q = 1 MGD.

Unit Process	Feb. 1973 costs cents/10 ³ gal treatment			Capital Costs (\$)	Annual O&M (\$)
	Cap.	O&M	Total		
1. Preliminary treatment	0.9	1.8	2.7	36,660	6,570
2. Primary sedimentation	3.2	3.8	7.0	130,000	13,870
3. Activated sludge-high rate (C-6)	8.4	9.5	17.9	341,000	34,675
4. Biological nitrifica- tion (G-1)	4.8	6.2	11.0	195,000	22,630
5. Biological denitrifica- tion (H)	4.2	5.5	9.7	171,000	20,075
6. Two-stage tertiary lime treatment (F-2)	4.8	6.2	11.0	195,000	22,630
7. Filtration (D)	5.5	5.5	11.0	223,000	20,075
8. Disinfection	1.3	1.7	3.0	53,800	6,205
9. Anaerobic Digestion (L2)	1.7	3.9	5.6	69,000	14,235
10. Dewatering (O6)	2.7	3.7	6.4	109,700	13,505
11. Incineration (P1)	3.0	8.0	11.0	122,000	29,200
12. Construction Related Costs	--	--	--	620,000	---
Σ	40.5	55.8	96.3	2,266,000	203,670
Total costs 1992					
Capital = \$6,300,000					
Present Worth O&M = \$6,697,000					
Total Life Cycle Cost = \$13,000,000 (\$1992)					

Table 5-9

SUMMARY OF ESTIMATED COSTS OF CONVENTIONAL PROCESS TO ACHIEVE VARYING LEVELS OF WASTEWATER TREATMENT IN 1992 DOLLARS FOR FLOWS OF ONE MGD AND 0.1 MGD. CAPITAL COSTS AND TOTAL PRESENT WORTH COSTS IN MILLION, OPERATION AND MAINTENANCE (O&M) IN ¢/1000 GAL. TREATED.

	Design Flow = 0.1 MGD	Design Flow = 1.0 MGD
I. Secondary Treatment		
Cap.	0.292	2.20
O&M	71.5	71.5
Total Present Worth Cost	0.600	5.29
II. Tertiary Treatment		
Cap.	0.838	6.30
O&M	155	155
Total Present Worth Cost	1.507	13.0

* Engineering News Record Construction Cost Index used to project costs from 1973 to 1992 using a factor of 2.78. Lower flow costs estimated using scale factor from 1.0 MGD to 0.1 MGD of 0.133.

Table 5-10

COMPARISON OF ESTIMATED COSTS FOR CONVENTIONAL TREATMENT TO
BIOLOGICAL-BASED RESOURCE RECOVERY WASTEWATER TREATMENT.

	COSTS		Lifetime Present
	Capital	O&M	Worth Cap. + O&M
I. Secondary Treatment			
A) Design Flow 0.1 MGD			
1) Conventional			
Alternatives	0.289	71.5	0.597
2) Resource Recovery Alt.	0.20-0.22	37	0.359-0.379
B) Design Flow 1.0 MGD			
1) Conventional			
Alternatives	2.2	71.5	5.29
2) Resource Recovery Alt.	1.49-1.64	37	3.08-3.23
II. Tertiary Quality Effluent			
A) Design Flow 0.1 MGD			
1) Conventional			
Alternatives	0.834	155	1.503
2) Resource Recovery Alt.	0.701-0.89	48-51	0.91-1.11
B) Design Flow 1.0 MGD			
1) Conventional			
Alternative	6.30	156	13.0
2) Resource Recovery Alt.	5.38-6.71	48-51	6.59-8.05
3) Resource Recovery with Sale of Plant By-Products	" " "	" "	1.80-3.26

Note: Values in 1992 dollars, capital and present worth costs in millions, operational and maintenance in cents per 1,000 gallons treated.

alternative has a lower capital cost of less than one-half the cost for the smaller flows for the secondary-quality effluent requirement. Because of the larger capital costs associated with the greenhouse in a large-size NFT system required for tertiary quality, the resource recovery alternative has a capital cost of ten percent to 20 percent less than the conventional alternative. However, because of the substantially lower operating cost, the total present worth cost of the system is about one-half of the conventional alternatives. This could result in resource recovery wastewater treatment systems with life cycle costs between one-quarter and one-third the costs of conventional alternatives. In addition, the sale of plants from the NFT system could easily generate revenue equal to operation and maintenance costs. Thus, the cost-effectiveness of the demonstrated system is obvious.

Section 6

DISCUSSION

The proposed wastewater treatment system has been referred to as a resource recovery wastewater treatment system to minimize the energy requirements and capital costs of the unit processes while maximizing the effluent quality and the value of other by-products. Additional processes may eliminate the ultimate disposal of sludge off-site.

The total proposed system was intended to convert all pollutants into environmentally neutral or useful materials at a cost advantage compared to other conventional unit processes. This is the first scale-up of an AAFEB and the NFT applied to a dilute sewage. The demonstration in a cold climate indicates that it may have potential for many areas.

This report covers the last nine months in an approximate 40-month test program. For review of earlier data, see Jewell et al, 1991. It should be noted that although this is the last period of the operation of the system, parts of the system were not operating optimally. Approximately 25 percent of the hydroponic system was destroyed by animal predation in the Fall of 1989, making this an immature plant system during 1991.

OVERALL TREATMENT SYSTEM RESULTS

Wastewater used was a dilute domestic sewage from an old collection system with significant inflow and infiltration problems and long residence times. This resulted in sulfide production, through biological sulfate reduction in the sewer, high total COD compared to the influent BOD (approximately 300 to 90 mg/l, respectively), and a relatively low nutrient concentration (influent of 25 mg/l of TKN and 3 to 5 mg/l of phosphorus). This also resulted in large temperature swings to this treatment system with daily averages varying between nine and 23°C during this nine-month period. Diurnal fluctuations were also observed but were usually less than several degrees Centigrade.

Perhaps the most difficult problem was the intermittent presence of chemical toxics. After a fish kill occurred at the effluent from the municipal treatment system, several batch analyses of wastewater showed the presence of significant concentrations of chloroform and trichloroethylene in the influent wastewater. Because of the hydraulics of the headworks and the location of the pilot system piping, the pilot also received doses of sludge whenever septage or landfill leachate was dumped into the headworks of the Ithaca wastewater treatment facility. Thus, accumulation of sludge in the first expanded bed to a sludge volume equal to half the bed volume in a period of twelve hours was not an unusual occurrence. This was considered a real-world problem. Though it complicated the interpretation of the pilot system performance, no effort was made to exclude these occurrences from data interpretation.

The proposed system operated exceptionally well throughout all test conditions and produced superior effluent quality compared to conventional unit process. The high quality of the effluent was apparent throughout all loading rates, having a low turbidity indicating low suspended solids. Effluent suspended solids and BOD were often less than five mg/l and under low hydraulic loadings, the nutrient concentrations were also decreased to values as low as zero for orthophosphorus and five mg/l for ammonia nitrogen. Because of the nutrient ratios and the low phosphorus concentrations, it appeared that the plant removals of nutrient were limited by phosphorus. When orthophosphorus approached zero, the ammonia concentrations were still immeasurable under some circumstances. Additional low loading conditions for nutrient removal of NFT are provided in the Disney/GRI/NYSERDA report (Jewell, et al., 1991).

The major difference between this treatment system and conventional unit processes is the extensive use of plants to purify the wastewater. Throughout this study it should be emphasized that no pesticides were used to control pests in the plant system. Instead, the introduction of various predators was provided by a private consultant, an apparently low-cost and effective way to control plant problems in this enriched biological environment.

It should be emphasized that the maximum economic value of this treatment system was not demonstrated, since a revenue beyond the energy value of the plants was not considered. It is obvious that other ornamental and useful plants could be grown in these wastewater treatment systems and provide substantial revenue.

AAFEB POLLUTANT REMOVAL CHARACTERISTICS

The combination of low temperature, dilute wastewater, substantial sulfates, and large quantities of sludge all present difficult problems for anaerobic-attached film processes. It was surprising to note the high efficiency of the two-stage anaerobic system, even with the accumulation of sludge that was allowed in the first stage. BOD conversion efficiency exceeded 70 percent under most circumstances. With effluent volatile fatty acids (VFA) often less than 10 mg/l, and at the lower loading conditions and higher temperatures less than five mg/l of VFA, the total COD was often significantly greater than the VFAs. This was a reflection of other oxygen-demanding substances that could not be affected or would be created by an anaerobic process such as dissolved sulfide and methane generation.

The influent sulfate sulfur concentrations of approximately 15 mg/l as sulfur were rapidly reduced in the first-stage anaerobic system and remained at approximately the same concentrations in the second stage reactor. Surprisingly, sulfate reduction was not 100 percent in the two-stage AAFEB reactor system with approximately two to three mg/l sulfate-sulfur remaining in the effluent from the systems. Since the sulfides have an immediate oxygen demand of approximately twice their concentration, it was essential that these be efficiently removed before discharge. Sulfides were always converted to sulfate and/or used by the plant materials so that a large portion of the sulfur coming into the system was removed at low loading conditions. In nearly all conditions greater than 50 percent total sulfur removal occurred, with all of the sulfur in the effluent in the re-oxydized sulfate form. Thus, the total system managed a sulfur problem without

adverse effects. No sulfur odors were observed in the NFT system. The limits to the sulfate reduction and the impact on the plant systems were not pursued in this study and would have to be examined carefully in waste with higher sulfate or sulfide concentrations.

In comparing the hydraulic retention times required to achieve efficient organic conversion, it appeared that the pilot system required longer residence times than has been demonstrated with substrates like sucrose under comparable conditions. It is unclear whether this is an effect of temperature, substrate characteristics, or other waste characteristics. However, since the efficiency of conversion was high and the volatile fatty acids remaining in the second-stage effluent were low, this is not a significant limitation.

Another observation that relates to the possible uses for the AAFEB relates to acid formation rates in the first stage. Under all conditions the first-stage AAFEB converted a large fraction of the organic matter into acetic acid. Thus, at a temperature of 9°C and a retention time as short as one hour, almost all of the organic matter was efficiently converted into fatty acids. This characteristic may be useful in other waste applications since the use or recovery of VFAs may be an option in downstream processes.

In proposing the pilot systems, it was suggested that it was not necessary to remove primary sludge and that the first-stage expanded bed could be used to provide partial treatment. Estimates for sludge production indicate that the total sludge produced by the facility is approximately equivalent to the stabilized sludge that would be produced from a primary treatment

plant. The settled sludge had a high ash content and was approximately equivalent to 800 to 1,300 gallons per MGD treated. This contained between 400 and 600 pounds of total solids per million gallons of wastewater treated. This sludge also settled rapidly to a concentration greater than six percent dry matter. Thus, every indication was that this sludge was acting like a partially stabilized primary settled sludge.

During the latter phases of this study, continuous management and analysis of the sludge beds was made to determine the rate of change of the bacterial system and the requirements for make-up of inert media. The high ash content of the sludge could have reflected the loss of media. However, during this nine month phase, there was little indication that the bed inert media were being lost. Thus, the turnover rates of the bed were lower than could be detected. No media was replaced during this last phase. In addition, it should be emphasized that throughout the study, all the sludge management occurred in the first-stage system and no sludge accumulated in the second stage. Thus, this supports the concept of accumulation of sludge blanket on top of the first-stage expanded bed to manage sludge.

Control of suspended solids in the effluents from anaerobic expanded beds are highly significant. The effluent suspended solids from an anaerobic process are black and small, and are therefore difficult to settle in a sedimentation process. An effluent from an anaerobic system containing 30 mg/l has a much poorer quality appearance than an activated sludge 30 mg/l because of color and size of the particles. For this reason, comprehensive settling tests were conducted at different temperatures to define the upper limits to suspended solids

removal by settling with this material. Studies indicated that effluent suspended solids of approximately 30 mg/l were fairly easy to achieve at the hydraulic retention times tested with the expanded beds during the higher temperature conditions, but were more difficult to achieve at lower temperatures. The resulting higher viscosity at the low temperatures (0°C) indicated that achieving less than 30 mg/l of suspended solids is difficult at sedimentation times less than six hours.

HYDROPONIC-NFT TREATMENT

Varying loading rates on the hydroponic NFT treatment system were examined by diverting part of the anaerobically treated effluent around portions of the hydroponic system. Long-term loading rates varying from 3.8 to 15 s/d were examined. By dividing the hydroponic process into different sections, it was possible to examine hydraulic loadings varying from four to 76 cm/d. This analytical approach led to development of the relationship between efficiency of pollutant removal and hydraulic loading rates.

Because of the high sulfide, dissolved methane, and volatile fatty acid concentrations, the total COD loadings were significant, especially in the first portion of the NFT. Substantial populations of sulfide oxidizers formed a white film on the root mass in the first sections. Influent total CODs of 90 to 140 mg/l were almost always reduced to less than 40 mg/l by the hydroponic system. The total COD removal efficiency was greater than 70 percent much of the time. This was true up to a total COD loading rate of 400 kg/hectare/d.

Because the vertical and horizontal velocities are so slow in the NFT process, it was anticipated that efficient suspended solids management would be easily achieved. The high clarity of the effluents indicated low suspended solids for all test conditions. This reflects that there was probably an exceptionally high population of filtering microorganisms, such as protozoa, to maintain suspended solids at low concentrations. Although the influent suspended solids was relatively low (28 to 48 mg/l) the effluent quality was always high (less than 10 mg/l with all runs, and less than five mg/l for most). At the highest loading rate of 40 cm/d, the effluent suspended solids was six mg/l. For most of the test conditions, the clarity of the water was exceptionally high indicating that the bacterial solids were low. In future testing, it would be useful to do turbidity examinations, since the suspended solids appeared to be plant debris and existed as large particles that would be easily removed.

NUTRIENT REMOVALS IN THE NFT SYSTEM

Plant removal of nitrogen and phosphorus and other dissolved nutrients is a relatively slow process. As such, the plant system requires a large surface area, especially with slowly growing plants or under cold temperatures. It was anticipated that the hydroponic system would have limited potential for nutrient removals at most of the loadings tested in this nine-month program. It also was felt that the use of the plant systems in the wintertime would have limited potential for nutrient removal. According to the data, it is not necessarily true.

At loading rates above 10 cm/d, the removal efficiencies of the nutrients were low, but the removal rates were substantially

increased, especially for nitrogen. This indicated that the reaction rates were possibly nutrient-limited for much of the low-loading conditions. To investigate the concentration effects on nutrient uptake, batch tests were run several times throughout the year that can be contrasted to the continuous flowing nutrient removal rates.

Perhaps most surprising was the significant and efficient nutrient removals during wintertime. Since the temperature of the water fluctuated with air temperature and was allowed to decrease to 4°C at various times, it was not anticipated that nutrient uptake would be significant for at least two to three months during the winter. The most effective nutrient removals were obtained at low loadings at the lower temperatures. Even though the cattails were in a dormant stage, apparently the growth of the root mass and the microbial decay cycle was operating as efficient nutrient removal mechanisms. Continuous flow removal rates for nitrogen ranged from 0.14 to 1.05 grams of ammonia nitrogen per square meter per day, and the phosphorus removal rates ranged from 0.05 to 0.22 g/m²-d. Batch uptake of nitrogen was as high as three grams of total nitrogen (ammonia and nitrates) per square meter per day. Phosphorus removal rates under batch conditions were five to ten times greater than the phosphorus removal rates in the continuous flow task.

The relationship between the nutrient concentrations and removal rate dictated the surface area requirements for efficient nutrient removal. At the highly efficient removal rates achieved at low nutrient concentrations, it would appear that design wastewater loadings between four and seven cm/d would result in removal of most of the nutrients from domestic sewage.

In addition to the relationship between nutrient uptake and efficiency and the area requirements as described above, there are numerous ways that nutrient removals can be affected. Nitrogen removal rates as high as 10 g/m²-d can be achieved by encouraging the nitrification/denitrification cycle in the system.

BIOMASS YIELDS IN AN NFT SYSTEM

The NFT system performed exceptionally well under a wide range of loading conditions and root characteristics. At the front end of the system, a substantial quantity of sludge accumulated over the root mass and wastewater flowed mainly over this material. At lower flows, the wastewater would migrate into the root mass and have a relatively low amount of flow over the roots. The tracer studies conducted with lithium chloride indicated that at the higher flow rates a substantial short-circuiting occurred in the system with overland flow; at the lower flow rates the hydraulic retention times approached the theoretical retention time with the volume of the water in the system.

Stalk densities for the *Typha sp.* varied from 24 to 151 stalks per square meter. The resulting stalk density would depend on the rate and method of harvesting. Frequent harvesting appeared to decrease the stalk density. Earlier in the program, more frequent harvesting increased the stalk density in some cases. The stage of growth of the plant and other seasonal conditions may affect the impact of the harvesting on stalk density.

The total volume of the root mass measured approximately 71 liters per square meter. Thus, with a void space in the root zone of

approximately 50 percent, the total depth of the root mass averaged about 14 cm.

The harvested biomass was characterized for digestibility and elemental composition. The material had relatively high ash content, but not significantly different from cattails harvested from the field. Total nitrogen content, however, was double to triple the field concentration with the protein content being as high as 15 to 16 percent of the dry weight, compared to about six percent in the field. Total digestible dry matter of material was estimated to be 63 percent of the volatile solids. The phosphorus content was six times as high as the original cattail material. This may reflect the large quantity of bacterial phosphorus that was entrapped in the root mass. Sulfur content was 0.7 percent, compared to 0.1 percent of the dry weight of the field material.

None of the heavy metal concentrations accumulated to concentrations that affected use of this material in other applications, such as animal food, humus, or digestion. However, there were substantial increases in several metal components. The absence of an increase of cadmium indicated that cadmium was either exceptionally low in the Ithaca wastewater or that anaerobic treatment entrapped the metal prior to the nutrient film system. Zinc increased by a factor of 10, but was still substantially less than the concentrations often found in other organic materials, averaging 263 ppm of the dry plant matter. Copper increased by a large factor in the total plant, and was concentrated in rhizomes, probably in the bacterial mass. Lead concentration increased from one ppm to an average of five ppm in the plant matter.

FECAL COLIFORM REDUCTIONS IN THE HYDROPONIC SYSTEM

Using chlorine for disinfection in wastewater treatment systems is expensive and generates toxic by-products. It was hoped that the hydroponic system would minimize the need for chemical disinfection. Testing over the last nine months for fecal coliform showed there was a significant relationship between flow rates and coliform reduction with low-loading rate conditions resulting in fecal coliforms that approached zero and were less than that required in disinfected secondary effluent. Thus, the data suggests that the system can meet regulatory requirements without chemical disinfection. Additional testing in this area needs to be done to confirm this important operating characteristic.

It should be noted that the hydroponic system requires careful monitoring of numerous pests that prey on the plants. In early testing, these pests were a significant problem; however, throughout the test program, no pesticides were used and when outbreaks of organisms occurred, they were controlled by introducing predators using standard integrated pest management procedures. It was estimated that the annual cost for controlling pests in the nutrient film treatment would be less than \$1,000 per acre per year.

RESOURCE RECOVERY SYSTEM ENERGY REQUIREMENTS

In order to obtain an estimate for energy requirements for a treatment system, both electrical and heat energy were monitored throughout the study. It should be emphasized that the system was non-optimum in terms of energy used because of the small and variable size and the oversized design of some of the pumps and

heat systems. A number of the pumps were significantly oversized, but operated continuously in a throttled-down position. Thus, all estimates of energy requirements should be considered to be conservative.

The maximum total electrical energy required for the system was 64 kw-hours per day. This is equivalent to approximately \$0.08 per cubic meter treated (\$0.30 per 1,000 gallons treated) at \$0.05 per kw-hr. Total fuel used to maintain the temperature at acceptable conditions was estimated to be less than eight liters of fuel oil per square meter of treatment surface per year. It is likely that this would be at least double what the full scale treatment system would be because of the large surface area that was not devoted to treatment as well as non-optimum types of structures that were utilized. For higher loading rate systems with smaller greenhouses, that would be utilizing secondary treatment systems, this would result in a heating cost of \$0.07/1,000 gallons treated. Because of the much larger greenhouse area for the tertiary quality effluent, this would amount to a heating cost of as high as \$0.48/1,000 gallons treated.

It is felt that the use of large greenhouses in cold climate areas would be adapted to drastically reduce this cost, if not eliminate it. The most obvious means of reducing the heating costs would be to utilize the existing heat in the wastewater by accumulating the wastewater or using deeper flooding depth, especially overnight. A substantial amount of heat, available in the wastewater, could be used to maintain minimal greenhouse temperatures and protect the plants from freezing.

ECONOMICS OF THE RESOURCE RECOVERY WASTEWATER TREATMENT ALTERNATIVE

In order to provide an economic basis for evaluating the resource recovery treatment alternative, the systems were designed for two different flow rates and two different levels of treatment - 0.1 and one million gallons per day, and secondary and tertiary quality effluent. The secondary quality effluent was assumed to produce an effluent of 30 mg/l of BOD and suspended solids, and the tertiary quality effluent was assumed to be less than five mg/l BOD and suspended solids and one mg/l of ammonia nitrogen and orthophosphorus.

A summary of the results of this analysis is given in Table 6-1. This shows that the resource recovery alternative has a substantial cost effective benefit over the conventional treatment systems that were estimated. Although the capital cost for the tertiary quality system do not have a 2:1 advantage over the conventional secondary systems, it is much more cost effective in lifetime analysis primarily because of lower operating costs and the energy benefits that could be derived from the digestion of the plants. A total energy value of \$73,000 per year per MGD treated was assumed for the tertiary treatment system.

It should be noted that one of the main advantages of the NFT system, the production of valuable terrestrial plants, is ignored in this economic analysis. It is anticipated that a wide range of products will be produced in this system when it is implemented. The use of approximately the last third of the treatment system as a nursery or as a plant propagation unit was proposed in earlier work. If typical returns for nursery stock or other products were

to be realized, the net cost of the treatment system could be substantially reduced from costs indicated here.

Table 6-1

COMPARISON OF COSTS OF RESOURCE RECOVERY WASTEWATER TREATMENT SYSTEMS TO CONVENTIONAL SYSTEMS FOR A DESIGN FLOW OF ONE MILLION GALLONS PER DAY. CAPITAL IN 1991 MILLION \$, OPERATION AND MAINTENANCE IN 1992 ¢ PER THOUSAND GALLONS TREATED, ENERGY VALUE IN ¢ PER THOUSAND GALLONS TREATED, AND PRESENT VALUE IS THE 20-YEAR TOTAL COST CAPITAL, O&M, AND ENERGY REVENUE

	Capital	O&M	Energy	Total Present Value Cost
I. Secondary Quality Effluent				
A. Conventional	2.20	71.5	0	5.29
B. Resource Recovery	1.49	37	0	3.08
II. Tertiary Quality Effluent				
A. Conventional	6.30	156	0	13.0
B. Resource Recovery	5.38	48	20	7.45
C. Resource Recovery with Plant Sales*	5.38	48	20	1.80

*Present worth of plant by-product sales estimated at \$4.79 million.

Section 7

SUMMARY AND CONCLUSIONS

GENERAL CONSIDERATIONS

This study summarizes the last nine months of a three-year documentation at pilot scale of two new wastewater treatment technologies - anaerobic-attached film treatment followed by hydroponic treatment using NFT. This study used raw sewage fed to the reactors under ambient temperature conditions in northern New York State. Thus the impact of cold weather on treatment characteristics of this biological treatment system are of interest.

The wastewater was characteristic of a dilute domestic sewage that results from an older collection system that receives significant infiltration. A total of six operating conditions were examined during this period with two main conditions operating as far as flow is concerned. Different loading rates were extracted from the system by dividing the units in different sections and taking samples at various intermediate points. The influent temperature of the wastewater varied from a low of 9°C to 23°C and total flows tested varied from 7.5 to 38 cubic meters per day (s/d). The hydraulic retention times of the attached film expanded beds varied from less than two hours to 12.5 hours.

The most outstanding characteristic of the system was the high clarity of effluent under all test conditions. Effluent BOD and suspended solids were often less than five mg/l. Even at high

loading rates, these values for these parameters seldom increased above 15 mg/l.

The combined anaerobic/hydroponic treatment also substantially reduced the total chemical oxygen demand. The total chemical oxygen demand was greater than 250 mg/l. This was reduced to less than 30 mg/l under many conditions; thus indicating that the refractory portions of the organic matter, as well as sulfides and other products were reduced or eliminated in the system.

POLLUTANT REMOVALS WITH AN ANAEROBIC ATTACHED FILM PROCESS - AAFEB

This is one of the first studies of an AAFEB applied to an ambient temperature dilute sewage application. The combined treatment using hydroponic polishing of the anaerobic effluent was proposed because it was necessary to provide re-oxygenation of an anaerobic effluent and suspended solids polishing on a continuing basis.

Early in the operation of this pilot system, it was clear that a combination of real-world problems would have a negative impact on the anaerobic treatment system. Toxic organics, such as chloroform, were observed in several instances and dumping septage and other sludges into the headworks produced in rapid accumulation of this sludge in the pilot system. To minimize detrimental problems to the pilot system, a two-stage unit was used with the first stage being somewhat larger than the second stage. The first stage was also proposed to be capable of receiving large quantities of sludge and acting as a preliminary stabilization system for the sludge. This would minimize the need for further stabilization of sludge and protect downstream systems.

The first-stage system did accumulate sludge and acted throughout the study mainly as an acidification unit. At all times it seemed to function well in this manner. No sludge accumulated in the second stage AAFEB.

Total effluent BOD from the two-stage system varied between 18 and 40 mg/l for the bulk of the study, with a soluble BOD ranging from five to 30 mg/l.

The volatile fatty acids concentration ranged from 4.5 to 21 mg/l, during this study and represented the bulk of the organic BOD in the effluent. The remaining total BOD was comprised mainly of sulfide and methane. At all times the sulfide concentration in the effluent for both the first and second stage anaerobic expanded beds averaged approximately 13 mg/l as sulfur. When the sulfide oxygen demand is deducted from the effluent BOD, it can be seen that the resultant BOD removal efficiency exceeded 70 percent of the total BOD for most runs, even during the low temperatures.

The influent total suspended solids fluctuated widely, but averaged between 50 and 90 mg/l for this dilute domestic sewage. The effluent suspended solids was almost always less than 30 mg/l and only exceeded 30 mg/l during two cold temperature runs.

To determine the effects of temperature on the fine anaerobic suspended solids and their capability to settle, comprehensive sedimentation tests were conducted. These studies confirmed that the anaerobic effluents would be difficult to clarify at relatively long hydraulic retention times to less than 25 mg/l at temperatures of 10°C. At higher temperatures, the effluent

suspended solids would be expected to be less than 20 mg/l at relatively long hydraulic retention times. Since a separate clarifier is unnecessary and can be incorporated into the top of the expanded bed, the longer settling times are not a problem.

SLUDGE ACCUMULATION IN THE EXPANDED BEDS AND FEED-BED INERT SOLIDS

Sludge was allowed to accumulate to a depth between 0.1 and 0.5 meters on the top of the first expanded bed. Depending on the flow rates, the accumulation period would range from one day to one month. The average accumulation of sludge was equivalent to 1.0 to 79.2 liters per cubic meter of wastewater treated. The average solids of this sludge would be approximately 6 percent after settling for less than two hours, and the volatile solids fraction would be less than 50 percent. Thus, the sludge that was generated in the system appeared to be partially stabilized. The volume represented a quantity similar to that produced from a primary plant after anaerobic digestion.

NFT System Characteristics

Flows taken from the anaerobic system through the hydroponic system varied between 3.8 and 15 s/d. The equivalent hydraulic loading on the NFT units vary from 3.7 cm/d to 40.3 cm/d.

The cattails performed in an outstanding manner in receiving heavy loads of sulfides, BOD, and suspended solids from the anaerobic treatment system. The effluent always had a highly clarified appearance with a sparkling quality, indicating low bacterial concentrations in the effluents.

NFT-BOD Removal Characteristics

At the highest hydraulic loading rate of 40 cm/d, the effluent BOD averaged 10 mg/l with an influent of 24 mg/l. At lower hydraulic loadings, the effluent BOD was almost always between 3 and 6 mg/l total BOD with influents varying between 30 and 44 mg/l. Essentially, all data showed that the total BOD in the NFT effluent was less than about 15 mg/l.

The fact that the soluble sulfides and other gases caused minimal problems and were efficiently removed is indicated by a large reduction of total COD in the NFT system. Influent total CODs of 90 to 145 mg/l were common and these were always reduced to less than 40 mg/l with the bulk of the COD as stabilized plant matter or bacterial cells. The total COD removal efficiency throughout the NFT was greater than 70 percent, even at loading rates as high as 400 kg of COD per hectare per day.

Suspended Solids Removal Characteristics

As was expected, the system was particularly effective in removing suspended solids. Influent concentrations throughout the study varied between 28 and 48 mg/l, with the effluent less than 10 mg/l for all samples and less than five mg/l for most of the time. At the maximum hydraulic loading rate of 40 cm/d, the effluent suspended solids were six mg/l.

NFT-Nutrient Removals

Nutrient concentration reduction at hydraulic loading rates above 10 cm/d was relatively insignificant although the mass of nutrients removed was substantial. At hydraulic loading rates

below this level, the nutrient removals began to be effective. Since the ratio of N:P in the system was relatively low, it appeared that the phosphorus was limiting at low loading conditions. Thus, the removal of ammonia was incomplete. At hydraulic loadings of three to five cm/d orthophosphorus decreased to zero, whereas the effluent ammonia concentrations remained at approximately five mg/l.

The batch rate testing indicated that the plants were capable of removing nutrients at much higher uptake rates than those rates observed under continuous operation.

Nutrient removals were as efficient in the winter at 10°C as during the summer, even though the cattails appeared dormant. Apparently large quantities of root mass growth and plant decay resulted in net nutrient removals in the winter.

Winter and summer nitrogen removal rates averaged 0.5 and 1.0 gm/m²/d, respectively. Phosphorus uptake rates ranged from 0.05 to 0.22 gm P/m²-d. Batch nutrient tests showed much higher nutrient uptake rates.

NFT-Biomass Characteristics

The volume of the root mass in the NFT averaged approximately 71 liters per square meter of root surface. The stalk density of cattails and other invading plants ranged from 24 to greater than 150 stems per square meter. Examination of the harvesting technique indicated that intermittent harvesting did not provide significant benefits over once-a-year harvesting.

The harvested stalk contained approximately 19 metric tons per hectare per year of biomass under maximum production conditions. Dry mass of the roots that were not harvested equalled approximately 50 metric tons per hectare. Rotating harvesting of the complete plant material should enable the total biomass production to significantly exceed 20 metric tons per hectare per year in the systems.

EFFLUENT QUALITY AND DISINFECTION

The proposed hydroponic system was theoretically capable of achieving bacterial quality that would exceed secondary standards without using chemical disinfection. At low loadings (5.3 s/d), fecal coliform were reduced from over 200,000 colonies per 100 mls to between one and 20 colonies per 100 mls, thus indicating that in the wintertime, as well as the summer, chemical disinfection with these systems may not be required for low-loading designs.

ENERGY REQUIREMENTS FOR RESOURCE RECOVERY WASTEWATER TREATMENT

It is highly conservative to extrapolate the energy use of the system to a full-scale system because the facility was a test unit. Using this approach, however, produces an estimated electrical energy requirement equivalent to approximately \$0.08 per cubic meter wastewater treated (\$0.30 per 1,000 gallons). Heating requirements for a greenhouse system large enough to achieve secondary effluent would cost approximately \$0.07/1,000 gallons. If the heating requirements were extrapolated to a tertiary-size system, this would increase to a heating requirement of \$0.48/1,000 gallons treated. However, the sensible heat content of domestic sewage could be used to reduce energy requirements.

ECONOMICS OF RESOURCE RECOVERY WASTEWATER TREATMENT

Two levels of effluent quality were examined, secondary (less than 30 mg/l of suspended solids and BOD) and tertiary quality (less than 5 mg/l BOD and suspended solids and one mg/l of orthophosphorus and ammonia nitrogen) at two flows 0.1 and 1.0 million gallons per day. Both operation and maintenance costs were estimated and the lifetime costs were also approximated using present worth analysis.

For secondary quality effluent, the resource recovery wastewater technology had approximately half the cost of conventional alternatives. For tertiary quality, the capital costs were less than a conventional treatment system costs. However, due to the large capital investment in greenhouses, the difference in capital costs was not as large. Due to the value of the energy in the tertiary quality system, and the lower operation and maintenance costs, the present cost analysis indicates that the resource recovery option has a total lifetime cost of a little more than half the cost of conventional alternatives.

In both cases, the plants produced from the hydroponic system may be used in parks and for other purposes. In these cases, the costs of treatment could decrease substantially, making it much more attractive than conventional options.

REFERENCES

- Albright, L.D. 1992. Personal Communication. Dept. Agricultural and Biological Engineering. Cornell University. Ithaca, New York 14853.
- Dames and Moore, Co. 1978. "Construction Costs for Municipal Wastewater Treatment Plants: 1973 - 1977. U.S. Environmental Protection Agency Technical Report Number MCD-37, EPA 430/9-77-013. Washington, D.C. January.
- Henze, M. and P. Harremoës. 1983. "Anaerobic Treatment of Wastewater in Fixed Film Reactors - A Literature Review." pp. 1-102. In: *Anaerobic Treatment of Wastewater in Fixed Film Reactors*. M. Henze, Editor. *Water Science and Technology*, 15 (No. 8/0), London. 389 pp.
- Jewell, W.J. 1980. "Development of the Attached Microbial Film Expanded Bed Process for Aerobic and Anaerobic Waste Treatment." Chapter 15, pp. 251-271. In: *Biological Fluidized Bed Treatment of Water and Wastewater*. P.F. Cooper and B. Atkinson, Editors. Ellis Horwood Limited, Publishers, Chichester, England. 411 pp.
- Jewell, W. J., R.J. Cummings, T. D. Nock, E. E. Hicks, K. P. Thompson, and T. E. White. 1993. "Energy and Biomass Recovery From Wastewater: Piloting Resource Recovery Wastewater Treatment." Gas Research Institute Report: GRI-93/0192.1 and 93/0192.2. Chicago, Illinois. 370 pages.
- Jewell, W.J., J.J. Madras, W.W. Clarkson, H. DeLancey-Pompe and R.M. Kabrick. 1982. "Wastewater Treatment with Plants in Nutrient Films." U.S. DOE and EPA Final Report. Available through NTIS as No. PB83-247494. 311 pp.
- McCarty, P.L. 1985. "Historical Trends in the Treatment of Dilute Wastewaters." In: *Anaerobic Treatment of Sewage: Proceedings of the Seminar/Workshop*. June 27 and 28. M.S. Switzenbaum, Editor. Report No. Env. E. 88-85-5. Department of Civil Engineering, University of Massachusetts, Amherst, MA.
- VanNote, R.H., P.V. Hebert, R.M. Peter, C. Chupek and L. Feldman. 1975. "A Guide to the Selection of Cost-Effective Wastewater Treatment Systems." U.S. Environmental Protection Agency Technical Report Number EPA-430/9-75-002. Office of Water Program Operation. Washington, D.C. 20460. July.
- Wahba, G. G. and G. M. Kosut. 1986. "Infrastructure in a Hurry." *Civil Engineering* (August): pp. 46-48.

APPENDIX A

A DAILY SUMMARY OF THE AAFEB REACTOR SYSTEM PERFORMANCE

Table A.1. A daily summary of operation of the pilot expanded bed system.

Surface area of AAFEB-1 was 1.82 m².Surface area of AAFEB-2 was 1.17 m².

INF			AAFEB-1							AAFEB-2									
DATE	TEMP	pH	RECYCLE		UPFLOW	TEMP	BED	VOL	pH	BED	INF	RECYCLE		UPFLOW	TEMP	BED	VOL	pH	BED
16-Jun-87	(C)		FLOW	FLOW	VEL	(C)	(s)			(hr)	FLOW	FLOW	VEL	(C)	(s)				(hr)
Condition #1																			
01-Jan-90	11	6.6	18.1				10		6.8		18.1				10		6.9		
02-Jan-90	9	6.3	17.9	69.5	2.0	8	2.5	6.6	3.4	17.9	27.8	1.6	11	1.6	6.7	2.08			
03-Jan-90	9	7.3	19.4	68.8	2.0	8	2.7	7.3	3.3	19.4	27.8	1.7	10	1.5	7.4	1.90			
04-Jan-90	10	7.2	19.2	69.1	2.0	8	2.8	7.0	3.5	19.2	28.3	1.7	10	1.1	7.0	1.32			
05-Jan-90	9	7.5	18.2	69.5	2.0	8	2.8	7.4	3.7	18.2			10	1.6	7.5	2.06			
06-Jan-90	10	7.3	20.5	67.1	2.0	9	2.2	7.4	2.6	20.5	28.3	1.7	11	1.6	7.5	1.85			
07-Jan-90	9	7.4	20.6	69.5	2.1	9	2.6	7.4	3.0	20.6	26.5	1.7	11	1.6	7.5	1.81			
08-Jan-90	9	7.3	20.3	66.2	2.0	9	2.9	7.2	3.5	20.3	27.8	1.7	11	1.6	7.3	1.86			
09-Jan-90	9	7.2	20.0	66.2	2.0	8	2.7	7.3	3.2	20.0	28.8	1.7	10	1.6	7.3	1.92			
10-Jan-90	9	7.5	20.6	69.5	2.1	8	2.8	7.4	3.2	20.6	28.4	1.7	10	1.6	7.4	1.87			
11-Jan-90	10	7.3	20.3	69.5	2.1	9	2.7	7.5	3.2	20.3	28.5	1.7	10	1.6	7.5	1.85			
12-Jan-90	10	7.3	20.0	66.5	2.0	9	2.8	7.3	3.3	20.0	28.3	1.7	11	1.6	7.4	1.91			
13-Jan-90	9	7.2	18.6	72.2	2.1	9	2.7	7.4	3.4	18.6	28.1	1.7	11	1.5	7.5	1.87			
14-Jan-90	9	7.3	19.1	72.0	2.1	9	2.7	7.4	3.4	19.1	24.2	1.5	11	1.5	7.5	1.84			
15-Jan-90	10	7.3	19.5	70.5	2.1	8	2.7	7.3	3.3	19.5	21.4	1.5	10	1.6	7.4	1.94			
16-Jan-90	9	7.4	19.2	73.5	2.1	8	2.7	7.4	3.4	19.2	31.3	1.8	10	1.5	7.3	1.91			
17-Jan-90	9	7.6	18.7	70.5	2.0	9	2.8	7.4	3.5	18.7	30.9	1.8	11	1.6	7.4	2.01			
18-Jan-90	10	7.3	20.3	71.6	2.1	9	2.8	7.4	3.4	20.3	27.6	1.7	11	1.5	7.4	1.76			
19-Jan-90	10	7.4	16.7	73.9	2.1	9	2.5	7.5	3.6	16.7	26.9	1.6	10	1.4	7.5	2.01			
20-Jan-90	9	7.4		71.3		9	2.6	7.2			26.5		10	1.5	7.3				
21-Jan-90	10	7.4	20.5	73.1	2.1	10	2.7	7.3	3.1	20.5	27.8	1.7	11	1.6	7.5	1.81			
22-Jan-90	12	7.7	20.5	71.3	2.1	9	2.7	7.6	3.1	20.5	26.6	1.7	10	1.6	7.5	1.86			
23-Jan-90	12	7.6	20.1	69.1	2.0	9	2.7	7.5	3.2	20.1	26.8	1.7	11	1.6	7.5	1.93			
24-Jan-90	10	7.5	19.4	70.2	2.0	8	2.7	7.5	3.3	19.4	25.2	1.6	11	1.6	7.5	1.98			
25-Jan-90	13	7.6	20.6	70.2	2.1	9	2.7	7.5	3.1	20.6	24.2	1.6	11	1.6	7.3	1.88			
Condition #2																			
26-Jan-90	10	7.4	7.7	74.7	1.9	10	2.6	7.1	8.0	7.7	25.2	1.2	12	1.6	7.3	5.06			
27-Jan-90	11	7.4	7.8	74.7	1.9	10	2.5	7.2	7.8	7.8	18.6	0.9	11	1.3	7.2	3.89			
28-Jan-90	11	7.5	6.2	73.1	1.8	9	2.6	7.1	10.0	6.2	19.1	0.9	12	1.4	7.1	5.31			
29-Jan-90	11	7.5	7.3	75.5	1.9	9	2.5	7.0	8.4	7.3	18.9	0.9	11	1.3	7.2	4.20			
30-Jan-90	12	7.3	7.5	71.3	1.8	9	2.6	7.1	8.4	7.5	17.7	0.9	10	1.4	7.1	4.42			
31-Jan-90	12	7.4	7.7	89.1	2.2	9	2.8	7.1	8.8	7.7	18.1	0.9	12	1.3	7.1	3.93			
01-Feb-90	12	7.3	7.5	85.8	2.1	9	2.5	7.3	8.0	7.5	18.6	0.9	12	1.3	7.3	4.15			
02-Feb-90	8	7.3	7.8	88.0	2.2	9	2.7	7.2	8.4	7.8	18.0	0.9	11	1.3	7.4	3.94			
03-Feb-90	11	7.3	7.9	88.0	2.2	8	2.7	7.3	8.2	7.9	16.9	0.9	10	1.2	7.4	3.68			
04-Feb-90	10	7.4	7.7	87.4	2.2	8	2.7	7.3	8.4	7.7	17.2	0.9	10	1.2	7.3	3.81			
05-Feb-90	9	7.2	7.9	87.4	2.2	7	2.7	7.3	8.1	7.9	16.9	0.9	9	1.3	7.4	3.91			
06-Feb-90	11	7.4	7.8	82.7	2.1	8	2.6	7.3	7.8	7.8	16.8	0.9	10	1.3	7.4	3.98			
07-Feb-90	10	7.3	7.6	85.3	2.1	9	2.6	7.3	8.1	7.6	16.9	0.9	11	1.3	7.4	4.12			
08-Feb-90	11	7.3	7.3	84.7	2.1	9	2.6	7.3	8.4	7.3	16.4	0.8	11	1.2	7.3	4.04			
09-Feb-90	11	7.2	6.6	86.3	2.1	10	2.7	7.1	9.6	6.6	17.0	0.8	12	1.2	7.3	4.35			
10-Feb-90	10	7.2	7.1	83.7	2.1	9	2.7	7.2	9.0	7.1	16.4	0.8	10	1.2	7.2	4.08			
11-Feb-90	9	7.3	6.9	84.2	2.1	8	2.6	7.4	9.2	6.9	17.4	0.9	10	1.2	7.4	4.34			
12-Feb-90	12	7.3	7.2	84.2	2.1	8	2.6	7.3	8.6	7.2	16.9	0.9	12	1.2	7.4	4.10			
13-Feb-90	9	7.2	7.6	85.3	2.1	9	2.7	7.1	8.5	7.6	16.7	0.9	11	1.2	7.1	3.71			
14-Feb-90	8	7.2	7.0	86.9	2.1	9	2.7	7.2	9.3	7.0	17.0	0.9	11	1.2	7.3	4.18			
15-Feb-90	11	7.2	8.0	88.0	2.2	9	2.8	7.3	8.3	8.0	16.8	0.9	10	1.2	7.4	3.73			
16-Feb-90	8	7.5	7.7	85.3	2.1	8	2.5	7.4	7.8	7.7	17.1	0.9	11	1.2	7.5	3.87			
17-Feb-90	9	7.3	7.4	88.0	2.2	8	2.6	7.3	8.4	7.4	43.5	1.8	10	1.6	7.4	5.01			
18-Feb-90	9	7.4	7.3	84.2	2.1	9	2.5	7.4	8.3	7.3	41.7	1.8	11	1.6	7.4	5.07			
19-Feb-90	10	7.5	7.4	83.7	2.1	8	2.6	7.3	8.3	7.4	41.5	1.7	11	1.6	7.5	5.14			
20-Feb-90	8	7.2	7.3	88.0	2.2	8	2.6	7.2	8.4	7.3	41.9	1.8	10	1.6	7.4	5.10			
21-Feb-90	9	7.4	7.2	86.9	2.1	8	2.7	7.3	9.0	7.2	41.5	1.7	10	1.6	7.4	5.31			
22-Feb-90	11	7.5	8.1	89.1	2.2	9	2.4	7.4	7.1	8.1	42.5	1.8	11	1.5	7.4	4.43			
23-Feb-90	11	7.0	7.7	88.0	2.2	11	2.6	7.3	8.0	7.7	40.6	1.7	13	1.3	7.5	4.09			
24-Feb-90	10	7.0	8.0	85.9	2.1	10	2.7	7.0	8.2	8.0	40.6	1.7	12	1.6	7.1	4.72			
25-Feb-90	10	7.2	7.1	83.3	2.1	9	2.8	7.1	9.4	7.1	41.5	1.7	10		7.2				
26-Feb-90	11	7.3	9.2	84.7	2.1	8	2.8	7.2	7.3	9.2	40.6	1.8	10	1.6	7.3	4.11			
27-Feb-90	8	7.4	7.7	85.8	2.1	8	2.8	7.3	8.6	7.7	41.5	1.8	10	1.6	7.3	5.01			
28-Feb-90	8	7.3	7.7	85.3	2.1	8	2.7	7.4	8.5	7.7	40.9	1.7	10	1.5	7.5	4.81			
01-Mar-90	10	7.4	7.7	85.3	2.1	9	2.7	7.4	8.3	7.7	41.2	1.7	10	1.6	7.5	4.83			

Table A.1. (Continued).

INF			AAFEB-1							AAFEB-2								
DATE	TEMP	pH	RECYCLE		UPFLOW		BED	VOL	pH	BED	RECYCLE		UPFLOW		BED	VOL	pH	BED
16-Jun-87	(C)		FLOW	FLOW	VEL	TEMP					FLOW	FLOW	VEL	TEMP				
			(s/d)	(s/d)	(m/hr)	(C)	(s)		(hr)		(s/d)	(s/d)	(m/hr)	(C)	(s)			(hr)
Condition #2 (Continued)																		
02-Mar-90	10	7.3	7.5	86.3	2.1	9	2.7	7.3	8.8	7.5	42.5	1.8	12	1.5	7.4	4.87		
03-Mar-90	10	7.4	7.5	85.3	2.1	10	2.8	7.3	9.0	7.5	41.5	1.7	12	1.4	7.3	4.55		
04-Mar-90	11	7.3	7.3	84.7	2.1	9	2.9	7.2	9.3	7.3	40.9	1.7	11	1.4	7.3	4.67		
05-Mar-90	8	7.1	7.9	86.3	2.2	8	2.8	7.0	8.5	7.9	40.9	1.7	10	1.5	7.2	4.64		
06-Mar-90	10	7.3	7.7	83.2	2.1	9	2.7	7.0	8.3	7.7	35.2	1.5	12	1.3	7.1	3.93		
07-Mar-90	9	7.4	7.5	86.1	2.1	8	2.7	7.2	8.6	7.5	34.4	1.5	11	1.5	7.3	4.65		
08-Mar-90	9	7.3	7.2	85.3	2.1	9	2.7	7.2	9.1	7.2	34.4	1.5	12	1.2	7.3	4.13		
09-Mar-90	11	7.3	8.2	89.1	2.2	10	2.6	7.3	7.6	8.2	33.9	1.5	13	1.2	7.4	3.63		
10-Mar-90	11	7.2	8.2	85.8	2.1	10	2.6	7.3	7.6	8.2	34.1	1.5	13	1.3	7.4	3.68		
11-Mar-90	11	7.4	8.2	87.4	2.2	10	2.7	7.2	8.0	8.2	34.4	1.5	13	1.2	7.3	3.54		
12-Mar-90	9	7.1	8.0	85.8	2.1	10	2.6	7.3	7.8	8.0	34.1	1.5	13	1.3	7.3	3.75		
13-Mar-90	11	7.1	7.5	85.3	2.1	12	2.8	7.2	8.8	7.5	34.6	1.5	14	1.3	7.2	4.17		
14-Mar-90	13	7.3	7.5	83.7	2.1	12	2.7	7.2	8.6	7.5	33.9	1.5	17	1.2	7.3	3.85		
15-Mar-90	13	7.3	7.5	84.2	2.1	13	2.2	7.3	7.1	7.5	33.7	1.5	18	1.3	7.4	4.01		
16-Mar-90	13	7.3	7.5	85.8	2.1	13	2.6	7.3	8.2	7.5	34.1	1.5	18	1.3	7.3	4.01		
Conditions # 3 and 4																		
17-Mar-90	11	7.2	37.4	69.5	2.4	12	2.6	7.1	1.7	7.5	34.6	1.5	13	1.3	7.2	4.01		
18-Mar-90	10	7.3	37.8	67.5	2.4	10	2.7	7.3	1.7	7.3	35.9	1.5	12	1.2	7.4	3.99		
19-Mar-90	12	7.2	36.8	67.5	2.4	10	2.9	7.3	1.9	7.1	36.4	1.6	12	1.5	7.3	4.93		
20-Mar-90	11	7.3	36.9	68.5	2.4	9	2.7	7.5	1.8	7.2	35.9	1.5	12	1.3	7.5	4.27		
21-Mar-90	11	7.6	37.5	68.1	2.4	11	2.7	7.5	1.7	7.3	36.4	1.6	13	1.3	7.4	4.10		
22-Mar-90	9	7.3	37.7	66.2	2.4	11	2.5	7.3	1.6	7.1	36.4	1.6	13	1.4	7.4	4.71		
23-Mar-90	10	7.3	39.0	63.2	2.3	10	2.6	7.4	1.6	7.9	36.9	1.6	13	1.4	7.3	4.27		
24-Mar-90	11	7.5	38.8	64.6	2.4	10	2.7	7.5	1.7	7.7	36.1	1.6	13	1.4	7.5	4.35		
25-Mar-90	11	7.4	38.0	70.5	2.5	12	2.7	7.5	1.7	6.9	36.3	1.5	14	1.4	7.4	4.83		
26-Mar-90	12	7.6	38.5	71.6	2.5	12	2.9	7.4	1.8	7.8	35.9	1.6	13	1.4	7.2	4.32		
27-Mar-90	11	7.7	37.8	71.6	2.5	11	3.0	7.4	1.9	7.2	36.1	1.5	11	1.4	7.3	4.70		
28-Mar-90	12	7.5	37.6	69.5	2.4	11	2.7	7.4	1.7	7.7	35.9	1.6	12	1.2	7.4	3.81		
29-Mar-90	13	8.0	37.5	69.1	2.4	13	2.6	7.2	1.7	7.0	35.7	1.5	14	1.2	7.1	4.20		
30-Mar-90	13	7.3	37.6	69.1	2.4	11	2.7	7.3	1.7	6.7	36.9	1.6	12	1.2	7.2	4.47		
31-Mar-90	13	7.3	37.1	64.6	2.3	13	2.7	7.2	1.7	6.3	37.4	1.6	13	1.2	7.1	4.68		
01-Apr-90	13	7.2	37.0	68.5	2.4	13	2.7	7.2	1.8	6.5	35.5	1.5	13	1.2	7.1	4.46		
02-Apr-90	14	7.4	38.0	69.1	2.4	13	2.7	7.1	1.7	7.7	36.4	1.6	13	1.2	7.1	3.79		
03-Apr-90	13	7.4	37.2	62.3	2.3	11	2.6	7.4	1.7	7.4	35.5	1.5	13	1.2	7.4	3.88		
04-Apr-90	10	7.2	37.8	63.2	2.3	9	2.7	7.4	1.7	8.3	35.9	1.6	11	1.2	7.3	3.60		
05-Apr-90	11	7.2		62.3		10	2.8	7.3			27.7		12	1.4	7.3			
06-Apr-90	10	7.0	37.8	62.0	2.3	9	2.8	7.0	1.8	7.9	27.4	1.3	11	1.4	6.9	4.23		
07-Apr-90	11	7.2		61.0		12	2.8	7.1			27.2		14	1.0	7.1			
08-Apr-90	12	7.1	37.2	62.0	2.3	13	2.7	7.1	1.7	7.2	27.6	1.2	13	1.4	7.1	4.70		
09-Apr-90	11	7.4	38.0	61.0	2.3	11	2.8	7.3	1.8	7.1	24.5	1.1	12	1.1	7.3	3.71		
10-Apr-90	13	7.2	37.7	59.1	2.2	12	2.8	7.3	1.8	7.2	25.9	1.2	13	1.1	7.3	3.63		
11-Apr-90	11	7.2	37.7	75.9	2.6	12	2.8	7.3	1.8	7.6	26.0	1.2	12	1.1	7.3	3.52		
12-Apr-90	12	7.2		75.5		13	2.6	7.3			35.7		13	1.4	7.3			
13-Apr-90	12	7.2	37.4	73.9	2.5	11	2.7	7.3	1.7	7.4	32.9	1.4	12	1.2	7.3	3.89		
14-Apr-90	12	7.4	38.4	75.5	2.6	12	2.8	7.2	1.8	7.8	33.9	1.5	13	1.3	7.3	3.84		
15-Apr-90	12	7.3	37.9	74.7	2.6	12	2.9	7.3	1.9	7.9	36.9	1.6	12	1.3	7.3	3.79		
16-Apr-90	13	7.3	39.4	79.4	2.7	12	3.0	7.2	1.8	8.2	38.4	1.7	14	1.3	7.3	3.64		
17-Apr-90	13	7.3	38.0	74.7	2.6	11	2.7	7.2	1.7	7.7	39.5	1.7	13	1.2	7.2	3.60		
18-Apr-90	12	7.2	39.3	77.6	2.7	10	2.7	7.1	1.6	9.5	45.3	2.0	11	1.2	7.1	2.91		
19-Apr-90	12	7.4	37.3	78.1	2.6	13	2.8	7.0	1.8	6.0	45.6	1.8	14	1.2	7.1	4.70		
20-Apr-90	12	7.2	35.6	74.3	2.5	11	2.8	7.1	1.9	6.3	43.5	1.8	14	1.3	7.1	4.79		
21-Apr-90	13	7.3	37.2	76.4	2.6	13	2.7	7.1	1.7	6.0	42.2	1.7	14	1.3	7.0	4.98		
22-Apr-90	13	7.3	37.0	75.5	2.6	13	2.7	7.1	1.8	6.2	42.8	1.8	14	1.3	7.1	4.94		
23-Apr-90	14	7.3	34.9	74.3	2.5	14	2.9	7.1	2.0	5.1	42.8	1.7	15	1.2	7.0	5.54		
24-Apr-90	14	7.1	37.8	75.9	2.6	13	2.7	7.0	1.7	8.4	47.6	2.0	15	1.2	7.1	3.55		
25-Apr-90	15	7.2	37.5	72.8	2.5	15	2.8	7.0	1.8	6.6	41.5	1.7	17	1.2	7.0	4.48		
26-Apr-90	16	7.3	38.4	69.8	2.5	15	2.9	7.0	1.8	6.7	40.3	1.7	17	1.2	7.0	4.31		
27-Apr-90	16	7.2	36.7	64.0	2.3	16	2.5	6.9	1.6	7.0	40.9	1.7	17	1.8	6.9	6.08		
28-Apr-90	18	7.2	38.3	65.2	2.4	17	2.7	6.9	1.7	7.2	41.5	1.7	18	1.5	7.0	4.98		
29-Apr-90	17	7.1	38.0	66.8	2.4	17	2.7	7.0	1.7	7.4	40.6	1.7	17	1.5	7.0	4.84		
30-Apr-90	16	7.1	37.5	64.3	2.3	17	2.8	7.0	1.8	8.0	43.1	1.8	19	1.1	7.0	3.21		
01-May-90	17	7.4	36.4	65.9	2.3	15	2.6	7.0	1.7	7.4	40.3	1.7	19	1.0	7.0	3.07		
02-May-90	16	7.2	37.4	68.1	2.4	13	2.7	7.1	1.7	7.4	41.9	1.8	16	1.1	7.1	3.49		

Table A.1. (Continued).

INF			AAFEB-1							AAFEB-2						
DATE	TEMP	pH	RECYCLE		UPFLOW				BED	INF	RECYCLE	UPFLOW				BED
16-Jun-87	(C)		FLOW	FLOW	VEL	TEMP	BED VOL	pH	HRT	FLOW	FLOW	VEL	TEMP	BED VOL	pH	HRT
			(s/d)	(s/d)	(m/hr)	(C)	(s)		(hr)	(s/d)	(s/d)	(m/hr)	(C)	(s)		(hr)
Conditions # 3 and 4 (Continued)																
03-May-90	16	7.2	38.4	66.8	2.4	16	3.0	6.9	1.9	7.5	35.9	1.6	18	1.1	7.0	3.34
04-May-90	16	7.1	37.0	59.1	2.2	16	2.5	6.9	1.6	7.0	41.9	1.7	18	1.0	7.0	3.46
05-May-90	16	7.1	37.2	66.8	2.4	16	2.2	7.0	1.4	6.9	41.4	1.7	16	1.0	7.0	3.39
06-May-90	15	7.1	37.2	65.6	2.3	16	2.5	7.1	1.6	6.7	39.8	1.7	16	1.0	7.0	3.58
07-May-90	15	7.3	37.4	62.6	2.3	15	2.6	7.0	1.7	6.8	44.5	1.8	15	1.1	7.1	3.87
08-May-90	16	7.3	36.7	52.1	2.0	15	2.2	7.1	1.4	5.8	40.6	1.7	16	1.2	7.0	4.74
09-May-90	15	7.1	37.0	51.5	2.0	15	2.2	7.0	1.4	7.5	43.8	1.8	18	1.0	6.9	3.31
10-May-90	18	7.4	38.4	71.2	2.5	17	2.7	7.1	1.7	7.6	44.9	1.9	18	1.1	7.2	3.31
11-May-90	16	7.1	37.1	66.8	2.4	15	2.9	7.0	1.8	7.5	43.8	1.8	16	1.1	6.9	3.48
12-May-90	16	7.2	36.9	65.9	2.3	15	2.6	7.1	1.7	6.7	43.5	1.8	16	1.1	7.0	4.06
13-May-90	15	7.2	37.3	67.5	2.4	15	2.6	7.1	1.7	7.4	44.9	1.9	16	1.1	7.0	3.65
14-May-90	15	7.3	37.0	67.8	2.4	15	2.8	7.2	1.8	6.8	41.2	1.7	16	1.1	7.1	3.99
15-May-90	16	7.2	37.6	67.8	2.4	15	2.6	7.1	1.7	7.6	41.5	1.8	17	1.1	7.1	3.46
16-May-90	15	7.2	37.1	67.8	2.4	15	2.7	7.2	1.7	7.9	41.2	1.8	18	1.0	7.1	3.11
17-May-90	16	7.3	37.0	67.8	2.4	16	2.6	7.2	1.7	7.5	41.5	1.8	19	1.0	7.2	3.28
18-May-90	15	7.2	37.5	68.5	2.4	14	2.7	7.1	1.7	7.9	43.5	1.8	16	1.0	7.1	3.05
19-May-90	14	7.1	37.3	69.5	2.4	14	2.7	7.1	1.7	7.9	44.5	1.9	16	1.0	7.1	3.03
20-May-90	15	7.2	36.8	69.1	2.4	14	2.7	7.2	1.8	8.0	44.5	1.9	16	1.0	7.1	3.01
21-May-90	13	7.2	37.1	71.3	2.5	13	2.7	7.2	1.8	7.2	44.2	1.8	15	1.0	7.2	3.35
22-May-90	14	7.2	38.1	71.3	2.5	13	2.7	7.2	1.7	7.5	42.5	1.8	15	1.0	7.2	3.12
23-May-90	13	7.2	37.8	67.1	2.4	13	2.6	7.2	1.6	6.9	43.1	1.8	15	1.1	7.2	3.94
24-May-90	14	7.2	38.9	66.5	2.4	14	2.5	7.2	1.5	7.8	42.1	1.8	15	1.0	7.2	2.96
25-May-90	14	7.1	37.0	68.1	2.4	13	2.5	7.1	1.6	6.7	44.9	1.8	15	0.9	7.0	3.36
26-May-90	14	7.1	38.4	66.9	2.4	14	2.5	7.0	1.5	7.9	43.0	1.8	18	1.0	6.9	2.97
27-May-90	14	7.1	38.1	67.7	2.4	15	2.5	7.0	1.5	7.5	44.9	1.9	17	1.0	6.9	3.11
28-May-90	15	7.0	37.3	66.8	2.4	15	2.6	7.0	1.6	6.6	43.6	1.8	19	0.9	6.9	3.22
29-May-90	16	7.2	37.7	67.3	2.4	14	2.6	7.0	1.7	8.4	45.6	1.9	19	0.9	6.9	2.56
30-May-90	15	7.2	36.1	68.7	2.4	14	2.7	7.1	1.8	6.5	43.8	1.8	18	0.9	7.0	3.26
31-May-90	16	7.0	34.6	69.5	2.4	15	2.6	7.0	1.8	4.4	43.8	1.7	19	0.9	7.0	4.63
01-Jun-90	15	7.0	35.5	67.3	2.3	15	2.6	7.0	1.8	5.8	44.2	1.8	19	0.8	6.9	3.41
Conditions #3 (Continued) and #5																
02-Jun-90	17	7.0	37.8	68.8	2.4	17	2.6	7.0	1.6	15.0	29.9	1.6	20	0.8	7.0	1.27
03-Jun-90	17	7.1	38.0	69.5	2.5	17	2.7	7.1	1.7	15.1	33.6	1.7	19	0.8	7.1	1.26
04-Jun-90	15	6.9	37.4	73.7	2.5	16	2.7	6.9	1.8	15.6	31.5	1.7	15	0.8	7.0	1.23
05-Jun-90	15	7.1	37.9	69.5	2.5	15	2.2	7.0	1.4	15.4	32.6	1.7	18	0.9	7.1	1.44
06-Jun-90	15	7.5	37.8	68.1	2.4	16	2.6	7.1	1.6	15.4	34.6	1.8	17	0.8	7.2	1.25
07-Jun-90	18	7.1	38.6	67.4	2.4	17	2.5	7.1	1.6	15.9	30.8	1.7	19	0.7	7.1	1.12
08-Jun-90	17	7.2	38.5	69.0	2.5	16	2.7	7.0	1.7	16.7	29.9	1.7	18	0.9	7.0	1.31
09-Jun-90	18	7.4	40.4	69.1	2.5	18	2.2	7.2	1.3	16.5	31.1	1.7	20	0.7	7.2	0.95
10-Jun-90	17	7.2	37.3	68.5	2.4	17	2.8	7.0	1.8	15.3	31.6	1.7	19	0.7	7.1	1.02
11-Jun-90	16	7.1	38.4	66.8	2.4	16	2.9	6.9	1.8	16.2	31.8	1.7	18	0.7	6.9	0.96
12-Jun-90	17	7.1	35.2	67.8	2.4	16	2.6	7.1	1.8	13.0	30.9	1.6	18	0.7	7.1	1.20
13-Jun-90	17	7.3		67.6		16	2.7	7.2		14.5	31.6	1.6	18	0.7	7.2	1.07
14-Jun-90	18	7.3		68.9		18	2.6	7.2		14.4	31.8	1.7	21	1.3	7.1	2.08
15-Jun-90	18	7.3	40.0	67.8	2.5	17	2.7	7.0	1.6	16.7	32.2	1.7	20	0.7	7.0	0.93
16-Jun-90	17	7.2	38.3	69.1	2.5	17	2.8	7.0	1.7	14.2	46.4	2.2	20	0.9	7.0	1.52
17-Jun-90	18	7.2	38.5	68.1	2.4	18	2.8	7.1	1.7	15.4	51.2	2.4	21	0.8	7.1	1.24
18-Jun-90	19	7.4	38.8	67.5	2.4	18	2.9	7.2	1.8	16.5	49.3	2.3	21	0.9	7.1	1.31
19-Jun-90	19	7.2	38.2	66.8	2.4	18	2.7	7.2	1.7	15.8	51.1	2.4	20	1.0	7.2	1.52
20-Jun-90	19	7.2	37.9	68.5	2.4	18	2.6	7.2	1.6	15.0	51.1	2.4	20	0.8	7.2	1.28
21-Jun-90	20	7.2	38.1	69.0	2.4	19	2.2	7.0	1.4	15.1	50.1	2.3	21	0.9	7.1	1.43
22-Jun-90	19	7.3	38.0	68.8	2.4	20	2.7	7.1	1.7	15.0	50.4	2.3	21	0.8	7.1	1.30
23-Jun-90	19	7.3	38.3	68.8	2.4	20	2.6	7.0	1.6	15.3	49.7	2.3	21	0.8	7.1	1.26
24-Jun-90	19	7.3	38.0	68.5	2.4	20	2.6	7.1	1.6	15.6	48.8	2.3	20	0.8	7.2	1.25
25-Jun-90	19	7.2	35.5	68.5	2.4	19	2.6	7.1	1.8	13.0	49.0	2.2	20	0.8	7.2	1.45
26-Jun-90	19	7.4	38.2	69.0	2.4	20	2.7	7.0	1.7	15.5	49.0	2.3	21	0.8	7.1	1.24
27-Jun-90	20	7.1	38.4	66.4	2.4	20	2.7	7.0	1.7	15.7	45.9	2.2	21	0.9	6.9	1.30
28-Jun-90	20	7.3	38.3	68.5	2.4	19	2.7	7.0	1.7	15.8	30.8	1.7	21	0.7	7.0	0.98
29-Jun-90	19	7.3	38.3	66.8	2.4	18	2.5	6.9	1.6	16.2	30.4	1.7	21	0.7	6.9	1.04
30-Jun-90	20		40.1	65.0	2.4	20	2.2		1.3	15.5	30.9	1.7	21	0.5		0.77
01-Jul-90	20	7.3	38.0	68.8	2.4	20	2.6	7.1	1.6	15.1	30.8	1.6	22	0.5	7.1	0.79
02-Jul-90	21	7.2	36.8	66.7	2.4	8	2.5	6.8	1.7	14.2	31.0	1.6	21	0.5	6.7	0.85
03-Jul-90	21	7.2	38.5	61.8	2.3	21	2.2	7.0	1.4	15.5	26.6	1.5	23	0.9	7.0	1.41

Table A.1. (Continued).

INF			AAFEB-1							AAFEB-2						
DATE	TEMP	pH	RECYCLE FLOW	UPFLOW FLOW	UPFLOW VEL	TEMP	BED VOL	pH	BED HRT	INF FLOW	RECYCLE FLOW	UPFLOW VEL	TEMP	BED VOL	pH	BED HRT
16-Jun-87	(C)		(s/d)	(s/d)	(m/hr)	(C)	(s)		(hr)	(s/d)	(s/d)	(m/hr)	(C)	(s)		(hr)
Conditions #3 (Continued) and #5 (Continued)																
04-Jul-90	21	7.1	39.1	68.5	2.5	21		7.0		16.4	31.0	1.7	23	0.8	6.8	1.18
05-Jul-90	22	7.1	37.2	67.9	2.4	21		6.8		15.3	29.2	1.6	23	0.9	6.7	1.43
06-Jul-90	21	7.4	36.5	66.5	2.4	20		7.1		15.3	27.3	1.5	21	0.8	7.1	1.23
07-Jul-90	21	7.4	38.2	68.1	2.4	21		7.0		15.6	27.6	1.5	25	1.3	7.0	2.02
08-Jul-90	21	7.3	37.7	69.5	2.4	21		7.0		15.7	27.7	1.5	22	1.3	6.9	2.02
09-Jul-90	21	7.3	38.2	65.2	2.4	21	1.6	7.1	1.0	15.8	24.4	1.4	22	1.4	7.0	2.09
10-Jul-90	21	7.2	37.4	64.0	2.3	20	2.0	7.1	1.3	15.1	24.6	1.4	22	1.3	7.0	2.07
11-Jul-90	21	7.2	37.7	65.6	2.4	20	2.8	7.2	1.8	15.9	24.1	1.4	21	1.3	7.0	1.98
12-Jul-90	21	7.1	37.5	70.9	2.5	20	2.6	7.0	1.7	15.6	25.3	1.5	21	1.4	7.0	2.08
13-Jul-90	21	7.1	37.0	68.5	2.4	20	2.6	6.9	1.7	14.8	24.7	1.4	22	1.4	6.9	2.18
14-Jul-90	22	7.2	37.1	67.5	2.4	21	2.7	6.8	1.7	14.9	24.8	1.4	22	1.4	6.9	2.17
15-Jul-90	22	7.0	37.4	68.1	2.4	20	2.7	6.6	1.7	15.0	25.3	1.4	22	1.4	6.7	2.18
16-Jul-90	21	6.9	36.5	67.5	2.4	21	2.7	7.0	1.8	14.4	24.7	1.4	23	1.3	6.9	2.22
17-Jul-90	21		36.2			19		2.7	1.8	14.3	25.1	1.4	22	1.3		2.24
18-Jul-90	21	7.1	35.0	57.0	2.1	20	2.8	7.0	1.9	13.5	24.3	1.3	22	1.4	7.0	2.47
19-Jul-90	23	7.7	37.5	55.6	2.1		2.2	7.2	1.4	15.0	27.8	1.5		1.4	7.1	2.19
20-Jul-90	22	7.3	38.6	80.3	2.7	21	2.8	7.3	1.7	15.9	21.3	1.3	23	1.3	7.0	1.97
21-Jul-90	22	7.2	39.8	68.5	2.5	21	2.7	7.2	1.6	17.3	25.2	1.5	23	1.5	7.2	2.01
22-Jul-90	22	7.3	38.0	67.8	2.4	21	2.7	7.2	1.7	15.4	24.8	1.4	22	1.4	7.1	2.18
23-Jul-90	22	7.4	37.6	69.5	2.4	21	2.7	7.3	1.7	15.7	25.0	1.5	23	1.4	7.3	2.15
24-Jul-90	22	7.2	37.5	68.8	2.4	21	2.6	7.3	1.7	15.0	24.6	1.4	22	1.4	7.2	2.25
25-Jul-90	22	7.0	37.1	67.1	2.4	21	2.6	7.1	1.7	15.2	25.0	1.4	23	1.4	7.0	2.21
26-Jul-90	22	7.2	36.5	64.0	2.3	21	2.6	7.2	1.7	14.9	24.5	1.4	23	1.4	7.2	2.25
27-Jul-90	21	7.2	39.0	68.1	2.4	21	2.7	7.1	1.7	16.7	24.7	1.5	22	1.4	7.1	2.00
28-Jul-90	23	7.2	37.1	59.1	2.2	24	2.7	6.9	1.7	15.7	24.2	1.4	24	1.3	7.0	2.05
29-Jul-90	22	7.0	38.1	66.5	2.4	23	2.7	7.0	1.7	14.9	26.3	1.5	25	1.3	7.0	2.11
30-Jul-90	23	6.9	37.9	62.3	2.3	23	2.7	6.8	1.7	15.1	25.7	1.5	24	1.3	6.7	2.08
31-Jul-90	23	7.1	36.5	61.5	2.2	22	2.6	6.9	1.7	15.3	25.4	1.5	24	1.5	6.9	2.27
01-Aug-90	22	7.1	37.0	64.0	2.3	21	2.6	7.0	1.7	14.5	27.7	1.5	22	1.5	7.0	2.41
02-Aug-90	23		44.7			22				14.3			23	1.4		2.40
Conditions #3 (Continued) and #6																
03-Aug-90	23	7.0	39.2	57.7	2.2		2.7	6.9	1.6	9.1				0.8	6.9	2.18
04-Aug-90	23	7.1	36.8	56.3	2.1	23	2.7	7.0	1.8	7.5		1.1	25	1.4	6.9	4.62
05-Aug-90	22	7.1	37.8	76.8	2.6		2.8	7.0	1.8	7.9	16.0	0.9		1.1	7.0	3.33
06-Aug-90	22	7.1	38.0	70.5	2.5	21	2.8	7.0	1.8	7.6	22.7	1.1	23	1.3	6.9	4.15
07-Aug-90	22	7.2	37.0	69.1	2.4	21	2.7	7.0	1.7	6.6	21.0	1.0	23	1.1	7.0	3.87
08-Aug-90	22	7.2	39.0	65.6	2.4	22	2.7	7.1	1.7	8.4	21.1	1.1	23	1.3	7.1	3.79
09-Aug-90	22	7.2	38.3	64.3	2.3	22	2.6	7.0	1.6	7.6	24.5	1.1	23	1.5	7.0	4.85
10-Aug-90	22		38.1	68.5	2.4		2.7		1.7	8.0	22.5	1.1		1.4		4.27
11-Aug-90																
12-Aug-90							2.8									
13-Aug-90	23	7.2	38.4	63.2	2.3	23	2.8	6.9	1.8	7.8	22.3	1.1	24	1.5	7.0	4.60
14-Aug-90	23	7.2	38.4	67.8	2.4	23	2.8	7.0	1.8	7.8	22.5	1.1	24	1.5	7.1	4.60
15-Aug-90	23	7.2	38.3	68.5	2.4	23	2.9	7.0	1.8	7.7	22.7	1.1	24	1.5	7.0	4.65
16-Aug-90	23	7.1	49.8	69.5	2.7	23	2.9	7.0	1.4	19.3	22.9	1.5	24	1.5	7.0	1.83
17-Aug-90	23	7.1	37.8	69.1	2.4	23	2.9	7.0	1.8	7.5	23.1	1.1	25	1.5	7.0	4.83
18-Aug-90	23	7.1	36.7	66.2	2.3	24	2.8	7.1	1.9	7.1	20.8	1.0	25	1.5	7.0	5.07
19-Aug-90	23	7.1														
20-Aug-90	23	7.1	36.6	64.6	2.3	23	2.9	7.0	1.9	6.9	20.7	1.0	24	1.5	7.0	5.27
21-Aug-90	23	7.1	37.7	55.6	2.1	20	2.9	7.0	1.9	7.5	20.0	1.0	22	1.5	6.9	4.81
22-Aug-90	23	7.1	37.0	64.6	2.3	21	2.6	7.0	1.7	6.3	21.5	1.0	23		7.0	
23-Aug-90	23	7.1	37.5	64.6	2.3	22	2.8	7.0	1.8	7.5	24.0	1.1	23	1.5	7.0	4.81
24-Aug-90	23	7.1	37.6	66.2	2.4	22	2.6	7.1	1.7	7.6	23.2	1.1	25	1.5	7.0	4.72
25-Aug-90	23	7.1	37.7	67.3	2.4	23	2.7	7.0	1.7	7.6	20.6	1.0			7.0	
26-Aug-90	23	7.1											26	1.4		
27-Aug-90	23	7.1	38.4	66.8	2.4	24	2.6	6.8	1.6	7.9	20.8	1.0	25	1.5	6.9	4.52
28-Aug-90	23	7.1	38.6	66.2	2.4	23	2.6	6.7	1.6	7.9	26.0	1.2	24	1.5	6.9	4.55
29-Aug-90	23	7.1	37.3	68.1	2.4	22	2.7	7.0	1.7	7.1	26.1	1.2	24	1.5	7.0	5.04
30-Aug-90	23	7.1	37.3	68.1	2.4	22	2.7	7.0	1.7	7.1	26.1	1.2	24	1.5	7.0	5.04
31-Aug-90	23	7.1	37.3	68.1	2.4	22	2.7	7.0	1.7	7.1	26.1	1.2	24	1.5	7.0	5.04

APPENDIX B

A SUMMARY OF THE NFT REACTOR SYSTEM PERFORMANCE

Table B.1. A daily summary of operation of the pilot NFT treatment system.

Surface area of the deep channels was 37.16 square meters per reactor.
Surface area of the shallow channels was 27.87 square meters per reactor.

DATE	NFT-DN						NFT-DS				NFT-S					
	FLOW (s/d)	FLOW (cm/d)	INF DEPTH (cm)	EFF DEPTH (cm)	TEMP (C)	pH	FLOW (s/d)	FLOW (cm/d)	INF DEPTH (cm)	EFF DEPTH (cm)	FLOW (s/d)	FLOW (cm/d)	INF DEPTH (cm)	EFF DEPTH (cm)	TEMP (C)	pH
Conditions 1, 2, 3																
01-Jan-90	3.3	8.9					3.3	8.9			3.3	11.9				
02-Jan-90	3.3	9.0					3.3	9.0			3.3	12.0				
03-Jan-90	5.4	14.5			6	7.5	5.4	14.5			5.4	19.3			6	7.6
04-Jan-90	4.2	11.3			7	7.4	4.2	11.3			4.2	15.1			6	7.3
05-Jan-90	3.6	9.6			7	7.5	3.6	9.6			3.6	12.8			7	7.4
08-Jan-90					9	7.1										
09-Jan-90	1.9	5.2			6	7.3	1.9	5.2			1.9	6.9			6	7.2
10-Jan-90	3.9	10.6			6	7.2	3.9	10.6			3.9	14.1			6	7.3
11-Jan-90	4.1	11.0			6	7.4	4.1	11.0			4.1	14.7			6	7.3
12-Jan-90	3.7	9.9			7	7.3	3.7	9.9			3.7	13.2			6	7.4
13-Jan-90	1.0	2.7			8	7.3	1.0	2.7			1.0	3.6			9	7.4
14-Jan-90	3.7	9.9			7	7.2	3.7	9.9			3.7	13.2			7	7.4
15-Jan-90	4.4	11.7			6	7.2	4.4	11.7			4.4	15.7			6	7.3
16-Jan-90	3.7	9.8			6	7.3	3.7	9.8			3.7	13.1			6	7.3
17-Jan-90	3.6	9.7			8	7.6	3.6	9.7			3.6	13.0			9	7.6
18-Jan-90	3.6	9.6			10	7.5	3.6	9.6			3.6	12.8			9	7.6
19-Jan-90	3.9	10.5			8	7.5	3.9	10.5			3.9	14.0			10	7.6
20-Jan-90	4.0	10.8			7	7.5	4.0	10.8			4.0	14.4			6	7.6
21-Jan-90	5.2	14.0			8	7.5	5.2	14.0			5.2	18.7			9	7.5
22-Jan-90	4.5	12.1			6	7.4	4.5	12.1			4.5	16.1			6	7.6
23-Jan-90	3.4	9.1			6	7.4	3.4	9.1			3.4	12.1			6	7.4
24-Jan-90	3.7	9.9			7	7.6	3.7	9.9			3.7	13.2			7	7.7
25-Jan-90	4.6	12.5			8	7.5	4.6	12.5			4.6	16.6			8	7.6
26-Jan-90					8	7.4									8	7.6
27-Jan-90	3.5	9.5			8	7.5	3.5	9.5			3.5	12.7			8	7.7
28-Jan-90	3.3	8.8			10	7.8	3.3	8.8			3.3	11.7			9	7.8
29-Jan-90	3.2	8.6			7	7.5	3.2	8.6			3.2	11.4			7	7.6
30-Jan-90	4.1	10.9			7	7.4	4.1	10.9			4.1	14.6			7	7.5
31-Jan-90	4.2	11.2			8	7.4	4.2	11.2			4.2	15.0			8	7.5
01-Feb-90	3.8	10.3			8	7.4	3.8	10.3			3.8	13.7			8	7.5
02-Feb-90	4.2	11.2			8	7.6	4.2	11.2			4.2	14.9			7	7.7
03-Feb-90	3.7	9.9			7	7.5	3.7	9.9			3.7	13.3			6	7.6
04-Feb-90	3.9	10.5			6	7.4	3.9	10.5			3.9	14.0			6	7.5
05-Feb-90	4.0	10.9			5	7.5	4.0	10.9			4.0	14.5			5	7.6
06-Feb-90	4.2	11.3			7	7.7	4.2	11.3			4.2	15.1			6	7.5
07-Feb-90	4.0	10.7			7	7.6	4.0	10.7			4.0	14.3			6	7.5
08-Feb-90	3.5	9.4			8	7.5	3.5	9.4			3.5	12.6			7	7.4
09-Feb-90					10										11	
10-Feb-90					11										10	
11-Feb-90					14										11	
12-Feb-90	3.8	10.2			9	7.5	3.8	10.2			3.8	13.6			9	7.5
13-Feb-90	3.8	10.1			9	7.4	3.8	10.1			3.8	13.5			8	7.3
14-Feb-90	3.5	9.5			8	7.5	3.5	9.5			3.5	12.6			8	7.5
15-Feb-90	4.3	11.4			7	7.5	4.3	11.4			4.3	15.3			7	7.5
16-Feb-90	4.1	11.1			8	7.4	4.1	11.1			4.1	14.8			7	7.5
17-Feb-90					11	7.3									9	7.3
18-Feb-90					10	7.3									9	7.3
19-Feb-90	4.1	11.0			11	7.3	4.1	11.0			4.1	14.6			10	7.3
20-Feb-90	4.0	10.9			7	7.5	4.0	10.9			4.0	14.5			7	7.4
21-Feb-90	4.5	12.0			6	7.5	4.5	12.0			4.5	16.0			7	7.4
22-Feb-90	5.2	14.0			10	7.5	5.2	14.0			5.2	18.6			10	7.3
23-Feb-90					10	7.7									11	7.3
24-Feb-90					11	7.7									11	7.4
25-Feb-90					9	7.5									9	7.4
26-Feb-90					6	7.4									6	7.4
27-Feb-90	3.7	10.1			7	7.6	3.7	10.1			3.7	13.4			7	7.4
28-Feb-90	3.8	10.2			6	7.3	3.8	10.2			3.8	13.6			6	7.3
01-Mar-90	3.8	10.2			8	7.4	3.8	10.2			3.8	13.6			8	7.4
02-Mar-90	3.9	10.4			8	7.4	3.9	10.4			3.9	13.8			8	7.5
03-Mar-90					9	7.5									9	7.5
04-Mar-90					10	7.6									10	7.4

Table B.1. (Continued).

DATE	NFT-DN						NFT-DS						NFT-S					
	FLOW (s/d)	FLOW (cm/d)	INF DEPTH (cm)	EFF DEPTH (cm)	TEMP (C)	pH	FLOW (s/d)	FLOW (cm/d)	INF DEPTH (cm)	EFF DEPTH (cm)	FLOW (s/d)	FLOW (cm/d)	INF DEPTH (cm)	EFF DEPTH (cm)	TEMP (C)	pH		
Conditions 1, 2, 3 (Continued)																		
05-Mar-90	3.6	9.7			6	7.3	3.6	9.7			3.6	13.0			6	7.3		
06-Mar-90	3.8	10.2			10	7.3	3.8	10.2			3.8	13.6			10	7.1		
07-Mar-90	3.3	8.8			7	7.5	3.3	8.8			3.3	11.8			7	7.2		
08-Mar-90	3.5	9.3			9	7.6	3.5	9.3			3.5	12.5			9	6.9		
09-Mar-90	3.9	10.5			8	7.5	3.9	10.5			3.9	14.0			9	7.8		
10-Mar-90					7	7.5									13			
11-Mar-90					12	7.6									13	8.3		
12-Mar-90	3.9	10.6			10	7.6	3.9	10.6			3.9	14.2			11	7.9		
13-Mar-90	3.8	10.2			13	7.3	3.8	10.2			3.8	13.5			14	8.0		
14-Mar-90	3.9	10.4			17	7.3	3.9	10.4			3.9	13.8			18	8.0		
15-Mar-90	3.8	10.2			21	7.3	3.8	10.2			3.8	13.5			15	8.0		
16-Mar-90	3.8	10.2			20	7.3	3.8	10.2			3.8	13.6			21	7.2		
17-Mar-90					16										16			
18-Mar-90					14										15			
19-Mar-90	3.8	10.2			10	7.2	3.8	10.2			3.8	13.5			11	8.5		
20-Mar-90	4.0	10.9			8	7.5	4.0	10.9			4.0	14.5			10	7.5		
21-Mar-90					15	7.2									16	8.7		
22-Mar-90	4.4	11.8			15	7.4	4.4	11.8			4.4	15.7			15	8.0		
23-Mar-90	3.9	10.5			12	7.3	3.9	10.5			3.9	14.0			13	7.4		
24-Mar-90					13	7.3									13	7.4		
25-Mar-90					23										24			
26-Mar-90	4.4	11.8			13	7.4	4.4	11.8			4.4	15.7			9	7.8		
27-Mar-90	3.8	10.3			10	7.4	3.8	10.3			3.8	13.7			10	7.8		
28-Mar-90	4.1	11.0			8	7.5	4.1	11.0			4.1	14.7			9	8.0		
29-Mar-90	4.1	11.1			15	7.4	4.1	11.1			4.1	14.8			15	7.4		
30-Mar-90	3.2	8.7			9	7.3	3.2	8.7			3.2	11.6			10	7.3		
02-Apr-90	4.5	12.0			11	7.4	4.5	12.0			4.5	16.0			12			
03-Apr-90	4.0	10.9			10	7.3	4.0	10.9			4.0	14.5			10	7.4		
04-Apr-90	4.4	11.9			7	7.2	4.4	11.9			4.4	15.8			8	7.3		
05-Apr-90					9	7.4									9			
06-Apr-90	2.7	7.4			8	7.1	2.7	7.4			2.7	9.8			9	7.3		
07-Apr-90					18	7.3									17	7.6		
08-Apr-90					20	8.4									15	7.7		
09-Apr-90	3.6	9.7			9		3.6	9.7			3.6	12.9			9			
10-Apr-90	3.7	9.8			12	7.3	3.7	9.8			3.7	13.1			13	7.4		
11-Apr-90	3.8	10.2			10	7.2	3.8	10.2			3.8	13.5			10	7.5		
12-Apr-90					9	7.3												
13-Apr-90	3.9	10.5			9	7.2	3.9	10.5			3.9	14.0			9	7.5		
14-Apr-90					13	7.3									12	7.4		
15-Apr-90					12	7.4									10	8.1		
16-Apr-90	3.9	10.5			13	7.3	3.9	10.5			3.9	14.0			15	9.4		
17-Apr-90	5.9	15.8			12	7.3	5.9	15.8			5.9	21.1			13	7.4		
18-Apr-90	6.0	16.2			10	7.3	6.0	16.2			6.0	21.6			10	7.4		
19-Apr-90	4.1	11.1			20	7.3	4.1	11.1			4.1	14.8			20	8.4		
20-Apr-90	3.7	10.1			12	7.3	3.7	10.1			3.7	13.4			14	7.4		
21-Apr-90					13	7.2									15	7.6		
22-Apr-90					20	7.3									17	7.6		
23-Apr-90	3.6	9.7			13	7.3	3.6	9.7			3.6	12.9			13	7.5		
24-Apr-90	3.8	10.2			14	7.1	3.8	10.2			3.8	13.5			15	7.3		
25-Apr-90					17	7.1									19	7.3		
26-Apr-90	4.9	13.3			18	7.3	4.9	13.3			4.9	17.7			2	7.3		
27-Apr-90	5.2	14.0			18	7.2	5.2	14.0			5.2	18.6			20	7.3		
28-Apr-90					21	7.2									21	7.3		
29-Apr-90					20	7.2									21	7.3		
Conditions 4, 5, 6																		
30-Apr-90	5.7	15.3			24	7.2	5.7	15.3			5.7	20.4			23	7.3		
01-May-90	6.1	16.5	12	4	14	7.0	6.1	16.5			6.1	22.0	8	1	15	7.1		
02-May-90	7.1	19.2	12	4	10	7.0	7.1	19.2			7.1	25.6	8	1	10	7.1		
03-May-90	5.2	14.1	12	5	12	7.2	5.2	14.1			5.2	18.8	8	1	11	7.2		
04-May-90	5.2	14.0	12	5	10	7.1	5.2	14.0			5.2	18.6	8	1	10	8.1		
05-May-90					10	7.3									1	12	7.8	
06-May-90					10	7.2									1	10	7.9	
07-May-90	5.4	14.4	11	2	10	7.2	5.4	14.4			5.4	19.2	2	1	10	7.8		

Table B.1. (Continued).

DATE	NFT-DN						NFT-DS						NFT-S					
	FLOW (s/d)	FLOW (cm/d)	INF DEPTH (cm)	EFF DEPTH (cm)	TEMP (C)	pH	FLOW (s/d)	FLOW (cm/d)	INF DEPTH (cm)	EFF DEPTH (cm)	FLOW (s/d)	FLOW (cm/d)	INF DEPTH (cm)	EFF DEPTH (cm)	TEMP (C)	pH		
Conditions 4, 5, 6 (Continued)																		
08-May-90	3.9	10.4	12	4	11	7.1	3.9	10.4			3.9	13.8	8	1	1	7.5		
09-May-90	5.2	14.0	12	5	14	7.0	5.2	14.0			5.2	18.6	8	1	15	7.2		
10-May-90	5.4	14.6	12	5	15	7.2	5.4	14.6			5.4	19.5	8	1	17	7.2		
11-May-90	6.5	17.6	12	5	10	7.0	6.5	17.6			6.5	23.5	8	1	9	7.4		
12-May-90					2	7.1								1	11	7.3		
13-May-90					11	7.1								1	11	7.2		
14-May-90	6.7	18.1	12	2	10	7.2	6.7	18.1			6.7	24.2	2	1	15	7.2		
15-May-90	7.5	20.2	12	3	14	7.2	7.5	20.2			7.5	26.9		1	16	7.2		
16-May-90	7.6	20.5	12	4	15	7.1	7.6	20.5			7.6	27.4		1	15	7.2		
17-May-90	7.5	20.2	12	4	17	7.3	7.5	20.2			7.5	26.9		1	14	7.6		
18-May-90	7.8	20.9	13	4	12	7.4	7.8	20.9			7.8	27.9		8	0	15	7.3	
19-May-90														8	0	17	7.4	
20-May-90														8	0	10	7.3	
21-May-90	7.4	20.0	12	3	10		7.4	20.0			7.4	26.7		8	0	11	7.3	
22-May-90	8.2	21.9	12	4	10	7.2	8.2	21.9			8.2	29.2		8	0	12	7.3	
23-May-90	6.7	18.1	12	4	10		6.7	18.1			6.7	24.1		8	0	11	7.3	
24-May-90	7.6	20.5	13	4	10	7.1	7.6	20.5			7.6	27.3		8	0	9	7.1	
25-May-90	6.5	17.4	13	4	9	7.0	6.5	17.4			6.5	23.3		7	0	12	7.1	
26-May-90			13	4	12	7.0								6	0	12	7.3	
27-May-90			13	3	12	7.1								6	0	17		
28-May-90			11	2	12									5	0	16	7.1	
29-May-90			10	2	14	6.9								8	0	10	7.0	
30-May-90	7.3	19.5	6	4	10	6.9	7.3	19.5			7.3	26.0		9	0	11	7.3	
31-May-90	3.9	10.6	12	4	10	7.1	3.9	10.6			3.9	14.2		9	0	10	7.0	
Conditions 7, 8, 9																		
01-Jun-90	5.4	14.6	13		10	7.1	5.4	14.6			5.4	19.5			0	21	7.1	
02-Jun-90	15.0	40.3	14	4	18	7.1	15.0	40.3			15.0	53.7			0	21	7.0	
03-Jun-90	14.8	39.8	14	13	18	7.1	14.8	39.8			14.8	53.0		10	0	10	7.1	
04-Jun-90	14.0	37.7	15	10	15	7.0	14.0	37.7			14.0	50.3		10	1	11	7.2	
05-Jun-90	15.5	41.8	15	4	10	7.0	15.5	41.8			15.5	55.7		11	1	13	7.2	
06-Jun-90	15.0	40.5	14	4	13	7.1	15.0	40.5			15.0	53.9		10	1	17	7.0	
07-Jun-90	15.5	41.7	14	5	17	7.2	15.5	41.7			15.5	55.6		11	1	14	7.2	
08-Jun-90	15.0	40.4	14	4	14	7.1	15.0	40.4			15.0	53.8		11	1	20	7.2	
09-Jun-90	16.2	43.6	14	4	19	7.3	16.2	43.6			16.2	58.2		11	1	18	7.2	
10-Jun-90	15.3	41.2	15	5	17	7.2	15.3	41.2			15.3	54.9		11	1	16	7.1	
11-Jun-90	15.8	42.4	15	5	16	7.1	15.8	42.4			15.8	56.5		11	1	12	7.1	
12-Jun-90	15.2	40.8	15	4	12	7.1	15.2	40.8			15.2	54.5		11	1	15	7.4	
13-Jun-90	14.9	40.2	15	6	15	7.5	14.9	40.2			14.9	53.6		11	1	22	7.1	
14-Jun-90	15.0	40.3	15	6	20	7.3	15.0	40.3			15.0	53.7		11	1	21	7.4	
15-Jun-90	12.0	32.3	15	5	19	7.2	12.0	32.3			12.0	43.1		12	1	22	7.4	
16-Jun-90	12.2	32.9	15	5	20	7.1	12.2	32.9			12.2	43.8		11	1	23	7.4	
17-Jun-90	13.6	36.7	15	5	21	7.4	13.6	36.7			13.6	48.9		10	1	23	7.2	
18-Jun-90	14.3	38.6	15	5		7.4	14.3	38.6			14.3	51.5		11	1	20	7.2	
19-Jun-90	15.5	41.6	15	5	19	7.4	15.5	41.6			15.5	55.5		11	1	18	7.2	
20-Jun-90	14.9	40.0	15	5	18	7.4	14.9	40.0			14.9	53.3		11	1	22	7.1	
21-Jun-90	14.8	39.9	15	5	22	7.3	14.8	39.9			14.8	53.2		11	1	20	7.2	
Conditions 10, 11, 12																		
22-Jun-90	14.8	39.8	15	5	19	7.4	14.8	39.8			14.8	53.0		11	1	20	7.1	
23-Jun-90	15.0	40.3	15	5	20	7.3	15.0	40.3			15.0	53.7		11	1	22	7.1	
24-Jun-90	15.4	41.5	15	5	20	7.3	15.4	41.5			15.4	55.3		11	1	18	7.3	
25-Jun-90	15.6	42.1	15	5	16	7.4	15.6	42.1			15.6	56.1		10	1	17	7.4	
26-Jun-90	13.1	35.3	15	5	16	7.4	13.1	35.3			13.1	47.1		10	1	19	7.2	
27-Jun-90	14.9	40.2	15	5	18	7.3	14.9	40.2			14.9	53.6		10	1	19	7.1	
28-Jun-90	15.7	42.2	15	5	17	7.3	15.7	42.2			15.7	56.2		10	1	18	7.1	
29-Jun-90	15.6	41.9	16	5	17		15.6	41.9			15.6	55.8		10	1	19		
30-Jun-90	16.0	42.9	15	5	18		16.0	42.9			16.0	57.2		11	1	21	7.3	
01-Jul-90	15.1	40.8	15	5	21	7.3	15.1	40.8			15.1	54.4		11	1			
02-Jul-90	15.5	41.7	15	5	17	7.4	15.5	41.7			15.5	55.6		14	1			
03-Jul-90			15	8	20	7.3								8	1			
04-Jul-90	16.6	44.6	15	4	25	7.3	16.6	44.6			16.6	59.4		10	1			
05-Jul-90	14.7	39.4	15	4	21	7.2	14.7	39.4			14.7	52.6		10	1			
06-Jul-90	15.6	41.9	15	4	19	7.3	15.6	41.9			15.6	55.9		10	1			

Table B.1. (Continued).

DATE	NFT-DN						NFT-DS						NFT-S			
	FLOW (s/d)	FLOW (cm/d)	INF DEPTH (cm)	EFF DEPTH (cm)	TEMP (C)	pH	FLOW (s/d)	FLOW (cm/d)	INF DEPTH (cm)	EFF DEPTH (cm)	FLOW (s/d)	FLOW (cm/d)	INF DEPTH (cm)	EFF DEPTH (cm)	TEMP (C)	pH
Conditions 10, 11, 12 (Continued)																
07-Jul-90	15.4	41.4	15	5	18	7.2	15.4	41.4			15.4	55.2	10	1		
08-Jul-90	15.2	40.8	15	5	17	7.2	15.2	40.8			15.2	54.5	10	1	20	7.1
09-Jul-90	15.3	41.2	16	5	20	7.3	15.3	41.2			15.3	55.0	11	8	21	7.3
10-Jul-90	14.8	39.8	16	5	19	7.3	14.8	39.8			14.8	53.1	11	8	20	7.2
11-Jul-90	15.6	42.1	16	5	17	7.1	15.6	42.1			15.6	56.1	12	12	18	7.1
12-Jul-90	15.1	40.8	16	4	17	7.2	15.1	40.8			15.1	54.4	11	1	17	7.1
13-Jul-90	14.5	39.1	16	5	17	7.3	14.5	39.1			14.5	52.2	10	1	18	7.3
14-Jul-90	14.7	39.5	16	5	20	7.2	14.7	39.5			14.7	52.7	11	1	20	7.2
15-Jul-90	14.8	39.8	16	5	21	7.0	14.8	39.8			14.8	53.0	11	1	22	7.1
16-Jul-90	12.8	34.5	16	5	20	7.0	12.8	34.5			12.8	46.0	11	1	21	7.0
17-Jul-90	14.1	38.0	16	5	20		14.1	38.0			14.1	50.6	11	1	20	
18-Jul-90	13.4	36.0	16	5	19	7.2	13.4	36.0			13.4	47.9	11	1	20	7.3
19-Jul-90	14.8	39.8	16	2	21	7.2	14.8	39.8			14.8	53.1	6	0	24	7.4
20-Jul-90	15.6	41.9				7.3	15.6	41.9			15.6	55.8				7.2
21-Jul-90	15.3	41.1	16	5	22	7.2	15.3	41.1			15.3	54.8	10	1	24	7.2
22-Jul-90	15.1	40.8	15	5	22	7.2	15.1	40.8			15.1	54.4	11	1	22	7.1
23-Jul-90	15.2	41.0	16	5	21	7.3	15.2	41.0			15.2	54.7	11	1	22	7.3
24-Jul-90	14.9	40.0	15	5	19	7.5	14.9	40.0			14.9	53.3	11	1	21	7.4
25-Jul-90	15.1	40.8	15	5	19	7.3	15.1	40.8			15.1	54.4	11	1	20	7.2
26-Jul-90	14.5	39.0	15	5	18	7.3	14.5	39.0			14.5	52.0	11	1	19	7.4
27-Jul-90	15.4	41.5	15	5	18	7.4	15.4	41.5			15.4	55.3	5	0	19	7.4
28-Jul-90	15.9	42.7	16	6	23	7.3	15.9	42.7			15.9	56.9				7.3
29-Jul-90	14.6	39.3	16	6	22	7.4	14.6	39.3			14.6	52.3				7.3
30-Jul-90	14.7	39.7	16	6	21	7.2	14.7	39.7			14.7	52.9				7.1
31-Jul-90	14.5	38.9	16	6	20	7.3	14.5	38.9			14.5	51.9				7.3
01-Aug-90	14.1	38.0	16	6	17	7.3	14.1	38.0			14.1	50.6				7.3
02-Aug-90					18											
Conditions 13 and 14																
06-Aug-90			15	5									12	7	21	
07-Aug-90					19										20	
27-Aug-90	7.6	20.5	14	5	22		7.6	20.5			7.6	27.4	9	1		

APPENDIX C

A SUMMARY OF THE PILOT-SCALE SYSTEM BIOCHEMICAL OXYGEN DEMAND AND VOLATILE FATTY ACID CONCENTRATIONS

Table C-1 summarizes the influent and effluent total and soluble biochemical oxygen demand (BOD and volatile fatty acid (VFA) concentrations of the AAFEB reactor system. Included are all measured values and the summary values of each of the six conditions examined. The Condition 2 summary effluent TBOD concentration from AAFEB-2 was assumed to be the March 14, 1990 concentration because of the steady improvement in performance noted throughout that condition. All other summarized values represent averages of all concentrations measured during that condition. Symbols in the table include:

TBOD	Total biochemical oxygen demand
SBOD	Soluble biochemical oxygen demand
VFA	Volatile fatty acid
INF-U	Raw domestic sewage
INF-S	Partially settled domestic sewage
A-1	First stage AAFEB reactor (AAFEB-1)
A-2	Second stage AAFEB reactor (AAFEB-2)

Table C-2 summarizes the influent and effluent total and soluble biochemical oxygen demand (BOD) concentrations of the NFT reactor system. Included are all measured values and the summary values of each of the thirteen conditions examined. Symbols in the table include:

DS	Southernmost deep-channel NFT reactor
D	Deep-channel reactor system
SN	Northernmost shallow-channel NFT reactor.

Table C.1. A summary of the pilot-scale AAFEB reactor system BOD and VFA concentrations. (Effluent data when not noted otherwise).

DATE	TIME	TBOD INF-U (mg/l)	TBOD INF-S (mg/l)	VFA INF (mg/l)	TBOD A-1 (mg/l)	SBOD A-1 (mg/l)	TBOD A-2 (mg/l)	SBOD A-2 (mg/l)	VFA A-1 (mg/l)	VFA A-2 (mg/l)
Condition 1										
01-Jan-90	930									
17-Jan-90	946		99.4		75.4		65.6		47.0	32.0
24-Jan-90	953		96.4		82.9		64.9		54.0	10.0
Condition 1 Summary			97.9		79.1		65.3		50.5	21.0
Condition 2										
07-Feb-90	967		88.8	12.0	79.8		52.8		37.0	11.0
14-Feb-90	974		120.5	13.0	81.5		57.5		55.0	22.0
21-Feb-90	981		82.8	11.0	70.8		46.8		41.0	12.0
28-Feb-90	988		108.5	18.0	81.5		53.7		36.0	7.0
07-Mar-90	995		110.2	11.0	90.7		44.9		57.0	1.0
14-Mar-90	1002		94.0	10.0	77.5		32.5		60.0	6.0
Condition 2 Summary			100.8	12.5	80.3		32.5		47.7	9.8
Condition 3 and 4										
20-Mar-90	1008			6.0					20.0	8.0
23-Mar-90	1011		72.6	4.0	60.6		33.6		15.0	3.0
28-Mar-90	1016		108.3	4.0	87.3		43.8		31.0	14.0
30-Mar-90	1018		109.9	7.0	96.4		44.7		35.0	14.0
04-Apr-90	1023		63.9	13.0	53.4		32.7		27.0	12.0
06-Apr-90	1025		57.9	1.0	52.4		33.9		17.0	5.0
11-Apr-90	1030		61.8	12.0	51.3		33.9		36.0	12.0
18-Apr-90	1037		70.9	10.0	64.9		38.8		40.0	11.0
20-Apr-90	1039		94.8	16.0	76.8		41.7		58.0	10.0
25-Apr-90	1044		102.4	4.0	81.4		41.8		47.0	8.0
27-Apr-90	1046		90.1	5.0	77.2	58.5	37.9		43.0	3.0
02-May-90	1051		101.5	10.0	71.0	52.2	31.7		53.0	3.0
09-May-90	1058		91.6	10.0	93.1	63.1	19.6		62.0	6.0
16-May-90	1065		55.6	10.0	70.6	37.6	27.7	16.6	38.0	5.0
23-May-90	1072		43.4	1.0	31.2	10.9	14.3	5.9	12.0	2.0
30-May-90	1079		57.4	3.0	55.0	37.0	29.6	18.9	26.0	2.0
Condition 4 Summary			78.8	7.3	68.2	43.2	33.7	13.8	35.0	7.4
Condition 3 (continued) and 5										
06-Jun-90	1086		71.2	4.0	52.2	31.2	42.0	24.3	20.0	6.0
13-Jun-90	1093		76.9		46.3	45.1	36.5	20.6	39.0	12.0
20-Jun-90	1100		53.6	1.0	36.6	33.6	23.6	8.6	38.0	2.0
27-Jun-90	1107		116.7		69.5	57.8	40.0	26.3	51.0	4.0
18-Jul-90	1128		115.6	18.0	78.2	56.7	47.0	34.4	45.0	27.0
25-Jul-90	1135		73.9	14.0	65.2	54.2	52.1	27.7	42.0	12.0
01-Aug-90	1142		97.6	14.0	65.0	59.5	36.6	28.7	49.0	16.0
Condition 5 Summary			86.5	10.2	59.0	48.3	39.6	24.4	40.6	11.3
Condition 3 (continued) and 6										
08-Aug-90	1149	65.7	89.3	16.0	55.2	49.6	28.9	17.5	46.0	4.0
29-Aug-90	1170	91.7	89.7	4.0	59.8	55.5	27.9	11.6	53.0	5.0
Condition 3 Summary			83.5	8.1	64.6	46.8	34.2	20.1	37.7	8.2
Condition 6 Summary			89.5	10.0	57.5	52.5	28.4	14.5	49.5	4.5

Table C.2.

A summary of the pilot-scale NFT system BOD and VFA concentrations. (Effluent data when not noted otherwise).

DATE	TBOD A-2 (mg/l)	SBOD A-2 (mg/l)	TBOD DS (mg/l)	TBOD D (mg/l)	TBOD SN (mg/l)
Conditions 1, 2, 3					
01-Jan-90					
17-Jan-90	65.6		19.0	5.5	4.0
24-Jan-90	64.9		19.6	6.2	6.6
07-Feb-90	52.8		15.3	10.7	17.4
14-Feb-90	57.5				
21-Feb-90	46.8				
28-Feb-90	53.7				
07-Mar-90	44.9		8.8	1.9	
14-Mar-90	32.5		8.2	4.0	
20-Mar-90					
23-Mar-90	33.6		18.6	16.8	5.2
28-Mar-90	43.8		21.9	8.7	2.1
30-Mar-90	44.7				
04-Apr-90	32.7		10.9	3.2	2.7
06-Apr-90	33.9				
11-Apr-90	33.9		14.7	15.9	4.9
18-Apr-90	38.8		13.3	9.9	4.3
20-Apr-90	41.7				
25-Apr-90	41.8		13.0	14.8	12.1
27-Apr-90	37.9				
Condition 1, 2, 3, Summary					
	38.3		14.8	8.9	6.6
Conditions 4, 5, 6					
02-May-90	31.7		14.0	6.2	4.5
09-May-90	19.6		10.8	5.0	5.6
16-May-90	27.7	16.6	9.9	4.3	
23-May-90	14.3	5.9	5.6	11.1	
30-May-90	29.6	18.9	10.5	5.3	5.8
Condition 4, 5, 6, Summary					
	24.6	13.8	10.1	6.4	5.3
Conditions 7, 8, 9					
06-Jun-90	42.0	24.3	19.8	13.5	6.3
13-Jun-90	36.5	20.6	20.5	13.3	9.5
20-Jun-90	23.6	8.6	13.2	8.6	16.8
Conditions 7, 8, 9 Summary					
	34.0	17.8	17.8	11.8	10.8
Conditions 10, 11, 12					
27-Jun-90	40.0	26.3	18.1	11.7	7.9
18-Jul-90	36.9	34.4	13.5	7.6	5.8
25-Jul-90	42.1	27.7	11.1	7.8	
01-Aug-90	36.6	28.7	13.2	10.7	12.6
Conditions 10, 11, 12 Summary					
	36.5	18.8	15.9	10.6	10.0
Conditions 13, 14					
08-Aug-90	28.9	17.5		8.0	4.6
29-Aug-90	27.9	11.6		6.2	3.2
Conditions 10, 11, 12 Summary					
	28.4	14.5		7.1	3.9

APPENDIX D

A SUMMARY OF THE PILOT-SCALE SYSTEM CHEMICAL OXYGEN DEMAND

Table D-1 summarizes the influent and effluent total and soluble chemical oxygen demand (COD) of the AAFEB reactor system. Included are all measured values and the summary values of each of the six conditions examined. Symbols in the table include:

TCOD	Total chemical oxygen demand
SCOD	Soluble chemical oxygen demand
INF-U	Raw domestic sewage
INF-S	Partially settled domestic sewage
A-1	First stage AAFEB reactor (AAFEB-1)
A-2	Second stage AAFEB reactor (AAFEB-2)

Table D-2 summarizes the influent and effluent total and soluble chemical oxygen demand (COD) concentrations of the NFT reactor system. Included are all measured values and the summary values of each of the thirteen conditions examined. Symbols in the table include:

DS	Southernmost deep-channel NFT reactor
D	Deep-channel reactor system
SN	Northernmost shallow-channel NFT reactor.

Table D.1.

A summary of the pilot-scale AAFEB reactor system TCOD and SCOD concentrations. (Effluent data when not noted otherwise).

DATE	TCOD INF-U (mg/l)	SCOD INF-U (mg/l)	TCOD INF-S (mg/l)	SCOD INF (mg/l)	TCOD A-1 (mg/l)	SCOD A-1 (mg/l)	TCOD A-2 (mg/l)	SCOD A-2 (mg/l)
Condition 1								
17-Jan-90			215.4	129.2	172.3	103.4	151.4	90.8
24-Jan-90			204.8	122.9	163.8	98.3	146.8	88.1
Summary of Condition 1								
			210.1	126.1	168.1	100.8	149.1	89.5
Condition 2								
07-Feb-90			186.6	111.6	133.3	75.9	112.2	62.9
14-Feb-90			224.0	124.6	145.9	98.2	120.2	71.8
21-Feb-90			184.7	111.6	132.7	86.1	119.6	64.1
28-Feb-90			207.8	145.3	153.6	93.9	115.9	67.0
07-Mar-90			238.0	149.7	172.9	130.2	122.1	81.3
14-Mar-90			201.2	114.7	174.2	127.1	106.7	61.1
Summary of Condition 2								
			207.0	126.2	152.1	101.9	116.1	68.0
Condition 3 and 4								
20-Mar-90			209.9	129.6	140.2	84.3	86.7	52.4
23-Mar-90			152.5	71.2	142.1	86.7	86.1	54.7
28-Mar-90			256.5	98.9	174.2	79.5	122.1	67.6
30-Mar-90			256.5	97.0	226.1	118.4	126.5	77.1
04-Apr-90			170.9	75.3	154.8	73.5	111.0	69.4
06-Apr-90			210.5	120.2	178.1	117.8	141.0	84.3
11-Apr-90			136.5	65.3	128.3	71.2	99.4	60.6
18-Apr-90			210.0	109.8	160.0	95.1	127.7	90.3
20-Apr-90			241.9	130.2	187.9	119.0	141.5	105.5
25-Apr-90			255.8	115.3	206.5	145.9	109.1	66.4
27-Apr-90			250.2	112.8	203.8	145.9	112.8	72.4
02-May-90			278.5	100.6	173.5	120.9	98.2	50.6
09-May-90			238.4	98.8	187.3	111.0	115.9	74.1
16-May-90			170.3	37.3	181.4	60.6	97.0	50.6
23-May-90			111.0	24.7	105.5	24.2	63.5	34.4
30-May-90			154.8	72.9	127.7	80.7	72.9	42.5
Summary Condition 4								
			206.5	91.2	167.3	95.9	107.0	65.8
Condition 5								
06-Jun-90			191.2	28.3	135.8	60.6	118.4	65.3
13-Jun-90			228.8	122.1	157.4	107.3	135.8	86.7
20-Jun-90			189.9	52.9	140.9	21.9	98.8	41.3
27-Jun-90			247.4	57.6	174.2	117.1	172.2	130.2
18-Jul-90			216.6	111.0	236.4	195.8	147.2	104.3
25-Jul-90			227.2	83.1	149.7	104.9	130.8	86.1
01-Aug-90			224.2	94.5	169.0	125.8	130.8	79.5
Summary Condition 5								
			217.9	78.5	166.2	104.8	133.4	84.8
Condition 6								
08-Aug-90	186.6	76.5	210.2	97.6	161.3	126.5	138.9	70.0
29-Aug-90	253.0	100.0	233.6	131.4	156.8	101.8	125.9	46.6
Summary Condition 3								
	219.8	88.2	210.9	89.5	166.4	99.8		
Summary Condition 6								
	219.8	88.2	221.9	114.5	159.0	114.1	132.4	58.3

Table D.2.

A summary of the pilot-scale NFT system TCOD and SCOD concentrations. (Effluent data when not noted otherwise).

DATE	TCOD A-2 (mg/l)	SCOD A-2 (mg/l)	TCOD DS (mg/l)	SCOD DS (mg/l)	TCOD D (mg/l)	SCOD D (mg/l)	TCOD SN (mg/l)	SCOD SN (mg/l)
Conditions 1, 2, 3								
17-Jan-90	151.4	90.8						
24-Jan-90	146.8	88.1						
07-Feb-90	112.2	62.9	48.3	32.2	48.3	46.0	20.2	17.9
14-Feb-90	120.2	71.8						
21-Feb-90	119.6	64.1						
28-Feb-90	115.9	67.0						
07-Mar-90	122.1	81.3	71.2	58.2	35.0	30.4		
14-Mar-90	106.7	61.1	77.7	58.2	39.0	30.4		
20-Mar-90	86.7	52.4						
23-Mar-90	86.1	54.7	49.5	41.3	61.1	58.8	21.3	20.2
28-Mar-90	122.1	67.6	38.5	24.2	34.4	31.6	22.5	19.6
30-Mar-90	126.5	77.1						
04-Apr-90	111.0	69.4	42.5	29.3	27.6	23.6	31.6	31.6
06-Apr-90	141.0	84.3	28.8	39.6	24.2	21.9	28.2	25.9
11-Apr-90	99.4	60.6						
18-Apr-90	127.7	90.3	41.9	31.6	58.2	51.2	28.2	23.6
20-Apr-90	141.5	105.5						
25-Apr-90	109.1	66.4	72.9	61.7	51.8	44.2	32.2	24.2
27-Apr-90	112.8	72.4						
Summary of Conditions 1, 2, 3								
	118.9	73.0	52.4	41.8	42.2	37.6	26.3	23.3
Conditions 4, 5, 6								
02-May-90	98.2	50.6	64.7	46.6	31.6	25.9	29.3	26.4
09-May-90	115.9	74.1	78.9	68.2	39.0	33.9	35.6	26.4
16-May-90	97.0	50.6	44.2	33.9	27.6	21.9		
23-May-90	63.5	34.4	32.2		10.6	3.9		
30-May-90	72.9	42.5	39.6	28.2	37.9	33.3	19.4	17.0
Summary of Conditions 4, 5, 6								
	89.5	50.5	51.9	44.2	29.3	23.8	28.1	23.3
Conditions 7, 8, 9								
06-Jun-90	118.4	65.3	71.2	35.0	42.5	35.0	33.5	22.9
13-Jun-90	135.8	86.7	55.9	44.8	43.7	39.0	39.5	21.8
20-Jun-90	98.8	41.3	91.5	83.1	34.4	27.6		
Summary of Conditions 7, 8, 9								
	117.7	64.4	72.8	54.3	40.2	33.9	36.5	22.4
Condition 10, 11, 12								
27-Jun-90	172.2	130.2	64.7	59.4	41.9	41.3	30.0	25.6
18-Jul-90	147.2	104.3	55.9	51.2	48.9	47.7	20.6	17.7
25-Jul-90	130.8	86.1	39.0	27.6	33.9	33.3		
01-Aug-90	130.8	79.5	44.8	38.5	33.3	32.7		40.8
Summary of Conditions 7, 8, 9								
	145.3	100.0	51.1	44.2	39.5	38.8	25.3	28.0
Condition 13 and 14								
08-Aug-90	138.9	70.0			92.7	91.5	45.1	40.8
29-Aug-90	125.9				56.5	47.7	37.3	32.2
Summary of Conditions 13 and 14								
	132.4	70.0			74.6	69.6	41.2	36.5

APPENDIX E

A SUMMARY OF THE PILOT-SCALE SYSTEM SUSPENDED AND VOLATILE SUSPENDED SOLIDS

Table E-1 summarizes the influent and effluent suspended (SS) and volatile suspended (VSS) solids concentrations of the AAFEB reactor system. Included are all measured values and the summary values of each of the six conditions examined. Symbols in the table include:

SS	Suspended solids
VSS	Volatile suspended solids
INF-U	Raw domestic sewage
INF-S	Partially settled domestic sewage
A-1	First stage AAFEB reactor (AAFEB-1)
A-2	Second stage AAFEB reactor (AAFEB-2)

Table E-2 summarizes the influent and effluent SS and VSS concentrations of the NFT reactor system. Included are all measured values and the summary values of each of the thirteen conditions examined. Symbols in the table include:

DS	Southernmost deep-channel NFT reactor
D	Deep-channel reactor system
SN	Northernmost shallow-channel NFT reactor.

Table E.1.

A summary of the pilot-scale AAFEB reactor system SS and VSS concentrations. (Effluent data when not noted otherwise).

DATE	SS INF-U (mg/l)	VSS INF-U (mg/l)	SS INF-S (mg/l)	VSS INF-S (mg/l)	SS A-1 (mg/l)	VSS A-1 (mg/l)	SS A-2 (mg/l)	VSS A-2 (mg/l)
Condition 1								
17-Jan-90			77.3	58.9	40.4	29.4	38.3	25.8
24-Jan-90			64.1	48.2	49.2	36.9	31.3	22.6
Summary of Condition 1								
			70.7	53.5	44.8	33.1	34.8	24.2
Condition 2								
07-Feb-90			42.2	27.5	19.6	9.6	19.3	2.6
14-Feb-90			49.0	47.3	23.4	15.2	26.3	16.0
21-Feb-90			62.4	30.3	22.3	13.6	19.0	17.7
28-Feb-90			43.4	28.3	35.5	21.7	24.8	16.0
07-Mar-90			51.9	37.4	28.1	17.3	25.0	17.6
14-Mar-90			59.2	45.0	21.7	15.7	27.7	21.9
Summary of Condition 2								
			51.4	36.0	25.1	15.5	23.7	15.3
Conditions 3 and 4								
20-Mar-90			59.9	46.7	33.5	24.3	23.6	23.6
23-Mar-90			58.3	46.1	37.0	27.0	24.2	14.1
28-Mar-90			61.6	51.6	56.4	44.3	34.4	20.8
30-Mar-90			102.4	77.9	45.4	30.9	33.4	22.0
04-Apr-90			59.3	41.0	32.5	22.7	20.9	12.3
06-Apr-90			48.2	32.6	32.1	19.8	22.6	13.4
11-Apr-90			69.5	53.1	38.5	29.3	28.9	18.6
18-Apr-90			71.0	61.5	38.0	31.2	28.4	17.6
25-Apr-90			98.8	80.8	35.8	29.5	32.2	20.4
27-Apr-90			89.1	75.7	29.2	23.2	32.0	18.0
02-May-90			96.4	80.5	46.2	36.3	36.8	19.8
09-May-90			108.1	93.4	26.7	22.5	31.4	17.6
16-May-90			61.2	51.6	42.9	34.1	32.5	18.6
23-May-90			46.8	37.4	29.5	22.0	20.4	11.5
30-May-90			57.9	44.6	32.1	25.1	24.1	12.4
Summary of Condition 4								
			72.6	58.3	37.0	28.1	28.4	17.4
Condition 5								
06-Jun-90			59.7	47.8	31.2	22.0	33.1	21.8
13-Jun-90			73.6	56.6	27.3	20.5	30.7	22.5
20-Jun-90			63.6	53.0	31.5	24.4	28.8	19.3
27-Jun-90					38.7	27.8	28.6	23.3
18-Jul-90			78.2	65.3	26.9	16.2	21.4	19.2
25-Jul-90			65.9	57.7	29.3	18.5	21.2	19.8
01-Aug-90			69.6	54.1	32.9	16.4	24.2	23.9
Summary of Condition 5								
			68.4	55.7	31.1	20.8	26.9	21.4
Condition 6								
08-Aug-90	78.4	61.6	75.3	60.1	28.4	19.4	29.3	20.7
29-Aug-90	121.2	86.6	68.5	49.8	29.3	21.2		
Summary of Condition 3								
	99.8	74.1	71.4	57.3	34.6	25.4		
Summary of Condition 6								
	99.8	74.1	71.9	54.9	28.9	20.3	29.3	20.7

Table E.2.

A summary of the pilot-scale NFT system SS and VSS concentrations. (Effluent data when not noted otherwise).

DATE	SS A-2 (mg/l)	VSS A-2 (mg/l)	SS DS (mg/l)	VSS DS (mg/l)	SS D (mg/l)	VSS D (mg/l)	SS SN (mg/l)	VSS SN (mg/l)
Condition 1, 2, 3								
17-Jan-90	38.3	25.8	21.5	14.7	5.3	3.6	3.7	1.7
24-Jan-90	31.3	22.6	39.9	23.5	10.8	6.7	28.8	12.8
07-Feb-90	19.3	2.6	9.4	5.1	2.6	0.4	3.5	0.9
14-Feb-90	46.3	16.0						
21-Feb-90	29.0	17.7						
28-Feb-90	34.8	16.0						
07-Mar-90	19.3	17.6	16.2	7.8	6.4	2.3		
14-Mar-90	26.3	21.9	10.7	6.8	7.5	4.4		
20-Mar-90	19.0	23.6						
23-Mar-90	24.8	14.1	8.1	4.7	4.2	2.1	2.9	2.0
28-Mar-90	25.0	20.8	9.5	6.3	3.1	2.1	2.7	2.2
30-Mar-90	27.7	22.0						
04-Apr-90	20.9	12.3	10.1	5.6	2.5	1.3	1.6	0.9
06-Apr-90	22.6	13.4						
11-Apr-90	28.9	18.6	7.9	4.5	3.6	1.9	3.8	2.2
18-Apr-90	28.4	17.6						
25-Apr-90	32.2	20.4	9.2	6.5	13.6	6.7	11.1	8.7
27-Apr-90	32.0	18.0						
Summary of Conditions 1, 2, 3								
	28.1	17.8	9.0	5.5	5.4	2.8	4.4	3.2
Conditions 4, 5, 6								
02-May-90	36.8	19.8	9.5	5.7	4.6	2.3	4.5	3.1
09-May-90	31.4	17.6	15.1	9.8	5.6	3.2	3.3	2.1
16-May-90	32.5	18.6	9.0	5.7	5.4	2.8		
23-May-90	20.4	11.5	4.7	12.0	4.4	2.0	9.1	6.5
30-May-90	24.1	12.4	10.7	5.7	7.6	3.3	4.0	2.1
Summary of Conditions 4, 5, 6								
	29.0	16.0	9.8	7.8	5.5	2.7	5.2	3.5
Conditions 7, 8, 9								
06-Jun-90	33.1	21.8	7.0	5.1	11.9	6.8	3.7	2.1
13-Jun-90	30.7	22.5	8.0	5.7	6.6	4.1	12.7	5.8
20-Jun-90	28.8	19.3	5.9	4.5	5.4	3.4	10.5	4.6
Summary of Conditions 7, 8, 9								
	30.9	21.2	6.9	5.1	8.0	4.8	9.0	4.1
Conditions 10, 11, 12								
27-Jun-90	28.6	23.3	3.9	2.9	3.0	2.0	7.5	4.3
18-Jul-90	21.4	19.2	2.4	1.1	3.3	2.2	4.4	2.0
25-Jul-90	21.2	19.8	2.9	1.4	0.8			
01-Aug-90	24.2	23.9	3.5	2.4	2.4	1.4	4.6	2.5
Summary of Conditions 7, 8, 9								
	23.9	21.5	3.2	2.0	2.4	1.9	5.5	2.9
Conditions 13 and 14								
08-Aug-90	29.3	20.7			2.6	1.4	3.2	1.1
29-Aug-90					4.5	2.8	4.6	1.8
Summary of Conditions 13 and 14								
	29.3	20.7			3.6	2.1	3.9	1.5

APPENDIX F

A SUMMARY OF THE PILOT-SCALE SYSTEM TOTAL AMMONIA AND KJELDAHL NITROGEN CONCENTRATIONS

Table F-1 summarizes the influent and effluent total ammonia (TAN) and total kjeldahl (TKN) nitrogen concentrations of the AAFEB reactor system. Included are all measured values and the summary values of each of the six conditions examined. Symbols in the table include:

TAN	Total ammonia nitrogen
TKN	Total kjeldahl nitrogen
INF-U	Raw domestic sewage
INF-S	Partially settled domestic sewage
A-1	First stage AAFEB reactor (AAFEB-1)
A-2	Second stage AAFEB reactor (AAFEB-2)

Table F-2 summarizes the influent and effluent TAN and TKN concentrations of the NFT reactor system. Included are all measured values and the summary values of each of the thirteen conditions examined. Symbols in the table include:

DS	Southernmost deep-channel NFT reactor
D	Deep-channel reactor system
SN	Northernmost shallow-channel NFT reactor.

Table F. A summary of the pilot nitrogen concentrations.

Table F.1.

A summary of the pilot-scale AAFEB reactor system TAN and TKN concentrations. (Effluent data when not noted otherwise).

DATE	TAN INF (mg/l)	TKN INF (mg/l)	TAN A-1 (mg/l)	TKN A-1 (mg/l)	TAN A-2 (mg/l)	TKN A-2 (mg/l)
01-Jan-90						
Condition 1						
17-Jan-90	16.1	27.1	18.7	25.9	19.7	26.2
Condition 2						
24-Jan-90	14.1	26.0	18.5	26.4	19.3	25.6
07-Feb-90	11.6	22.5	17.1	23.5	15.1	21.4
14-Feb-90	12.5	23.2	16.0	21.9	16.1	21.0
21-Feb-90	11.6	23.4	16.9	22.1	16.6	21.7
28-Feb-90	14.5	23.3	19.0	23.4	19.9	23.9
07-Mar-90	14.6	27.1	20.4	26.2	20.3	25.6
14-Mar-90	13.5	22.2	16.7	21.3	17.1	21.9
Summary of Condition 2						
	13.2	23.9	17.8	23.5	17.8	23.0
Condition 3 and 4						
23-Mar-90	8.8	16.5	12.0	17.3	12.6	18.1
28-Mar-90	13.2	24.6	17.7	23.9	18.2	23.1
04-Apr-90	10.1	18.0	13.0	18.6	16.0	20.4
11-Apr-90	10.6	20.3	14.1	19.2	14.7	18.6
18-Apr-90	13.7	24.0	17.4	23.6	18.0	23.3
25-Apr-90	14.4	26.6	17.4	25.0	20.1	24.9
02-May-90	16.6	28.8	19.7	25.9	20.7	27.4
09-May-90	18.3		19.8	27.6	20.7	26.2
16-May-90	12.8	21.4	17.0	24.3	19.1	24.3
23-May-90	7.6	14.3	10.0		10.5	
30-May-90	9.0	16.8	12.5	17.9	13.6	17.7
Summary of Condition 4						
	12.3	21.1	15.5	22.3	16.8	22.4
Condition 5						
06-Jun-90	12.3	20.6	13.4	18.2	15.3	20.2
13-Jun-90	13.4	23.2	15.2	20.9	16.8	22.9
20-Jun-90	12.0	19.8	15.8	20.4	15.7	20.0
27-Jun-90	9.8	19.5	14.3	19.6	15.9	20.6
18-Jul-90	13.0	22.7	15.9	21.1	17.8	22.6
25-Jul-90	11.6	18.5	14.6	19.3	16.8	19.9
01-Aug-90	12.4	19.1	15.5	19.3	17.0	20.7
Summary of Condition 5						
	12.1	20.5	14.9	19.8	16.5	21.0
Condition 6						
29-Aug-90	14.1	21.3	16.4	20.2	20.0	23.9
Summary of Condition 3						
	12.3	20.9	15.3	21.2		

Table F.2.

A summary of the pilot-scale NFT system TAN and TKN concentrations. (Effluent data when not noted otherwise).

DATE	TAN A-2 (mg/l)	TKN A-2 (mg/l)	TAN DS (mg/l)	TKN DS (mg/l)	TAN D (mg/l)	TKN D (mg/l)	TAN SN (mg/l)	TKN SN (mg/l)
01-Jan-90								
Condition 1, 2, 3								
17-Jan-90	19.7	26.2	17.5	22.4	16.2	20.0	14.5	17.6
24-Jan-90	19.3	25.6	17.4	21.7	17.0	21.7	14.7	17.7
07-Feb-90	15.1	21.4	15.1	19.2	15.2	18.6	10.9	15.6
14-Feb-90	16.1	21.0						
21-Feb-90	16.6	21.7						
28-Feb-90	19.9	23.9					14.5	
07-Mar-90	20.3	25.6	18.0	22.7	15.6	19.9		
14-Mar-90	17.1	21.9	17.8	20.7	15.3	17.7		
23-Mar-90	12.6	18.1	13.2	16.0	13.0	15.5	4.6	7.1
28-Mar-90	18.2	23.1	15.0	18.5	13.2	15.4	2.7	5.3
04-Apr-90	16.0	20.4	15.6	18.7	13.8	16.3	8.1	11.5
11-Apr-90	14.7	18.6	14.5	17.3	11.7	14.0	5.7	8.0
18-Apr-90	18.0	23.3	16.2	20.2	14.1	17.5	9.2	12.2
25-Apr-90	20.1	24.9	17.9	21.4	15.0	18.4	7.4	12.1
Summary of Conditions 1, 2, 3								
	17.4	22.5	16.2	19.9	14.5	17.7	9.2	11.9
Conditions 4, 5, 6								
02-May-90	20.7	27.4	18.4		16.4		11.1	
09-May-90	20.7	26.2	18.8	28.3	18.0	22.2	10.4	15.4
16-May-90	19.1	24.3	17.5	21.4	15.3	18.7		
23-May-90	10.5		10.8		11.6	14.9	11.1	
30-May-90	13.6	17.7	13.4	16.0	11.7	13.9	8.0	10.2
Summary of Conditions 4, 5, 6								
	16.9	23.9	15.8	21.9	14.6	17.4	10.1	12.8
Conditions 7, 8, 9								
06-Jun-90	15.3	20.2	14.5	18.9	14.7	17.1	13.0	15.0
13-Jun-90	16.8	22.9	15.8	19.4	15.9	18.8	13.9	16.4
20-Jun-90	15.7	20.0	15.5	18.1	14.8	17.0	16.3	
Summary of Conditions 7, 8, 9								
	15.9	21.0	15.3	18.8	15.1	17.6	14.4	15.7
Conditions 10, 11, 12								
27-Jun-90	15.9	20.6	15.7	18.3	16.6	18.5	14.5	16.4
18-Jul-90	17.8	22.6	17.2	20.0	17.6	19.5	17.8	19.8
25-Jul-90	16.8	19.9	15.1	17.1	16.0	17.6		
01-Aug-90	17.0	20.7	16.1	17.9	15.8	17.4	16.0	17.9
Summary of Conditions 10, 11, 12								
	16.9	20.9	16.0	18.3	16.5	18.3	16.1	18.0
Conditions 13 and 14								
29-Aug-90	20.0	23.9			19.2	20.6	17.9	19.7

APPENDIX G

A SUMMARY OF THE PILOT-SCALE SYSTEM TOTAL PHOSPHOROUS (TP) AND ORTHOPHOSPHATE (OP) CONCENTRATIONS

Table G-1 summarizes the influent and effluent total phosphorous (TP) and orthophosphate (OP) concentrations of the AAFEB reactor system. Included are all measured values and the summary values of each of the six conditions examined. Symbols in the table include:

TP	Total phosphorous
OP	Orthophosphate
INF-U	Raw domestic sewage
INF-S	Partially settled domestic sewage
A-1	First stage AAFEB reactor (AAFEB-1)
A-2	Second stage AAFEB reactor (AAFEB-2)

Table F-2 summarizes the influent and effluent TP and OP concentrations of the NFT reactor system. Included are all measured values and the summary values of each of the thirteen conditions examined. Symbols in the table include:

DS	Southernmost deep-channel NFT reactor
D	Deep-channel reactor system
SN	Northernmost shallow-channel NFT reactor.

Table G.1.

A summary of the pilot-scale AAFEB reactor system TP and OP concentrations. (Effluent data when not noted otherwise).

DATE	OP INF (mg/l)	TP INF (mg/l)	OP A-1 (mg/l)	TP A-1 (mg/l)	OP A-2 (mg/l)	TP A-2 (mg/l)
Condition 1						
17-Jan-90	1.5	3.8	1.8	3.5	2.0	3.8
Condition 2						
07-Feb-90	1.2	2.9	1.7	3.0	1.7	3.7
14-Feb-90	1.3	3.3	1.8	2.8	6.1	3.1
21-Feb-90	1.4	4.3	1.9	2.7	1.8	3.0
28-Feb-90	1.7	3.0	2.4	4.2	2.2	3.5
07-Mar-90	1.8	3.9	2.6	3.8	2.5	3.4
14-Mar-90	1.6	3.9	2.6	3.5	2.6	3.7
Summary of Condition 2						
	1.5	3.6	2.2	3.3	2.8	3.4
Condition 3 and 4						
21-Mar-90	1.2	1.4	1.2	2.4	1.1	2.4
28-Mar-90	1.2	3.5	1.9	4.2	2.0	3.6
04-Apr-90	1.1	2.4	1.4	3.6	1.8	2.8
11-Apr-90	1.5	3.2	2.1	3.0	2.3	3.2
18-Apr-90	1.5	3.0	2.2	3.2	2.3	3.2
25-Apr-90	1.5	5.1	2.3	4.2	2.5	3.7
27-Apr-90	1.3		2.1		2.2	
02-May-90	1.4	4.0	2.4	3.5	1.6	3.3
09-May-90	1.9	4.3	2.2	3.9	2.7	3.3
16-May-90	1.1		1.6		2.4	
23-May-90		1.4		2.0		1.6
30-May-90	1.1	1.7	1.8	2.4	2.7	2.9
Summary of Condition 4						
	1.3	3.0	1.9	3.2	2.1	3.0
Condition 5						
06-Jun-90	0.0	3.2	0.6	3.0	1.8	3.4
13-Jun-90	1.4	3.5	1.9	3.9	2.0	3.7
20-Jun-90	1.0	3.2	1.9	3.0	2.0	3.0
27-Jun-90	1.2	3.9	9.2	10.7	8.4	10.3
18-Jul-90	1.7	3.8	2.9	3.5	2.5	3.9
25-Jul-90	1.0	3.5	1.5	3.5	1.5	3.7
01-Aug-90	1.0		1.7		1.7	
Summary of Condition 5						
	1.0	3.5	2.8	4.6	2.9	4.7
Condition 6						
29-Aug-90	1.7	4.5	1.7	4.0	1.7	4.7
Summary of Condition 3						
	1.2	3.3	2.2	3.8	2.4	3.7

Table G.2.

A summary of the pilot-scale NFT system TP and OP concentrations. (Effluent data when not noted otherwise).

DATE	OP A-2 (mg/l)	TP A-2 (mg/l)	OP DS (mg/l)	TP DS (mg/l)	OP D (mg/l)	TP D (mg/l)	OP SN (mg/l)	TP SN (mg/l)
Condition 1, 2, 3								
07-Feb-90	1.7	3.7	1.6	2.9	1.9	2.6	1.0	1.2
14-Feb-90	6.1	3.1						
21-Feb-90	1.8	3.0						
28-Feb-90	2.2	3.5						
07-Mar-90	2.5	3.4	1.2	2.0	1.0	1.3		
14-Mar-90	2.6	3.7	1.8	2.6	2.1	2.7		
21-Mar-90	1.1	2.4	0.9	1.9	0.6	1.3	0.1	0.3
28-Mar-90	2.0	3.6	1.2	2.2	1.1	1.2	0.0	0.3
04-Apr-90	1.8	2.8	1.2	2.3	1.2	0.9	0.0	0.1
11-Apr-90	2.3	3.2	4.2	2.3	1.1	0.9	0.0	0.1
18-Apr-90	2.3	3.2	1.9	2.6	1.5	1.7	0.9	0.7
25-Apr-90	2.5	3.7	1.3	2.2	1.2	1.7	0.0	0.8
27-Apr-90	2.2							
Summary of Conditions 1, 2, 3								
	2.4	3.3	1.7	2.3	1.3	1.6	0.3	0.5
Conditions 4, 5, 6								
02-May-90	1.6	3.3	1.1	1.9	0.8	0.4	0.0	0.3
09-May-90	2.7	3.3	1.5	2.5	1.0	0.8	0.0	
16-May-90	2.4		1.6		1.3			
23-May-90		1.6		1.5		0.5		
30-May-90	2.7	2.9	4.1	2.1	1.1	4.7	0.0	2.0
Summary of Conditions 4, 5, 6								
	2.3	2.8	2.1	2.0	1.0	1.6	0.0	1.1
Conditions 7, 8, 9								
06-Jun-90	1.8	3.4	0.6	3.4	2.3	3.8	1.4	2.1
13-Jun-90	2.0	3.7	2.3	3.8	2.5	4.3	1.4	2.9
20-Jun-90	2.0	3.0	2.1	3.2	2.2	3.3	1.1	2.5
Summary of Conditions 7, 8, 9								
	1.9	3.4	1.7	3.5	2.3	3.8	1.3	2.5
Conditions 10, 11, 12								
27-Jun-90	8.4	10.3	7.5	9.3	6.7	9.0	3.9	6.2
18-Jul-90	2.5	3.9	2.7	4.0	4.0	3.8	3.6	5.7
25-Jul-90	1.5	3.7	1.5	3.2	1.8	3.3		
01-Aug-90	1.7		1.7		2.0		2.5	
Summary of Conditions 10, 11, 12								
	3.5	6.0	3.4	5.5	3.6	5.4	3.3	6.0
Conditions 13 and 14								
29-Aug-90	1.7	4.7			2.0	3.8	2.5	3.7

APPENDIX H

A SUMMARY OF THE SETTLING COLUMN STUDIES

A total of six batch settling column studies were conducted over the period from March 2, 1990 through August 30, 1990 to interpret the first stage AAFEB reactor effluent and recycle liquid settling characteristics. In these studies, either the liquid effluent or liquid from the recycle stream was carefully siphoned into a settling column. The settling characteristics of the liquids were interpreted in terms of the suspended solids concentration at specific heights in the column with respect to time.

Table H. A summary of the studies to examine the settling characteristics of the recycle and effluent liquids of the AAFEB reactor system.

Settling Column Test #1
Average Temperature 11°C
Date: March 2, 1990

PORT HEIGHT (cm)	15	76	152	213	274
PORT #	#5	#4	#3	#2	#1
TIME (hrs)	SS (mg/l)	SS (mg/l)	SS (mg/l)	SS (mg/l)	SS (mg/l)
0.0	32.0	32.0		32.0	32.0
1.0	32.0	25.0	26.0	26.0	26.0
4.0	25.0	22.0	25.0	24.0	
6.5	18.0	18.0	19.0	18.0	
24.0	20.0	21.0	18.7	19.5	

Settling Column Test #2
Average Temperature 11.5°C
Date: March 9, 1990

PORT HEIGHT (cm)	15	91	152	183	213	274	305	LIQUID HEAD LEVEL
PORT #	#5		#3		#2	#1		
TIME (hrs)	SS (mg/l)	TEMP (C)	SS (mg/l)	TEMP (C)	SS (mg/l)	SS (mg/l)	TEMP (C)	(cm)
0.00	37.8	11		12		38.4	12	305
0.50	39.7	11	37.4	12	35.3	35.7	12	299
1.50	43.5	11	37.2	12	36.7	32.3	12	295
4.00	33.5	11	42.1	12	33.6	38.4	11	291
6.75	33.2	10	33.9	11	25.9	26.3	11	287
23.50	32.9	9	30.7	11	28.5	23.6	12	283

Table H. Continued.

Settling Column Test #3
Average Liquid Temperature 13°C
Date: April 19, 1990

PORT HEIGHT (cm)	15	91	152	183	213	274	305	LIQUID HEAD LEVEL
PORT #	#5		#3		#2	#1		
TIME (hrs)	SS (mg/l)	TEMP (C)	SS (mg/l)	TEMP (C)	SS (mg/l)	SS (mg/l)	TEMP (C)	(cm)
0.00	118.8	13		12		108.0	13	300
0.50	115.0	13	104.0	12	102.6	86.6	13	297
1.50	80.9	13	79.7	12	78.5	61.5	13	293
4.00	59.8	13	62.5	12	56.0	51.9	13	290
6.50	50.2	13	51.3	12	44.1	33.0	13	286
24.00	25.0		24.6		20.5	13.9		281

Settling Column Test #4
Average Liquid Temperature 14.9 to 16.0°C
Date: May 5, 1990

PORT HEIGHT (cm)	15	91	152	183	213	274	305	LIQUID HEAD LEVEL
PORT #	#5		#3		#2	#1		
TIME (hrs)	SS (mg/l)	TEMP (C)	SS (mg/l)	TEMP (C)	SS (mg/l)	SS (mg/l)	TEMP (C)	(cm)
0.00	174.5	16		15		172.4	16	305
0.50	146.5	15	138.6	15	128.6	125.3	16	302
1.50	98.6	15	98.5	15	95.7	89.7	16	298
4.00	72.1	15	75.7	15	65.1	61.6	16	294
6.50	58.1	15	57.0	14	52.0	54.1	15	290
24.00	32.8	14	30.4	13	33.2	34.0	15	284

Table H. Continued.

Settling Column Test #5
Average Liquid Temperature 19.0 to 20.9°C
Date: June 29, 1990

PORT HEIGHT (cm)	15	91	152	183	213	274	305	LIQUID HEAD LEVEL
PORT #	#5		#3		#2	#1		
TIME (hrs)	SS (mg/l)	TEMP (C)	SS (mg/l)	TEMP (C)	SS (mg/l)	SS (mg/l)	TEMP (C)	(cm)
0.00	85.5	20		19		132.4	20	305
0.50	62.9	20	59.3	19	53.8	53.6	20	302
1.50	46.1	20	41.5	19	46.8	32.5	21	297
4.00	35.1	20	33.5	19	29.4	25.9	21	293
6.75	29.1	20	22.3	19	22.5	22.5	21	290
23.50	15.3		16.3		15.4	11.5		

Settling Column Test #6
Average Liquid Temperature 25.1 to 27.0°C
Date: August 30, 1990

PORT HEIGHT (cm)	15	91	152	183	213	274	305	LIQUID HEAD LEVEL
PORT #	#5		#3		#2	#1		
TIME (hrs)	SS (mg/l)	TEMP (C)	SS (mg/l)	TEMP (C)	SS (mg/l)	SS (mg/l)	TEMP (C)	(cm)
0.00	351.6	24		24		400.0	25	305
0.50	138.2	23	136.9	24	112.6	110.7	26	301
1.50	84.6	23	78.4	23	73.2	57.4	26	298
4.00	60.3	24	68.7	24	43.3	32.1	27	293
6.50	38.7	23	41.6	21	45.9	32.5	27	290
24.00	23.7	24	32.2	24	27.0	29.7	27	

APPENDIX I

A SUMMARY OF THE PILOT-SYSTEM FECAL COLIFORM CONCENTRATIONS

Table I. A summary of pilot-system fecal coliform concentrations.

DATE	WASTEWATR FLOW (s/d)	INF (col/100 ml)	AAFEB-2 EFF (col/100 ml)	DN EFF (col/100 ml)	SN EFF (col/100 ml)
19-Jun-90	16.1	1,000,000	260,000	160,000	146,000
26-Jun-90	14.2	470,000	420,000		4,400
03-Jul-90	14.8	700,000	61,800		45
10-Jul-90	15.4	434,000	131,000		4,800
17-Jul-90	14.4	740,000	178,000		14,200
24-Jul-90	15.4	1,100,000	326,000		1,700
31-Jul-90	15.2	846,000	192,000	23,100	3,750
07-Aug-90	7.1	1,200,000	240,000		9,300
22-Aug-90	6.9	640,000	84,000	9,900	4,600
28-Aug-90	7.9	682,000	250,000		120
30-Aug-90	7.1	406,000	133,000		40
27-Sep-90	7.1	1,560,000	124,000	4,000	30
10-Dec-90	5.3	280,000	35,000	180	0
31-Dec-90	5.3	2,000,000	170,000	910	20

APPENDIX J

A SUMMARY OF THE NFT REACTOR SYSTEM BIOMASS PRODUCTION

Table J.1.a. summarizes the November 1989 biomass harvest of the southernmost shallow-channel NFT reactor. Three representative .093 square meter areas were removed from the reactor for analysis of the stalk and rhizome wet dry and volatile masses.

Table J.1.b. summarizes the June and July 1990 stalk biomass harvest wet, dry and volatile masses from specific sections of the total NFT reactor system. Included are stalk density measurements.

Table J.1.c. summarizes the January 1991 wet, dry, and volatile stalk biomass yields for each section of the deep and shallow-channel NFT reactors.

Table J.1.d. summarizes the December 1990 composite biomass yields of the southernmost shallow-channel NFT reactor. It includes the combined results of the stalk and rhizome wet, dry, and volatile mass yields.

Table J.2. summarizes the fiber analysis results of the stalk and rhizome biomass samples from the southernmost shallow-channel NFT reactor measured in December 1990 as compared to Cattails supplied by Dr Leland Marsh as a control.

Table J.3. summarizes the elemental analysis of the June, July, and December 1990 harvest of the stalk and rhizome biomass from representative section of the NFT reactor system as compared to samples of cattails supplied by Dr Leland Marsh as controls.

Table J.4. summarizes the definition of the southernmost shallow-channel NFT reactor root-zone volume, mass, and density as measured at five points during throughout 1990.

Table J.1.a. A summary of the biomass harvest of the northernmost shallow-channel NFT reactor.

DATE	UNIT NO	STALK	RHYZOME	RHYZOME	TS	TVS	DRY MASS	DRY MASS	VOLATILE MASS
		WET MASS	WET MASS	WET MASS					
		(kg)	(kg)	YIELD (kg/m^2)					
Total biomass present as of November 15, 1989.									
Unit Area = 0.093 square meters.									
15-Nov-89	NFT-S:3-1'	1.96	5.30	57.01	12.35	77.96	0.90	96.43	75.18
15-Nov-89	NFT-S:7-9'	2.31	4.83	51.95	16.89	85.06	1.21	129.71	110.33
15-Nov-89	NFT-S:11-9'	0.97	2.87	30.93	14.78	77.56	0.57	61.17	47.45

Table J.1.b.

A summary of the June 13, 1990 and July 13, 1990 biomass harvest of the NFT reactors.

DATE	UNIT NO	STALK WET MASS (kg)	STALK WET MASS YIELD (kg/m ²)	TS (%)	TVS (%)	DRY MASS (kg)	DRY MASS (mt/ha)	VOLATILE MASS (mt/ha)	STALK NUMBER	STALK DENSITY (#/m ²)
First Harvest of Stalks 1990.										
Unit Area NFT-D =				3.72 square meters.						
Unit Area NFT-S =				2.79 square meters.						
13-Jun-90	NFT-D-2	26.03	7.00	15.40	88.64	4.01	10.79	9.56	209	56
13-Jun-90	NFT-D-4	18.83	5.07	14.28	89.49	2.69	7.24	6.48	113	30
13-Jun-90	NFT-D-7	16.23	4.37	18.47	89.98	3.00	8.07	7.26	154	41
13-Jun-90	NFT-D-9	14.39	3.87	17.52	89.72	2.52	6.78	6.09	189	51
13-Jun-90	NFT-D-12	15.59	4.20	15.15	88.54	2.36	6.36	5.63	121	33
13-Jun-90	NFT-D-14	14.88	4.00	17.24	89.12	2.57	6.90	6.15	158	43
13-Jun-90	NFT-D-17	7.58	2.04	16.80	89.63	1.27	3.43	3.07	40	11
13-Jun-90	NFT-D-19	13.00	3.50	15.07	87.71	1.96	5.27	4.62	31	8
13-Jun-90	NFT-S-2	15.92	5.71	17.58	88.66	2.80	10.04	8.90	200	72
13-Jun-90	NFT-S-4	14.84	5.32	14.84	87.92	2.20	7.90	6.95	168	60
13-Jun-90	NFT-S-7	25.51	9.15	15.71	88.94	4.01	14.38	12.79	310	111
13-Jun-90	NFT-S-9	18.14	6.51	17.48	88.75	3.17	11.38	10.10	280	100
Second Harvest of Stalks 1990.										
Unit Area NFT-D =				3.72 square meters.						
Unit Area NFT-S =				2.79 square meters.						
13-Jul-90	NFT-D-2	6.15	1.65	16.12	88.93	0.99	2.67	2.37		
13-Jul-90	NFT-D-4	5.21	1.40	16.12	88.93	0.84	2.26	2.01		
13-Jul-90	NFT-D-7	5.59	1.50	16.12	88.93	0.90	2.42	2.16		
13-Jul-90	NFT-D-9	5.71	1.54	16.12	88.93	0.92	2.48	2.20		
13-Jul-90	NFT-D-12	3.44	0.93	16.12	88.93	0.55	1.49	1.33		
13-Jul-90	NFT-D-14	5.64	1.52	16.12	88.93	0.91	2.45	2.18		
13-Jul-90	NFT-D-17	2.46	0.66	16.12	88.93	0.40	1.07	0.95		
13-Jul-90	NFT-D-19	2.67	0.72	16.12	88.93	0.43	1.16	1.03		
13-Jul-90	NFT-S-2	7.27	2.61	10.61	85.17	0.77	2.77	2.36		
13-Jul-90	NFT-S-4	3.60	1.29	10.61	85.17	0.38	1.37	1.17		
13-Jul-90	NFT-S-7	13.50	4.84	10.61	85.17	1.43	5.14	4.38		
13-Jul-90	NFT-S-9	19.84	7.12	10.61	85.17	2.11	7.55	6.43		
13-Jul-90	NFT-S-11*	16.61	5.96	14.08	88.93	2.34	8.39	7.46		
13-Jul-90	NFT-S-18-20**	16.61	1.99	14.08	85.08	2.34	8.39	7.14		

* - The biomass in this section of the southernmost shallow NFT reactor was mainly bulrushes.

** - The biomass in these three sections of the southernmost shallow NFT reactor was mainly reed canary grass.

Table J.1.c.

A summary of the January 11, 1991 biomass harvest of the NFT reactors.

DATE	UNIT NO	STALK WET MASS (kg)	STALK WET MASS YIELD (kg/m ²)	TS (%)	TVS (%)	DRY MASS (kg)	DRY MASS (mt/ha)	VOLATILE MASS (mt/ha)
Third Harvest of Stalks 1990.								
Unit Area NFT-D =				3.72 square meters.				
Unit Area NFT-S =				2.79 square meters.				
11-Dec-90	NFT-D-1	21.53	5.79	29.31	88.79	6.31	16.98	15.07
11-Dec-90	NFT-D-2	3.90	1.05	29.31	88.79	1.14	3.08	2.73
11-Dec-90	NFT-D-3	17.63	4.74	29.41	88.11	5.15	13.85	12.21
11-Dec-90	NFT-D-4	5.34	1.44	29.31	88.79	1.56	4.21	3.74
11-Dec-90	NFT-D-5	17.14	4.61	29.20	89.46	5.00	13.47	12.05
11-Jan-91	NFT-D-6	13.90	3.74	39.67	87.67	5.51	14.84	13.01
11-Jan-91	NFT-D-7	2.48	0.67	39.67	87.67	0.98	2.65	2.32
11-Jan-91	NFT-D-8	12.68	3.41	39.67	87.67	5.03	13.54	11.87
11-Jan-91	NFT-D-9	4.83	1.30	39.67	87.67	1.92	5.16	4.52
11-Jan-91	NFT-D-10	15.73	4.23	39.67	87.67	6.24	16.79	14.72
11-Jan-91	NFT-D-11	9.07	2.44	39.67	87.67	3.60	9.68	8.49
11-Jan-91	NFT-D-12	0.00						
11-Jan-91	NFT-D-13	14.14	3.81	39.67	87.67	5.61	15.09	13.23
11-Jan-91	NFT-D-14	2.37	0.64	39.67	87.67	0.94	2.53	2.22
11-Jan-91	NFT-D-15	13.83	3.72	39.67	87.67	5.49	14.76	12.94
11-Jan-91	NFT-D-16	8.53	2.30	39.67	87.67	3.38	9.11	7.98
11-Jan-91	NFT-D-17	1.20	0.32	39.67	87.67	0.48	1.28	1.12
11-Jan-91	NFT-D-18	7.14	1.92	39.67	87.67	2.83	7.62	6.68
11-Jan-91	NFT-D-19	13.83	3.72	39.67	87.67	5.49	14.76	12.94
11-Jan-91	NFT-D-20	17.62	4.74	39.67	87.67	6.99	18.81	16.49
11-Jan-91	NFT-S-1	13.44	4.82	39.67	87.67	5.33	19.13	16.77
11-Jan-91	NFT-S-2	2.96	1.06	39.67	87.67	1.17	4.21	3.69
11-Jan-91	NFT-S-3	10.30	3.70	39.67	87.67	4.09	14.66	12.85
11-Jan-91	NFT-S-4	2.96	1.06	39.67	87.67	1.17	4.21	3.69
11-Jan-91	NFT-S-5	8.24	2.96	39.67	87.67	3.27	11.73	10.28
11-Jan-91	NFT-S-6	17.04	6.11	39.67	87.67	6.76	24.25	21.26
11-Jan-91	NFT-S-7	2.51	0.90	39.67	87.67	1.00	3.57	3.13
11-Jan-91	NFT-S-8	12.37	4.44	39.67	87.67	4.91	17.61	15.44
11-Jan-91	NFT-S-9	3.41	1.22	39.67	87.67	1.35	4.85	4.26
11-Jan-91	NFT-S-10	18.85	6.76	39.67	87.67	7.48	26.83	23.52
11-Jan-91	NFT-S-11	9.50	3.41	39.67	87.67	3.77	13.52	11.85
11-Jan-91	NFT-S-12	3.27	1.17	39.67	87.67	1.30	4.65	4.08
11-Jan-91	NFT-S-13	1.75	0.63	39.67	87.67	0.69	2.49	2.18
11-Jan-91	NFT-S-14	5.24	1.88	39.67	87.67	2.08	7.46	6.54
11-Jan-91	NFT-S-15	7.65	2.74	39.67	87.67	3.03	10.89	9.55
11-Jan-91	NFT-S-16	9.64	3.46	39.67	87.67	3.82	13.72	12.03
11-Jan-91	NFT-S-17	3.00	1.08	39.67	87.67	1.19	4.27	3.74
11-Jan-91	NFT-S-18	8.45	3.03	39.76	86.61	3.36	12.05	10.44
11-Jan-91	NFT-S-19	8.35	3.00	39.76	86.61	3.32	11.91	10.32
11-Jan-91	NFT-S-20	9.21	3.30	39.76	86.61	3.66	13.14	11.38

Table J.1.d.

A summary of the December 11, 1990 composite biomass harvest of the southernmost shallow channel NFT reactor.

DATE	UNIT NO	STALK WET MASS (kg)	RHYZOME WET MASS (kg)	RHYZOME WET MASS YIELD (kg/m ²)	TS (%)	TVS (%)	DRY MASS (kg)	DRY MASS (mt/ha)	VOLATILE MASS (mt/ha)	UNIT AREA STALK DENSITY (#/u.a.)	STALK DENSITY (#/m ²)
Composite harvest of stalks and rhizomes.											
Unit Area Sampled =						0.093 square meters.					
11-Dec-90	NFT-S-2	0.40			24.44	84.56	0.10	10.52	8.90	9	97
11-Dec-90	NFT-S-2		5.70	61.35	7.83	81.62	0.45	48.04	39.21		
11-Dec-90	NFT-S-3	0.82			27.02	84.94	0.22	23.85	20.26	14	151
11-Dec-90	NFT-S-3		4.76	51.24	11.10	86.07	0.53	56.87	48.95		
11-Dec-90	NFT-S-6	1.06			33.07	84.08	0.35	37.73	31.73	14	151
11-Dec-90	NFT-S-6		5.54	59.63	10.47	89.19	0.58	62.43	55.69		
11-Dec-90	NFT-S-7	0.10			25.38	83.93	0.03	2.73	2.29	3	32
11-Dec-90	NFT-S-7		4.08	43.92	6.16	86.37	0.25	27.05	23.37		

Table J.2. A summary of fiber analysis of December 11, 1990 *Typha glauca* cattail stalk and rhizome samples of the southernmost shallow-channel NFT reactor as compared to samples from *Typha glauca* cattails grown by Dr Leland Marsh in Oswego, New York.

SAMPLE ID	YIELD (kg/m ² -yr)	-----percent of TS-----				-----Percent of the volatile -----							TDOM (%)	DCW (%)
		VS	ASH	TKN	CP	CS	HC	CE	LS	Lsk	CUTIN	CW		
Grown by Dr. Leland Marsh in Oswego, New York														
CULTURED STERILE		83.3	16.8	0.8	5.2	39.9	19.4	29.8	10.9	9.3	1.7	60.1	42.8	20.7
CULTURED STERILE		92.9	7.1	0.9	5.3	24.9	17.5	36.7	10.9	9.1	1.8	75.1	50.8	29.7
CULTURED FERTILE		89.2	10.8	0.8	4.7	32.0	14.0	41.3	12.8	10.0	2.8	68.0	41.3	23.0
Average		88.5	11.5	0.8	5.1	32.3	17.0	35.9	11.5	9.5	2.1	67.7	44.9	24.5
Grown in the Pilot Scale Nutrient Film Technique northern most shallow chanenel														
NFTS2 STALK		85.5	14.5	1.8	11.5	36.8	19.8	32.0	9.1	6.2	2.8	63.2	53.9	38.6
NFTS2 RHYZOME		84.6	15.4	2.5	15.6	44.9	19.6	23.1	12.5	10.4	2.1	55.1	65.1	53.1
NFTS6 STALK		83.5	16.5	1.1	7.1	32.5	17.5	40.5	9.5	6.4	3.1	67.5	50.2	38.4
NFTS6 RHYZOME		89.3	10.7	3.0	18.9	50.5	20.8	18.3	10.4	7.0	2.7	49.5	69.5	44.9
AVERAGE STALK	1.9	84.5	15.5	1.5	9.3	34.7	18.6	36.2	9.3	6.3	3.0	65.5	52.1	38.5
AVERAGE RHYZOME	4.8	86.9	13.1	2.8	17.3	47.7	20.2	20.7	11.5	8.7	2.4	44.3	67.3	49.0
Average		86.3	13.7	2.4	15.0	44.0	19.8	25.1	10.8	8.0	2.6	50.3	63.0	46.0

CP = Crude Protein
 CS = Cellular soluble material from neutral detergent.
 HC = Hemicellulose resulting from acid detergent.
 CE = Cellulose from sulfuric acid wash.
 LS = Crude lignin as acid wash residual.
 LSK = Crude lignin - cutin
 CUTIN = Lignin
 CW = Cell wall material comprised of HC + CE + LS.

Table J.3. Elemental analysis of the harvest of the NFT reactors.

UNIT AREA NFT-1 = 3.72 (sq m)

UNIT AREA NFT-2 = 2.79 (sq m)

DATE	UNIT NO	ELEMENTAL ANALYSIS										ELEMENTAL ANALYSIS										ELEMENTAL ANALYSIS									
		N (%)	K (%)	P (%)	Ca (%)	Mg (%)	Mn ppm	Fe ppm	Cu ppm	B ppm	Zn ppm	Mo ppm	Al ppm	Na ppm	Co ppm	Cd ppm	Cr ppm	Ni ppm	Pb ppm	S (%)	Si ppm	V ppm	As ppm	Se ppm	Y ppm						
FIRST HARVEST (June 13, 1990)																															
6/13/90	NFT-DS	2.3		0.3	1.4	0.2	289	144	8.5	18.2	56	0.0	75	11180	trace	trace	1.2	0.5	trace	0.3	14	0.1	0.5	trace	190						
6/13/90	NFT-DN	2.3		0.4	1.3	0.2	337	134	6.4	14.7	47	0.1	69	8021	trace	trace	1.2	0.7	trace	0.3	47	0.2	0.8	1.0	189						
6/13/90	NFT-SN	2.2		0.3	1.3	0.2	209	168	5.7	20.0	42	0.4	57	8823	0.1	0.1	1.4	0.8	trace	0.3	13	0.2	trace	trace	188						
SECOND HARVEST (July 13, 1990)																															
7/13/90	NFT-D	3.2		0.4	1.1	0.3	270	217	10.9	19.9	46	0.2	74	10290	0.7	0.2	1.9	1.5	trace	0.4	55	0.2	1.5	trace	189						
7/13/90	NFT-S	3.4	4.0	0.5	1.3	0.3	228	156	5.6	14.6	34	0.1	77	4749	0.6	0.1	1.7	0.5	trace	0.3	41	0.3	0.9	trace	190						
NFT-SS-11 Primarily Bulrushes																															
NFT-SS-18 through 20 Primarily Reed Canary Grass																															
7/13/90	NFT-SS-11	4.1		0.5	0.8	0.3	427	602	10.6	9.6	39	3.9	91	10160	1.4	0.2	2.2	1.4	6.7	0.7	738	0.0	1.6	5.7	188						
7/13/90	NFT-SS-18-20	2.4		0.5	0.4	0.2	84	452	4.5	13.2	51	7.4	92	1579	4.4	0.2	2.7	1.3	2.8	0.4	28	0.9	3.2	4.5	157						
COMPOSITE HARVEST (December 11, 1990)																															
Each sample was taken from a representative point in the southernmost shallow-channel NFT reactor. The Unit Area of each Sample was .093 m ² .																															

STALKS ONLY																															
12/11/90	NFT-SS-2	1.8	3.3	0.3	1.8	0.3	276	4491	11.8	17.8	194	0.8	194	63	trace	0.4	2.6	0.2	14.5	0.6	347	trace	trace	9.5	199						
12/11/90	NFT-SS-3	1.3	1.5	0.3	2.4	0.3	315	1951	11.4	21.2	185	1.0	244	10200	trace	0.0	2.2	0.3	3.3	0.4	112	trace	trace	6.5	198						
12/11/90	NFT-SS-6	1.1	2.1	0.2	2.2	0.3	266	2278	11.5	23.0	105	0.5	280	12270	trace	0.2	1.9	trace	7.2	0.4	230	trace	trace	5.6	196						
12/11/90	NFT-SS-7	1.6	2.5	0.4	2.0	0.3	459	5122	21.4	36.6	441	1.0	438	8415	trace	0.2	2.6	trace	5.1	0.4	379	trace	trace	10.8	204						
	Average	1.5	2.4	0.3	2.1	0.3	329	3461	14.0	24.6	231	0.8	289	7737	0.0	0.2	2.3	0.1	7.5	0.4	267	0.0	0.0	8.1	199						
RHIZOMES ONLY																															
12/11/90	NFT-SS-2	2.5	1.0	0.6	1.6	0.3	500	13900	67.3	36.0	288	3.1	1797	4524	trace	0.3	6.4	3.4	7.6	0.8	1953	trace	trace	10.5	205						
12/11/90	NFT-SS-3	2.6	1.0	0.7	1.4	0.3	316	20170	69.2	29.6	303	3.1	2091	3461	trace	trace	6.5	3.6	2.1	0.8	3573	trace	trace	20.2	207						
12/11/90	NFT-SS-6	3.0	1.2	0.7	1.3	0.3	409	10880	26.5	33.0	122	1.7	515	4349	trace	trace	2.4	0.8	1.0	0.4	332	trace	trace	17.3	206						
12/11/90	NFT-SS-7	2.3	0.9	0.5	1.7	0.3	248	16280	67.8	33.1	391	4.8	1332	5800	trace	0.0	4.4	5.9	5.6	1.0	1588	trace	0.1	21.6	205						
	Average	2.6	1.0	0.7	1.5	0.3	368	15308	57.7	32.9	276	3.2	1434	4534	0.0	0.1	5.0	3.4	4.1	0.8	1861	0.0	0.0	17.4	206						
	TOTAL PLANT	2.3	1.4	0.6	1.7	0.3	357	11968	45.4	30.6	263	2.5	1111	5437	0.0	0.1	4.2	2.5	5.1	0.7	1412	0.0	0.0	14.8	204						
CATTAILS GROWN BY DR. LELAND MARSH IN OSWEGO, NEW YORK (1987)																															
	S-30	0.8	0.5	0.1	0.9	0.2	880	2008	9.7	4.3	25	0.0	1024	2461	0.6	0.1	3.4	2.2	2.1	0.1	160	0.13	0.0	0.0	202						
	S-31	0.8	0.6	0.1	0.9	0.0	987	5550	8.5	4.1	20	0.0	1729	1874	0.0	0.1	4.2	2.4	1.9	0.2	588	0.00	1.1	0.0	205						
	S-32	0.7	0.5	0.1	1.0	0.2	450	1293	3.1	5.8	14	0.0	345	5394	0.2	0.2	1.8	0.9	1.8	0.2	552	0.00	0.0	0.0	202						
	Average	0.8	0.5	0.1	0.9	0.1	772	2950	7.1	4.7	19.5	0.0	1033	3243	0.3	0.1	3.1	1.8	1.9	0.1	433	0.0	0.4	0.0	203						

Table J.4. A summary of the root mass volume and density.

Surface Area Harvested For Analysis = 0.093 square meters.
 Reactor Surface Area = 27.9 meters.

DATE	ROOT VOLUME					TOTAL ROOT VOLUME (l)	ROOT VOLUME (l/m ²)
	INITIAL DEPTH (cm)	FINAL DEPTH (cm)	LIQUID REMOVED (l)	VOLUME EXPOSED (l)	ROOT VOLUME EXPOSED (l)		
20-Feb-90	9.2	3.3	300	1644	1344	2096	75.2
06-Mar-90	7.9	3.0	250	1366	1116	1799	64.5
16-May-90	8.6	3.1	315	1533	1218	1904	68.3
17-Oct-90	8.6	3.0	315	1561	1246	1913	68.6
11-Jan-91	10.8	3.2	600	2118	1518	2157	77.4
Averages						1974	71

AVERAGE ROOT MASS DENSITIES							
SAMPLE ID and LOCATION	WET MASS (kg)	TS (%)	VS (%)	AREA DENSITY (kg/m ²)	BULK DENSITY (kg/m ³)	DRY DENSITY (kg/m ³)	VOLATIL DENSITY (kg/m ³)
NFT-S2	5.7	7.8	81.6	61	866	68	55
NFT-S3	4.8	11.1	86.1	51	723	80	69
NFT-S6	5.5	10.5	89.2	60	842	88	79
NFT-S7	4.1	6.2	86.4	44	620	38	33
Averages	5.0	8.9	85.8	54	763	69	59

APPENDIX K

A SUMMARY OF THE PARTICULATE CLARIFIER PERFORMANCE

Table K summarizes the clarifier influent and effluent total and soluble COD, total BOD, and SS and VSS concentrations.

Table K.1. A summary of the performance of the gross particulate clarifier.

The clarifier began operation September 13, 1988 and was used throughout the remainder of the study.

DATE	TCOD	TCOD	SCOD	SCOD	TBOD	TBOD	SS	SS	VSS	VSS
	INF	EFF	INF	EFF	INF	EFF	INF	EFF	INF	EFF
	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)
05-Apr-90	189.6	172.9	77.0	93.0	95.6	82.1	95.7	53.9	76.3	39.4
12-Apr-90	219.8	272.1	100.5	184.6	94.3	105.5	93.3	70.1	73.3	54.4
19-Apr-90	253.9	289.2	108.2	142.6	119.6	123.4	95.1	97.6	79.3	81.6
26-Apr-90	250.5	304.7	135.0	202.9	128.3	150.1	112.4	74.0	97.7	61.1
03-May-90	203.9	171.6	78.5	94.6	110.5	94.9	121.0	66.0	93.8	49.4
10-May-90	198.7	171.6	75.8	106.2	102.1	83.5	119.9	53.3	94.1	42.4
17-May-90	103.3	132.4	44.6	61.7	51.1	62.4	47.0	52.0	36.1	40.9
24-May-90	182.3	178.3	77.4	82.2	72.6	77.6	82.5	63.4	64.5	50.4
31-May-90	167.2	158.4	64.7	81.2	81.3	70.1	90.3	68.3	67.4	49.2
07-Jun-90	128.7	123.7	42.7	51.2	77.9	61.4	69.4	55.1	53.9	43.1
14-Jun-90	127.0	133.1	32.2	58.7	74.9	83.1	74.2	62.3	59.0	49.4
21-Jun-90	100.2	111.4	50.1	72.0	63.7	71.5	67.0	55.8	52.6	44.2
28-Jun-90	170.7	146.8	73.1	67.0	60.3	56.5	94.8	63.5	73.3	50.8
05-Jul-90	158.4	176.1	266.5	297.7	71.7	65.7	105.3	60.3	63.2	51.1
12-Jul-90	176.3	105.1	31.8	31.8	74.9	67.8	95.0	75.2	65.1	53.1
19-Jul-90	212.7	162.8	128.8	112.2	82.4	67.4	99.0	53.5	75.0	44.6
26-Jul-90	185.0	137.1	61.3	61.3	75.0	72.0	81.2	58.5	59.8	47.1

APPENDIX L

A SUMMARY OF THE NFT REACTOR BATCH NUTRIENT UPTAKE STUDIES

Tables L.1 through L.4 summarize the results of the four batch nutrient uptake studies.

Table L.1.

A summary of the first batch nutrient uptake study conducted in the shallow north NFT reactor during the week of February 20 through 26, 1990.

Reactor Surface Area = 27.9 square meters.

Reactor Liquid Volume = 1029.0 liters.

DATE	TIME	TKN (mg/l)	TAN (mg/l)	NO3-N (mg/l)	PO4 (mg/l)	TKN LOG	TAN LOG	NO3-N LOG	PO4 LOG	TKN LOG	TAN LOG	NO3-N LOG	PO4 LOG
20-Feb-90	0.0		6.9	2.3	2.1		0.84	0.35	0.33		0.89	0.55	0.51
20-Feb-90	3.3		6.8	3.8	2.2		0.83	0.58	0.35		0.86	0.51	0.49
21-Feb-90	19.0		6.5	2.2	2.7		0.82	0.34	0.43		0.75	0.35	0.42
21-Feb-90	27.3		4.4	1.5	3.2		0.64	0.19	0.50		0.69	0.27	0.37
22-Feb-90	43.4		4.0	1.2	2.5		0.60	0.09	0.40		0.57	0.10	0.30
22-Feb-90	51.4		3.3	1.0	1.9		0.51	-0.01	0.29		0.51	0.02	0.26
23-Feb-90	67.3		2.4	0.8	1.1		0.38	-0.08	0.04		0.40	-0.14	0.18
23-Feb-90	74.6		1.6	0.8	0.9		0.21	-0.08	-0.05		0.35	-0.22	0.14
24-Feb-90	92.3		1.5	0.8	0.9		0.17	-0.09	-0.03		0.22	-0.40	0.05
24-Feb-90	97.8		1.2	0.8	1.0		0.08	-0.11	-0.02		0.18	-0.45	0.03
25-Feb-90	117.3		1.1	0.8	0.0		0.03	-0.10			0.04	-0.65	-0.07
25-Feb-90	121.0		1.6	0.8	0.9		0.20	-0.11	-0.06		0.01	-0.69	-0.09

TAN*		NO3-N*		OP*	
Constant	0.8873	Constant	0.5464	Constant	0.5086
Std Err of Y Est	0.0456	Std Err of Y Est	0.0625	Std Err of Y Est	0.1308
R Squared	0.9447	R Squared	0.9475	R Squared	0.4885
No. of Observations	6.0000	No. of Observations	6.0000	No. of Observations	6.0000
Degrees of Freedom	4.0000	Degrees of Freedom	4.0000	Degrees of Freedom	4.0000
X Coefficient(s)	-0.0073	X Coefficient(s)	-0.0102	X Coefficient(s)	-0.0049
Std Err of Coef.	0.0009	Std Err of Coef.	0.0012	Std Err of Coef.	0.0025
Uptake concentration	1.0174	Uptake concentration	1.0248	Uptake concentration	1.0117
Uptake Rate (g/m ² -d)	0.900	Uptake Rate (g/m ² -d)	0.906	Uptake Rate (g/m ² -d)	0.895

* The data was regressed from 3.3 hours through 67.3 hours.

Table L.2.

A summary of the second batch nutrient uptake study conducted in the shallow north NFT reactor during the week of March 6 through 14, 1990.

Reactor Surface Area = 27.9 square meters.
Reactor Liquid Volume = 1514.0 liters.

DATE	TIME	TKN (mg/l)	TAN (mg/l)	NO3-N (mg/l)	PO4 (mg/l)	TKN LOG	TAN LOG	NO3-N LOG	PO4 LOG	TKN LOG	TAN LOG	NO3-N LOG	PO4 LOG
06-Mar-90	0.0		28.6	16.2	8.1		1.46	1.21	0.91	1.9	1.72	1.23	0.41
07-Mar-90	21.8	32.1	20.9	10.7	1.8	1.5	1.32	1.03	0.25	1.5	1.35	0.84	0.27
07-Mar-90	30.8	21.4	15.4	6.2	1.6	1.3	1.19	0.79	0.20	1.4	1.19	0.68	0.21
08-Mar-90	46.0	15.4	10.8	0.8	1.4	1.2	1.03	-0.08	0.14	1.1	0.94	0.41	0.11
08-Mar-90	54.5	8.0	5.5	1.7	1.2	0.9	0.74	0.22	0.06	1.0	0.79	0.26	0.05
09-Mar-90	70.5	5.0	3.1	1.0	0.9	0.7	0.49	-0.02	-0.03	0.7	0.52	-0.03	-0.05
09-Mar-90	76.5	3.9	2.7	1.2	0.7	0.6	0.43	0.06	-0.14	0.6	0.42	-0.14	-0.09
10-Mar-90	96.5	1.7		0.7	0.8	0.2		-0.14	-0.10	0.3	0.08	-0.50	-0.22
10-Mar-90	103.0	2.1		0.6	0.9	0.3		-0.21	-0.07	0.2	-0.03	-0.61	-0.27
11-Mar-90	121.5	0.8		0.5	0.9	-0.1		-0.27	-0.06	-0.2	-0.35	-0.95	-0.39
11-Mar-90	125.5	0.8		0.5	0.9	-0.1		-0.27	-0.04	-0.2	-0.41	-1.02	-0.42
12-Mar-90	137.5	0.7		0.5	0.9	-0.2		-0.30	-0.07	-0.4	-0.62	-1.23	-0.49
12-Mar-90	146.8			0.7	0.9			-0.18	-0.05	-0.6	-0.78	-1.40	-0.55
13-Mar-90	162.0			0.6	0.8			-0.21	-0.08	-0.8	-1.03	-1.67	-0.65
13-Mar-90	168.0			0.6	0.8			-0.21	-0.12	-0.9	-1.14	-1.78	-0.69
14-Mar-90	187.0			0.6	0.7			-0.25	-0.15	-1.3	-1.46	-2.12	-0.82
TAN		TKN		NO3-N		OP*							
Constant	1.7165	Constant	1.8723	Constant	1.2320	Constant	0.4090						
Std Err of Y Est	0.0601	Std Err of Y Est	0.0528	Std Err of Y Est	0.2849	Std Err of Y Est	0.0325						
R Squared	0.9789	R Squared	0.9831	R Squared	0.6969	R Squared	0.9595						
No. of Observations	6.0000	No. of Observations	6.0000	No. of Observations	6.0000	No. of Observations	6.0000						
Degrees of Freedom	4.0000	Degrees of Freedom	4.0000	Degrees of Freedom	4.0000	Degrees of Freedom	4.0000						
X Coefficient(s)	-0.0170	X Coefficient(s)	-0.0170	X Coefficient(s)	-0.0179	X Coefficient(s)	-0.0066						
Std Err of Coef.	0.0012	Std Err of Coef.	0.0012	Std Err of Coef.	0.0059	Std Err of Coef.	0.0007						
Uptake concentration	1.040	Uptake concentration	1.040	Uptake concentration	1.042	Uptake concentration	1.015						
Uptake Rate (g/m ² -d)	1.354	Uptake Rate (g/m ² -d)	1.354	Uptake Rate (g/m ² -d)	1.357	Uptake Rate (g/m ² -d)	1.322						

* The data was regressed from 21.8 hours through 76.1 hours.

Table L.3.

A summary of the third batch nutrient uptake study conducted in the shallow north NFT reactor during the week of May 16 through 24, 1990.

Reactor Surface Area = 27.9 square meters.

Reactor Liquid Volume = 1324.8 liters.

DATE	TIME	TKN (mg/l)	TAN (mg/l)	NO3-N (mg/l)	PO4 (mg/l)	TKN LOG	TAN LOG	NO3-N LOG	PO4 LOG	TKN LOG	TAN LOG	NO3-N LOG	PO4 LOG
16-May-90	1.3	60.7	56.1	25.6	31.6	1.8	1.75	1.41	1.50	1.7	1.70	1.38	1.39
17-May-90	11.7	42.4	38.7	20.9	14.7	1.6	1.59	1.32	1.17	1.7	1.61	1.29	1.16
17-May-90	18.7	41.8	34.8	17.7	9.7	1.6	1.54	1.25	0.99	1.6	1.55	1.22	1.00
18-May-90	39.2	28.4	25.4	9.3	6.8	1.5	1.40	0.97	0.83	1.4	1.37	1.03	0.53
18-May-90	53.3	21.8	18.5	7.8	0.9	1.3	1.27	0.89	-0.06	1.3	1.25	0.90	0.21
19-May-90	61.3	19.5	15.9	6.4	0.6	1.3	1.20	0.81	-0.23	1.3	1.18	0.82	0.03
19-May-90	71.1	14.9	12.1	4.8	0.8	1.2	1.08	0.68	-0.09	1.2	1.10	0.73	-0.19
20-May-90	90.1	11.8	8.2	4.1	0.3	1.1	0.91	0.61	-0.51	1.1	0.93	0.55	-0.63
20-May-90	99.9	10.5	6.6	2.7	0.3	1.0	0.82	0.43	-0.51	1.0	0.85	0.46	-0.85
21-May-90	109.8	5.2	2.8	2.3	0.7	0.7	0.45	0.36	-0.16	0.9	0.76	0.37	-1.08
21-May-90	118.3	2.9	1.0	2.0	0.5	0.5	-0.02	0.30	-0.28	0.8	0.69	0.29	-1.27
22-May-90	133.3	2.3	0.5	1.9	0.3	0.4	-0.28	0.28	-0.57	0.7	0.56	0.14	-1.61
22-May-90	140.1	2.0	0.3	1.4	0.3	0.3	-0.52	0.16	-0.51	0.7	0.50	0.08	-1.77
23-May-90	157.9	1.7	0.3	0.8	0.2	0.2	-0.57	-0.11	-0.77	0.6	0.34	-0.09	-2.17
23-May-90	166.9			0.6	2.0			-0.22	0.31	0.5	0.27	-0.17	-2.38
24-May-90	181.9			0.6	5.3			-0.24	0.73	0.4	0.14	-0.31	-2.72

TAN		TKN		NO3-N		OP	
Constant	1.7123	Constant	1.7391	Constant	1.3970	Constant	1.4245
Std Err of Y Est	0.0240	Std Err of Y Est	0.0215	Std Err of Y Est	0.0479	Std Err of Y Est	0.2240
R Squared	0.9920	R Squared	0.9915	R Squared	0.9734	R Squared	0.9078
No. of Observations	7.0000	No. of Observations	7.0000	No. of Observations	7.0000	No. of Observations	7.0000
Degrees of Freedom	5.0000	Degrees of Freedom	5.0000	Degrees of Freedom	5.0000	Degrees of Freedom	5.0000
X Coefficient(s)	-0.0087	X Coefficient(s)	-0.0087	X Coefficient(s)	-0.0094	X Coefficient(s)	-0.0228
Std Err of Coef.	0.0003	Std Err of Coef.	0.0003	Std Err of Coef.	0.0007	Std Err of Coef.	0.0032
Uptake concentration	1.020	Uptake concentration	1.020	Uptake concentration	1.022	Uptake concentration	1.054
Uptake Rate (g/m ² -d)	1.163	Uptake Rate (g/m ² -d)	1.163	Uptake Rate (g/m ² -d)	1.165	Uptake Rate (g/m ² -d)	1.201

* The data was regressed from 11.7 hours through 90.1 hours.

Table L.4.

A summary of the fourth batch nutrient uptake study conducted in the shallow north NFT reactor during the week of October 17 through 27, 1990.

Reactor Surface Area = 27.9 square meters.

Reactor Liquid Volume = 1324.8 liters.

DATE	TIME	TKN (mg/l)	TAN (mg/l)	NO ₃ -N (mg/l)	PO ₄ (mg/l)	TKN LOG	TAN LOG	NO ₃ -N LOG	PO ₄ LOG	TKN LOG	TAN LOG	NO ₃ -N LOG	PO ₄ LOG
17-Oct-90	0.5		42.9	20.2	21.2		1.63	1.31	1.33	1.7	1.60	1.42	1.39
18-Oct-90	2.0		39.1	20.4	20.7		1.59	1.31	1.32	1.7	1.58	1.37	1.31
18-Oct-90	4.0		37.2	17.6	16.6		1.57	1.25	1.22	1.7	1.56	1.30	1.20
19-Oct-90	6.0		35.0	16.5	12.0		1.54	1.22	1.08	1.7	1.55	1.23	1.09
19-Oct-90	8.0		32.7	15.3	9.3		1.51	1.19	0.97	1.7	1.53	1.17	0.98
20-Oct-90	12.0		30.9	12.8	5.8		1.49	1.11	0.76	1.6	1.49	1.03	0.76
20-Oct-90	16.0		27.8	10.1	3.5		1.44	1.00	0.54	1.6	1.46	0.89	0.54
21-Oct-90	20.0		27.0	7.1	2.1		1.43	0.85	0.32	1.6	1.42	0.76	0.33
21-Oct-90	24.0		24.9	3.8	1.3		1.40	0.58	0.11	1.6	1.39	0.62	0.11
22-Oct-90	26.0		23.0	2.7	1.0		1.36	0.43	0.01	1.5	1.37	0.55	-0.00
22-Oct-90	36.5		20.1	0.9	1.9		1.30	-0.06	0.29	1.5	1.27	0.20	-0.58
23-Oct-90	42.5		18.2	1.0	1.0		1.26	-0.00	0.02	1.4	1.22	-0.01	-0.90
23-Oct-90	48.5		16.2	1.1	0.9		1.21	0.06	-0.07	1.4	1.17	-0.21	-1.23
24-Oct-90	54.5		14.9	1.4	3.2		1.17	0.13	0.51	1.3	1.11	-0.42	-1.56
24-Oct-90	60.5		13.2	1.5	6.1		1.12	0.17	0.79	1.3	1.06	-0.62	-1.89
25-Oct-90	66.5		11.3	1.5	2.1		1.05	0.19	0.31	1.2	1.00	-0.82	-2.22
25-Oct-90	72.5		10.2	1.6	0.0		1.01	0.20		1.2	0.95	-1.03	-2.54
26-Oct-90	78.5		9.0	1.7	0.9		0.95	0.23	-0.03	1.1	0.90	-1.23	-2.87
26-Oct-90	84.5		8.0	1.7	2.1		0.90	0.22	0.33	1.1	0.84	-1.44	-3.20
27-Oct-90	90.5		5.8	1.7	0.8		0.76	0.23	-0.10	1.1	0.79	-1.64	-3.53
27-Oct-90	96.5		4.8	1.7	0.0		0.68	0.24		1.0	0.74	-1.84	-3.85
TAN*		NO ₃ -N*				OP*							
Constant	1.6003	Constant	1.4383		Constant	1.4193							
Std Err of Y Est	0.0103	Std Err of Y Est	0.0862		Std Err of Y Est	0.0123							
R Squared	0.9854	R Squared	0.9328		R Squared	0.9994							
No. of Observations	9.0000	No. of Observations	9.0000		No. of Observations	9.0000							
Degrees of Freedom	7.0000	Degrees of Freedom	7.0000		Degrees of Freedom	7.0000							
X Coefficient(s)	-0.0090	X Coefficient(s)	-0.0340		X Coefficient(s)	-0.0547							
Std Err of Coef.	0.0004	Std Err of Coef.	0.0034		Std Err of Coef.	0.0005							
Uptake concentration	1.021	Uptake concentration	1.082		Uptake concentration	1.134							
Uptake Rate (g/m ² -d)	1.163	Uptake Rate (g/m ² -d)	1.232		Uptake Rate (g/m ² -d)	1.292							

* The data was regressed from 2.0 hours through 26.0 hours.

APPENDIX M

A SUMMARY OF THE BENCH-SCALE AAFEB REACTOR EXPERIMENTS

Table M.1. A summary of the bench-scale AAFEB reactor studies.

REACTOR ID	ACETIC ACID SUBSTRATE (mg/L)	TEMP (C)	INF pH	INF COD (mg/L)	INF BOD (mg/L)	INF VFA (mg/L)	EFF pH	EFF COD (mg/L)	EFF BOD (mg/L)	EFF VFA (mg/L)	HRT	BOD OLR (g/L-d)	BOD RR (g/L-d)	BOD RE (%)	VFA RR (g/L-d)	VFA RE (%)
MATURE BED	80	20	7.0	170	131	123	6.9	8	15	11	8.5	0.37	0.33	89.2	0.32	91.1
			7.0	132	122	117	7.4	9	21	13	5.1	0.57	0.48	84.2	0.49	88.9
			7.5	105	87	83	7.7	53	49	45	2.9	0.72	0.31	43.1	0.31	45.8
		10	7.1	121	99	90	7.2	99	82	71	0.9	2.64	0.45	17.0	0.51	21.1
			7.3	181	128	125	7.0	45	40	37	9.5	0.32	0.22	68.8	0.22	70.4
			7.0	95	81	70	7.1	51	51	40	4.7	0.41	0.15	36.6	0.15	42.9
			7.1	93	83	78	7.2	53	62	56	2.9	0.69	0.17	24.6	0.18	28.2
			7.1	101	98	94	7.2	92	89	87	1.0	2.35	0.22	9.4	0.17	7.4
			7.4		101	89	7.5		12	5	8.2	0.30	0.26	86.7	0.25	94.4
AAFEB-2 BED	80	20	7.6		99	82	7.5		15	9	5.3	0.45	0.38	84.4	0.33	89.0
			7.3		103	89	7.3		25	15	3.3	0.75	0.57	76.0	0.54	83.2
			7.2		98	86	7.2		58	43	1.1	2.14	0.87	40.7	0.94	50.0
		10	7.6		102	84	7.5		6	2	9.3	0.26	0.25	96.2	0.21	97.6
			7.3		103	88	7.4		11	7	5.2	0.48	0.42	87.5	0.37	92.0
			7.2		104	82	7.3		36	29	3.2	0.78	0.51	65.4	0.40	64.4
			7.1		99	82	7.6		64	57	1.1	2.16	0.76	35.2	0.55	30.5
			7.0		845	811	7.0		220	170	10.0	2.03	1.50	73.9	1.54	79.0
			7.3		811	789	7.1		511	292	4.4	4.42	1.64	37.1	2.71	63.0
MATURE BED	800	20	7.5		823	796	7.2		494	438	2.1	9.41	3.76	40.0	4.09	45.0
			7.2		789	808	6.9		615	654	0.9	21.04	8.64	41.1	4.11	19.1
			7.2		850	796	7.1		272	239	10.8	1.89	1.28	67.7	1.24	70.0
		10	7.1		829	810	7.0		456	462	5.1	3.90	1.76	45.1	1.64	43.0
			7.5		877	799	7.2		596	535	3.0	7.02	2.25	32.1	2.11	33.0
			7.3		853	778	7.0		776	669	1.2	17.06	1.54	9.0	2.18	14.0
			7.3		853	800	7.0		580	552	10.3	1.99	0.64	32.2	0.58	31.0
			7.2		812	769	7.1		601	546	4.5	4.15	1.08	26.0	1.14	29.0
			7.4		845	809	6.9		718	663	3.1	6.54	0.98	15.0	1.13	18.0
AAFEB-2 BED	800	20	7.5		862	811	7.0		828	762	1.2	17.24	0.68	3.9	0.98	6.0
			7.4		789	799	7.1		615	599	10.2	1.86	0.41	22.0	0.47	25.0
			7.2		849	812	7.0		679	666	5.9	3.45	0.69	20.0	0.59	18.0
		10	7.3		845	803	7.2		752	707	3.3	6.15	0.68	11.1	0.70	12.0
			7.2		812	793	7.3		796	785	0.8	24.36	0.48	2.0	0.24	1.0

APPENDIX N

AAFEB REACTOR BIOMASS CONCENTRATIONS

Table N. A summary of the biomass concentrations in the two AAFEB bed reactors.

DATE	AAFEB-1 ENTRAPPED MASS (g-VS/l)	AAFEB-2 ENTRAPPED MASS (g-VS/l)	AAFEB-1 ATTACHED MASS (g-VS/l)	AAFEB-2 ATTACHED MASS (g-VS/l)	AAFEB-1 TOTAL MASS (g-VS/l)	AAFEB-2 TOTAL MASS (g-VS/l)
07-Feb-88	1.17		10.93		12.10	
25-Mar-88	1.82		17.96		19.78	
11-Apr-88	1.58		18.60		20.18	
17-May-88	9.34		13.99		23.34	
21-Jun-88	8.36		13.87		22.23	
15-Jul-88	5.93	3.90	17.97	9.52	23.90	13.42
05-Aug-88		5.18		10.16		15.34
12-Oct-88	3.62	5.10	25.28	8.22	28.91	13.32
02-Jul-90					27.40	20.00
05-Dec-90						19.60
18-Dec-90					28.20	

APPENDIX O

LITHIUM TRACER STUDIES TO DETERMINE ACTUAL REACTOR HYDRAULIC RETENTION TIMES

Table O.1. summarizes the information from the lithium tracer studies to interpret the first-stage AAFEB reactor actual HRT, Table O.2. summarizes that for the second-stage AAFEB reactor, and Table O.3 summarizes that of the four NFT reactors.

Table O.1. A summary of the lithium tracer studies to interpret the actual hydraulic retention time in the first-stage AAFEB reactor.

DATE: 12/13/89		Theoretical HRT
Total Reactor Volume =	4.29 s	5.17 hrs
Reactor Mixing Zone =	3.00 s	3.62 hrs
Expanded Bed Volume =	2.80 s	3.38
Influent Wastewater Flow Rate =	19.9 s/d	
Recycle Liquid Flow Rate =	68.1 s/d	
Hydraulic Upflow Velocity within the Reactor = 2.0 m/hr		

SAMPLE ID	REAL TIME (hrs.)	EFFLUENT ACTUAL Li CONC. (ug/ml)	LOG Li	RECYCLE ACTUAL Li CONC. (ug/ml)	LOG Li
1	0.00	0.00		0.00	
2	0.17	0.00		0.04	
3	0.33	0.02		1.90	
4	0.50	0.14	-1.97	52.12	3.95
5	0.67	0.32	-1.14	67.76	4.22
6	0.83	0.46	-0.78	56.40	4.03
7	1.00	0.60	-0.51	46.96	3.85
8	1.17	1.60	0.47	45.80	3.82
9	1.33	6.20	1.82	44.08	3.79
10	1.50	21.62	3.07	41.56	3.73
11	1.67	36.26	3.59	39.00	3.66
12	1.83	47.70	3.86	37.28	3.62
13	2.00	51.40	3.94	35.38	3.57
14	2.17	51.70	3.95	33.42	3.51
15	2.33	49.50	3.90	31.96	3.46
16	2.50	36.42	3.60	28.66	3.36
17	2.67	35.28	3.56	27.00	3.30
18	2.83	34.20	3.53	24.06	3.18
19	3.00	32.22	3.47	21.90	3.09
20	3.17	30.86	3.43	21.12	3.05
21	3.33	29.82	3.40	20.12	3.00
22	3.50	28.14	3.34	19.28	2.96
23	3.67	27.14	3.30	18.36	2.91
24	3.83	26.12	3.26	17.56	2.87
25	4.00	25.10	3.22	16.60	2.81
26	4.17	23.82	3.17	16.14	2.78
27	4.33	23.38	3.15	15.48	2.74
28	4.50	22.36	3.11	15.30	2.73
29	4.67	21.78	3.08	13.74	2.62
30	4.83	20.72	3.03	13.40	2.60
31	5.00	20.02	3.00	13.06	2.57
32	5.17	19.24	2.96	12.78	2.55
33	5.33	18.76	2.93	12.24	2.50
34	5.50	17.52	2.86	11.70	2.46
35	5.67	17.10	2.84	11.18	2.41
36	5.83	16.32	2.79	10.78	2.38
37	6.00	15.44	2.74	10.28	2.33
38	6.17	14.82	2.70	10.12	2.31
39	6.33	14.66	2.69	9.72	2.27
40	6.50	13.52	2.60	8.60	2.15
41	6.67	14.12	2.65	8.32	2.12
42	6.83	12.26	2.51	7.86	2.06
43	7.00	11.74	2.46	7.74	2.05
44	7.17	11.46	2.44	8.62	2.15
45	7.33	11.48	2.44	7.04	1.95
46	7.50	10.76	2.38	7.20	1.97

Table O.1. Continued.

SAMPLE ID	REAL TIME (hrs.)	EFFLUENT	LOG Li	RECYCLE	LOG Li
		ACTUAL Li CONC. (ug/ml)		ACTUAL Li CONC. (ug/ml)	
47	7.67	10.16	2.32	9.26	2.23
48	7.83	10.10	2.31	6.58	1.88
49	8.00	10.30	2.33	6.60	1.89
50	8.17	9.68	2.27	5.88	1.77
51	8.33	9.64	2.27	5.70	1.74
52	8.50	9.26	2.23	5.46	1.70
53	8.67	8.52	2.14	5.16	1.64
54	8.83	8.04	2.08	4.80	1.57
55	9.00	7.68	2.04	4.68	1.54
56	9.17	7.14	1.97	4.46	1.50
57	9.33	6.90	1.93	4.24	1.44
58	9.50	6.20	1.82	3.64	1.29
59	9.67	5.88	1.77	3.86	1.35
60	9.83	5.42	1.69	3.64	1.29
61	10.00	5.14	1.64	3.58	1.28
62	10.17	4.96	1.60	3.40	1.22
63	10.33	4.16	1.43	3.28	1.19
64	10.50	4.16	1.43	3.14	1.14
65	10.67	3.68	1.30	3.02	1.11
66	10.83	3.56	1.27	2.92	1.07
67	11.00	2.98	1.09	2.88	1.06
68	11.17	2.74	1.01	2.76	1.02
69	11.33	2.76	1.02	2.64	0.97
70	11.50	2.36	0.86	2.52	0.92
71	11.67	2.12	0.75	2.42	0.88
81	23.33	0.16	-1.83	0.40	-0.92
82	46.67	0.04	-3.22	0.18	-1.71

Table O.2. A summary of the lithium tracer studies to interpret the actual hydraulic retention time in the second-stage AAFEB reactor.

DATE: 12/7/89

Theoretical HRT

Total Reactor Volume =	2.37 s	3.01 hrs
Reactor Mixing Zone =	1.70 s	2.16 hrs
Expanded Bed Volume =	1.10 s	1.40
Influent Wastewater Flow Rate =	18.9 s/d	
Recycle Liquid Flow Rate =	28.5 s/d	
Hydraulic Upflow Velocity within the Reactor = 1.7 m/hr		

SAMPLE ID	REAL TIME (hrs.)	EFFLUENT	LOG Li	RECYCLE	LOG Li
		ACTUAL Li CONC. (ug/ml)		ACTUAL Li CONC. (ug/ml)	
1	0.00	0.00		0.00	
2	0.10	0.00		0.00	
3	0.20	0.00		0.00	
4	0.30	0.28	-1.27	0.08	-2.53
5	0.40	1.00	0.00	1.34	0.29
6	0.50	1.66	0.51	11.74	2.46
7	0.60	2.26	0.82	38.20	3.64
8	0.70	3.74	1.32	50.80	3.93
9	0.80	7.00	1.95	45.70	3.82
10	0.90	22.30	3.10	40.60	3.70
11	1.00	26.70	3.28	36.30	3.59
12	1.10	27.80	3.33	32.70	3.49
13	1.20	27.30	3.31	29.70	3.39
14	1.30	25.90	3.25	28.70	3.36
15	1.40	25.60	3.24	27.60	3.32
16	1.50	25.50	3.24	27.30	3.31
17	1.60	24.80	3.21	25.10	3.22
18	1.70	25.60	3.24	23.70	3.17
19	1.80	23.50	3.16	22.70	3.12
20	1.90	22.10	3.10	21.60	3.07
21	2.00	22.60	3.12	20.40	3.02
22	2.10	20.90	3.04	19.10	2.95
23	2.20	20.70	3.03	18.36	2.91
24	2.30	20.00	3.00	17.10	2.84
25	2.40	18.36	2.91	16.00	2.77
26	2.50	17.50	2.86	14.70	2.69
27	2.60	17.12	2.84	14.20	2.65
28	2.70	15.20	2.72	13.16	2.58
29	2.80	15.58	2.75	12.64	2.54
30	2.90	14.44	2.67	11.98	2.48
31	3.00	13.90	2.63	11.10	2.41
32	3.10	13.14	2.58	11.08	2.41
33	3.20	12.40	2.52	1.74	0.55
34	3.30	11.62	2.45	4.02	1.39
35	3.40	11.74	2.46	0.00	ERR
36	3.50	11.86	2.47	4.22	1.44
37	3.60	11.54	2.45	7.94	2.07
38	3.70	10.40	2.34	7.48	2.01
39	3.80	9.48	2.25	7.16	1.97
40	3.90	8.94	2.19	6.80	1.92
41	4.00	8.62	2.15	6.38	1.85
42	4.10	8.36	2.12	6.16	1.82
43	4.20	7.92	2.07	5.74	1.75
44	4.30	7.56	2.02	5.40	1.69
45	4.40	7.28	1.99	4.98	1.61

Table O.2. Continued.

SAMPLE ID	REAL TIME (hrs.)	EFFLUENT	LOG Li	RECYCLE	LOG Li
		ACTUAL Li CONC. (ug/ml)		ACTUAL Li CONC. (ug/ml)	
46	4.50	6.92	1.93	4.78	1.56
47	4.60	6.72	1.91	4.58	1.52
48	4.70	6.54	1.88	4.16	1.43
49	4.80	5.72	1.74	3.90	1.36
50	4.90	5.74	1.75	3.70	1.31
51	5.00	5.68	1.74	3.50	1.25
52	5.10	5.24	1.66	1.84	0.61
53	5.20	5.00	1.61	2.12	0.75
54	5.30	4.54	1.51	1.46	0.38
55	5.40	4.34	1.47	0.66	-0.42
56	5.50	4.38	1.48	0.14	-1.97
57	5.60	3.92	1.37	0.08	-2.53
58	5.70	3.78	1.33	0.02	-3.91
59	5.80	3.68	1.30	0.24	-1.43
60	5.90	3.50	1.25	0.68	-0.39
61	6.00	3.38	1.22	1.26	0.23
62	6.10	3.18	1.16	1.60	0.47
63	6.20	2.98	1.09	1.40	0.34
64	6.30	2.82	1.04	1.42	0.35
65	6.40	2.80	1.03	1.30	0.26
66	6.50	2.54	0.93	1.14	0.13
67	6.60	2.50	0.92	1.12	0.11
68	6.70	2.38	0.87	0.93	-0.07
69	6.80	2.28	0.82	0.74	-0.30
70	6.90	2.18	0.78	0.72	-0.33
71	7.00	2.00	0.69	0.48	-0.73
72	7.10	1.94	0.66	0.38	-0.97
73	7.20	1.86	0.62	0.46	-0.78
74	7.30	1.78	0.58	0.32	-1.14
75	7.40	1.66	0.51	0.36	-1.02
76	7.50	1.66	0.51	0.64	-0.45
77	7.60	1.68	0.52	0.86	-0.15
78	7.70	1.68	0.52	0.84	-0.17
79	7.80	1.74	0.55	0.38	-0.97
80	7.90	1.72	0.54	0.22	-1.51
81	8.00	1.60	0.47	0.20	-1.61
82	8.10	1.48	0.39	0.18	-1.71
83	8.20	1.42	0.35	0.10	-2.30
84	8.30	1.38	0.32	0.08	-2.53
85	8.40	1.26	0.23	0.06	-2.81
86	8.50	1.20	0.18	0.00	
87	22.33	0.00		0.00	

Table O.3. A summary of the lithium tracer studies conducted to the actual hydraulic retention times in the NFT reactors.

TIME (hrs)	LITHIUM CONCENTRATIONS				LN OF LITHIUM CONCENTRATIONS			
	NFT-DS (mg/l)	NFT-DN (mg/l)	NFT-SN (mg/l)	NFT-SS (mg/l)	NFT-DS	NFT-DN	NFT-SN	NFT-SS
0.0	0.04	0.00	0.00	0.04	-3.22			-3.22
1.0	0.04	0.00			-3.22			
2.0	1.08				0.08			
2.5		0.00						
3.0	11.54				2.45			
4.0	29.10	0.00			3.37			
5.0	39.70				3.68			
5.5		2.54				0.93		
6.0	41.00				3.71			
7.0	39.66	12.82	3.80	0.06	3.68	2.55	1.34	-2.81
7.5	35.74	17.26			3.58	2.85		
8.0	33.12	20.34			3.50	3.01		
8.5	31.50	22.74			3.45	3.12		
9.0	28.98	24.60			3.37	3.20		
9.5	26.72	26.08			3.29	3.26		
10.0	24.84	27.04			3.21	3.30		
10.5	23.22	27.22			3.15	3.30		
11.0	21.30	27.06			3.06	3.30		
11.5	19.56	26.60			2.97	3.28		
12.0	18.06	26.18			2.89	3.26		
12.5	16.62	25.42			2.81	3.24		
13.0	15.56	24.48			2.74	3.20		
13.5	14.48	23.58			2.67	3.16		
14.0	13.32	22.66			2.59	3.12		
14.5	12.26	21.70			2.51	3.08		
15.0	11.28	20.64	16.90	2.68	2.42	3.03	2.83	0.99
15.5	10.28	19.72			2.33	2.98		
16.0	9.48	18.62			2.25	2.92		
16.5	8.78	17.80	19.26	4.88	2.17	2.88	2.96	1.59
17.0	8.20	16.70			2.10	2.82		
17.5	7.50	15.78			2.01	2.76		
18.0	7.06	14.98			1.95	2.71		
18.5	6.60	14.20			1.89	2.65		
19.0	6.04	13.42	20.38	9.50	1.80	2.60	3.01	2.25
19.5	5.52	12.94			1.71	2.56		
19.8		12.46				2.52		
20.0	5.12	12.00	20.54	11.24	1.63	2.48	3.02	2.42
20.5		11.54				2.45		
21.0	4.38	11.08			1.48	2.41		
21.3		10.62	19.42	12.70		2.36	2.97	2.54
22.0	3.88	9.86	18.98	13.32	1.36	2.29	2.94	2.59
22.8		9.08	18.85			2.21	2.94	
23.0	3.28	8.60	18.72	13.54	1.19	2.15	2.93	2.61
23.5		8.12	18.26			2.09	2.90	
24.0	2.82	7.71	17.80	13.24	1.04	2.04	2.88	2.58
24.3		7.30	17.38			1.99	2.86	
25.0	2.56	6.60	16.96	12.56	0.94	1.89	2.83	2.53
26.0			16.06	11.79			2.78	2.47
27.0			15.04	11.26			2.71	2.42
28.0			14.18	10.56			2.65	2.36
29.0			13.26	9.85			2.58	2.29
29.8	2.36	4.54	12.86	9.55	0.86	1.51	2.55	2.26
30.0			12.46	9.35			2.52	2.24
31.0			11.58	9.03			2.45	2.20

Table O.3. Continued.

TIME (hrs)	LITHIUM CONCENTRATIONS				LN OF LITHIUM CONCENTRATIONS			
	NFT-DS (mg/l)	NFT-DN (mg/l)	NFT-SN (mg/l)	NFT-SS (mg/l)	NFT-DS	NFT-DN	NFT-SN	NFT-SS
32.0			10.82	8.43			2.38	2.13
33.0			10.10	7.96			2.31	2.07
34.0			9.52	7.56			2.25	2.02
40.0			6.58	5.40			1.88	1.69
41.0	0.60	2.44	6.20	5.20	-0.51	0.89	1.82	1.65
42.0	0.38	2.20	5.84	4.86	-0.97	0.79	1.76	1.58
43.0	0.24	1.72	5.50	4.56	-1.43	0.54	1.70	1.52
44.0			5.26	4.34			1.66	1.47
45.0	0.08	1.50	5.16	4.08	-2.53	0.41	1.64	1.41
46.0	0.00	1.18	4.78	3.90		0.17	1.56	1.36
47.0			4.52	3.70			1.51	1.31
48.0			4.28	3.50			1.45	1.25
49.0		0.86	4.19	3.32		-0.15	1.43	1.20
50.0			4.10	3.14			1.41	1.14
52.0			3.60	2.80			1.28	1.03
54.0			3.22	2.52			1.17	0.92
56.0			2.92	2.32			1.07	0.84
64.5		0.58				-0.54		
Actual Total HRT Calculation NFT-DS					Actual Total HRT Calculation NFT-DN			
Y Intercept			4.78		Y Intercept		4.60	
Std Err of Y Est			0.01		Std Err of Y Est		0.03	
R Squared			1.00		R Squared		1.00	
No. of Observation			25.00		No. of Observation		28.00	
Degrees of Freedom			23.00		Degrees of Freedom		26.00	
X Coefficient(s)			-0.16		X Coefficient(s)		-0.11	
Std Err of Coef.			0.00		Std Err of Coef.		0.00	
X intercept			30.44		X intercept		43.40	
Total Area			72.68		Total Area		99.89	
1/2 total area			36.34		1/2 total area		49.94	
Angle (radians)			0.13		Angle (radians)		0.09	
Angle (degrees)			7.49		Angle (degrees)		5.27	
Actual HRT			6.92		Actual HRT		10.48	
Time period			7 - 19		Time period		12 - 25	
Actual Total HRT Calculation NFT-SN					Actual Total HRT Calculation NFT-SS			
Y Intercept			4.47		Y Intercept		3.89	
Std Err of Y Est			0.01		Std Err of Y Est		0.01	
R Squared			1.00		R Squared		1.00	
No. of Observation			11.00		No. of Observation		14.00	
Degrees of Freedom			9.00		Degrees of Freedom		12.00	
X Coefficient(s)			-0.07		X Coefficient(s)		-0.05	
Std Err of Coef.			0.00		Std Err of Coef.		0.00	
X intercept			68.63		X intercept		70.92	
Total Area			153.44		Total Area		137.84	
1/2 total area			76.72		1/2 total area		68.92	
Angle (radians)			0.06		Angle (radians)		0.06	
Angle (degrees)			3.34		Angle (degrees)		3.23	
Actual HRT			17.32		Actual HRT		21.48	
Time period			25 - 34		Time period		40 - 56	

APPENDIX P

A SUMMARY OF THE SLUDGE PRODUCTION FROM THE FIRST-STAGE AAFEB REACTOR

Table P. A summary of digested sludge accumulation in the AAFEB first-stage reactor.

FROM	DATE	TO	OPERATION	TEMP	TIME	SLUDGE	SLUDGE	SLUDGE	SLUDGE	TOTAL					SLUDGE	SLUDGE	SLUDGE					
										PERIOD	VOLUME	TS	VS	VOLUME				SEWAGE	SEWAGE	SLUDGE	SLUDGE	SLUDGE
			TIME	(C)						(s)	(s/d)	(l/s)	(g/s)			(g/s)						
			(d)																			
01-Jan-90	09-Jan-90		0	9.5	9	570	1.53	44.98	63.3	174.2	19.4	3.3	50.05		22.51							
09-Jan-90	11-Jan-90		8	9.8	2	390	0.87	45.48	195.0	40.9	20.5	9.5	82.67		37.60							
11-Jan-90	18-Jan-90		10	9.5	7	550	0.93	45.64	78.6	135.3	19.3	4.1	37.80		17.25							
18-Jan-90	31-Jan-90		17	11.0	13	850	0.63	43.98	65.4	161.8	12.4	5.3	33.09		14.55							
31-Jan-90	05-Feb-90		30	10.0	5	510	0.37	44.66	102.0	38.9	7.8	13.1	48.53		21.68							
06-Feb-90	15-Feb-90		36	9.0	10	360	0.57	54.17	36.0	73.1	7.3	4.9	28.08		15.21							
15-Feb-90	23-Feb-90		45	9.4	8	550	0.32	43.53	68.8	62.2	7.8	8.8	28.30		12.32							
23-Feb-90	26-Feb-90		53	10.0	3	300	0.48	46.97	100.0	24.2	8.1	12.4	59.53		27.96							
26-Feb-90	27-Feb-90		56	9.5	1	570	0.68	44.51	570.0	7.7	7.7	73.8	502.07		223.47							
27-Feb-90	01-Mar-90		57	9.0	2	550			275.0	15.4	7.7	35.6										
01-Mar-90	05-Mar-90		59	9.8	4	570	0.30	40.54	142.5	30.2	7.5	18.9	56.66		22.97							
05-Mar-90	06-Mar-90		63	10.0	1	570			570.0	7.8	7.8	73.5										
06-Mar-90	07-Mar-90		64	9.0	1	570	0.53	37.15	570.0	7.5	7.5	76.1	403.34		149.84							
07-Mar-90	08-Mar-90		65	9.0	1	570	0.44	39.06	570.0	7.2	7.2	79.2	348.33		136.06							
08-Mar-90	13-Mar-90		66	9.5	5	550	0.37	39.92	110.0	40.1	8.0	13.7	50.80		20.28							
13-Mar-90	19-Mar-90		71	12.5	6	570	0.69	41.41	95.0	134.4	22.4	4.2	29.25		12.11							
19-Mar-90	21-Mar-90		77	11.5	2	550	0.26	34.41	275.0	74.4	37.2	7.4	19.22		6.61							
21-Mar-90	27-Mar-90		79	10.0	6	570	1.61	45.72	95.0	229.8	38.3	2.5	39.93		18.26							
27-Mar-90	28-Mar-90		85	11.0	1	550	0.85	50.61	550.0	37.6	37.6	14.6	124.20		62.86							
28-Mar-90	29-Mar-90		86	12.0	1	570	0.66	59.40	570.0	37.5	37.5	15.2	100.32		59.59							
29-Mar-90	30-Mar-90		87	13.0	1	550	0.76	52.80	550.0	37.6	37.6	14.6	111.05		58.64							
30-Mar-90	02-Apr-90		88	13.0	3	570	0.56	53.85	190.0	112.1	37.4	5.1	28.47		15.33							
02-Apr-90	03-Apr-90		91	14.0	1	570			570.0	37.2	37.2	15.3										
03-Apr-90	05-Apr-90		92	11.5	2	570	0.79	49.17	285.0	75.6	37.8	7.5	59.56		29.28							
05-Apr-90	06-Apr-90		94	11.0	1	570	0.42	49.84	570.0	37.8	37.8	15.1	63.27		31.53							
06-Apr-90	10-Apr-90		95	11.0	4	580	0.92	51.93	145.0	150.4	37.6	3.9	35.49		18.43							
10-Apr-90	16-Apr-90		99	12.0	6	600			100.0	227.8	38.0	2.6										
16-Apr-90	17-Apr-90		105	13.0	1	550			550.0	38.0	38.0	14.5										
17-Apr-90	21-Apr-90		106	12.2	4	550			137.5	149.4	37.3	3.7										
21-Apr-90	23-Apr-90		110	13.0	2	550	1.14	47.97	275.0	71.9	36.0	7.6	87.16		41.81							
23-Apr-90	24-Apr-90		112	14.0	1	570	1.07	59.31	570.0	37.8	37.8	15.1	161.52		95.80							
24-Apr-90	26-Apr-90		113	14.5	2	550			275.0	75.9	37.9	7.2										
26-Apr-90	30-Apr-90		115	17.3	4	570	0.58	50.92	142.5	150.5	37.6	3.8	21.96		11.18							
30-Apr-90	03-May-90		119	16.3	3	560	1.70	42.60	186.7	112.2	37.4	5.0	84.85		36.15							
03-May-90	11-May-90		122	16.0	8	570	2.48	48.88	71.3	297.9	37.2	1.9	47.45		23.19							
11-May-90	16-May-90		130	15.8	5	600	0.44	51.39	120.0	186.0	37.2	3.2	14.19		7.29							

Table P. Continued.

FROM	DATE TO	OPERATION TIME (d)	TEMP (C)	TIME PERIOD (days)	SLUDGE VOLUME (l)	SLUDGE TS (%)	SLUDGE VS (%)	SLUDGE VOLUME (l/d)	TOTAL				
									SEWAGE FLOW (s)	SEWAGE FLOW (s/d)	SLUDGE WET (l/s)	SLUDGE DRY (g/s)	SLUDGE VOLATILE (g/s)
16-May-90	22-May-90	135	14.8	6	600	0.66	48.75	100.0	223.8	37.3	2.7	17.69	8.62
23-May-90	31-May-90	142	14.0	8	600	0.38	49.82	75.0	301.4	37.7	2.0	7.57	3.77
31-May-90	05-Jun-90	150	16.0	5	600	0.63	47.92	120.0	183.4	36.7	3.3	20.61	9.88
05-Jun-90	12-Jun-90	155	16.2	7	600	0.64	52.17	85.7	268.9	38.4	2.2	14.28	7.45
12-Jun-90	14-Jun-90	162	16.5	2	550	1.12	58.09	275.0	71.6	35.8	7.7	86.20	50.07
14-Jun-90	19-Jun-90	164	17.7	5	570	0.74	35.92	114.0	191.3	38.3	3.0	22.05	7.92
19-Jun-90	23-Jun-90	169	19.3	4	550	0.61	50.18	137.5	152.2	38.0	3.6	22.05	11.06
23-Jun-90	30-Jun-90	173	19.2	7	600	1.46	45.66	85.7	265.1	37.9	2.3	33.05	15.09
30-Jun-90	12-Jul-90	180	19.2	12	540			45.0	455.4	38.0	1.2		
12-Jul-90	21-Jul-90	192	21.2	9	430	1.32	21.00	47.8	340.0	37.8	1.3	16.69	3.51
21-Jul-90	24-Jul-90	201	22.0	3	560	0.40	25.72	186.7	113.1	37.7	5.0	19.81	5.09
24-Jul-90	27-Jul-90	204	22.0	3	560			186.7	112.6	37.5	5.0		
27-Jul-90	31-Jul-90	207	22.0	4	560			140.0	149.6	37.4	3.7		
31-Jul-90	06-Aug-90	211	23.0	6	560			93.3	233.5	38.9	2.4		
06-Aug-90	21-Aug-90	217	22.5	15	570			38.0	581.0	38.7	1.0		
21-Aug-90	28-Aug-90	232	22.8	7	570			81.4	264.9	37.8	2.2		
AVERAGE VALUES						0.79	46.05	224.1	135.5	29.5	7.6	60.04	27.65
MAXIMUM VALUES						2.48	59.40	570.0	581.0	38.9	14.7	363.39	215.86
MINIMUM VALUES						0.26	21.00	36.0	7.2	7.2	5.0	13.00	2.73

APPENDIX Q

PILOT SYSTEM SULFATE AND SULFIDE SULFUR CONCENTRATIONS

Table Q.1. summarizes the sulfate-sulfur concentrations in the influent and effluent from each reactor of the pilot system. During the period from June 8, 1990 through July 27, 1990, both the sulfate and sulfide-sulfur concentrations in the influent and effluent of the AAFEB reactor system were also measured, as summarized in Table Q.2. In this table the total influent sulfur (sulfate plus sulfide-sulfur) was compared to that in the effluent from each AAFEB reactor.

Table Q.1. A summary of the pilot system sulfate sulfur (SO₄-S) concentrations.

DATE	TIME (d)	INF (mg/l)	AAFEB-1 (mg/l)	AAFEB-2 (mg/l)	NFT-DS (mg/l)	NFT-DN (mg/l)	NFT-SN (mg/l)	NFT-SS (mg/l)
17-Jan-90	16	12.84	2.76	2.55	11.33	10.91	10.82	
24-Jan-90	23	13.48	2.98	2.90	3.76	3.97	6.95	
07-Feb-90	37	11.23	2.69	2.67	4.54	4.54	4.73	
14-Feb-90	44	12.68	2.97	2.78			3.71	
21-Feb-90	51	13.00	3.25	2.87				
28-Feb-90	58	12.26	2.98	3.03				
07-Mar-90	65	12.95	2.91	2.91	7.29	10.92		
14-Mar-90	72	13.38	2.83	2.81	6.45	7.78		
23-Mar-90	81	12.11	3.54	3.67	5.74	6.77	10.06	
28-Mar-90	86	6.50	3.50	3.83	6.78	9.73	15.06	
30-Mar-90	88	10.08	3.21	3.27				
04-Apr-90	93	7.89	3.48	3.46	4.40	8.89	13.53	
06-Apr-90	95	12.30	3.82	3.50				
11-Apr-90	100	13.77	4.05	3.37	8.14	10.69	16.73	
18-Apr-90	107	12.92	3.05	3.46	5.92	6.67	8.95	
20-Apr-90	109	12.02	2.82	2.50				
25-Apr-90	114	12.76	3.25	3.01	12.54	11.88	19.10	
27-Apr-90	116	12.93	4.12	4.78				
02-May-90	121	7.90	2.90	2.95	13.30	20.51	30.21	
09-May-90	128	12.65	3.63	3.07	8.28	11.98	19.17	
16-May-90	135	8.77	3.58	6.21	7.98	9.70		
22-May-90	141	10.01	2.39	3.76	4.12	8.32		
30-May-90	149	11.73	3.43	3.72	11.26	13.11	15.72	
06-Jun-90	156	2.44	1.70	5.08	1.10	3.70		3.60
13-Jun-90	163	11.09	3.43	3.20	4.89	5.16		5.82
20-Jun-90	170	7.40	6.84	6.18	4.82	5.56		2.67
27-Jun-90	177	11.27	1.52	1.21	2.90	3.85		2.67
18-Jul-90	198	13.71	3.90	2.78	6.03	6.63	5.32	
25-Jul-90	205	10.53	1.52	3.28	4.20	3.73		
01-Aug-90	212	11.50	0.53	0.39	3.28	3.93	4.09	
08-Aug-90	219	12.97	3.96	3.37	NA	7.40	8.10	
15-Aug-90	226	12.92	5.69	6.04	NA	6.58	5.88	

Table Q.2. A summary of the AAFEB reactor system influent and effluent sulfate and sulfide-sulfur concentrations over the period from June 8, 1990 through July 27, 1990.

DATE	TIME	INF SO ₄ -S (mg/l)	AAFEB-1 SO ₄ -S (mg/l)	AAFEB-2 SO ₄ -S (mg/l)	INF H ₂ S (mg/l)	AAFEB-1 H ₂ S (mg/l)	AAFEB-2 H ₂ S (mg/l)	TOTAL INF SULFUR (mg/l)	TOTAL AAFEBR-1 SULFUR (mg/l)	TOTAL AAFEBR-2 SULFUR (mg/l)
01-Jan-90	(d)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)
08-Jun-90	158	11.87	2.68	1.32	1.55	14.43	13.59	13.42	17.11	14.91
21-Jun-90	171	11.92	7.16	2.25	2.21	15.16	14.84	14.13	22.32	17.09
22-Jun-90	172	12.98	2.92	3.81	3.86	19.66	16.40	16.84	22.58	20.22
25-Jun-90	175	14.99	2.09	2.44	5.08	18.37	14.17	20.07	20.46	16.61
26-Jun-90	176	13.55	2.56	2.44	2.64	14.10	12.17	16.19	16.66	14.61
27-Jun-90	177	11.20	0.87	0.35	2.92	17.70	13.70	14.12	18.57	14.05
28-Jun-90	178	10.57	0.33	0.31	3.37	16.42	13.18	13.94	16.75	13.49
28-Jun-90	178	9.64	0.82	0.76	3.10	17.10	14.59	12.74	17.92	15.36
29-Jun-90	179	15.44	0.54	0.67	1.31	15.10	13.48	16.75	15.64	14.14
02-Jul-90	182	10.42	1.40	0.30	5.85	16.49	14.80	16.27	17.89	15.10
03-Jul-90	183	10.32	0.82	1.04	3.59	14.54	10.03	13.91	15.36	11.07
04-Jul-90	184	11.43	0.92	1.47	2.03	17.62	14.78	13.46	18.54	16.24
05-Jul-90	185	14.47	3.04	2.93	4.17	21.51	15.09	18.64	24.55	18.02
06-Jul-90	186	15.05	2.55	2.32	1.46	14.29	12.75	16.51	16.84	15.07
09-Jul-90	189	15.47	2.33	4.74	3.89	16.79	16.48	19.36	19.11	21.21
11-Jul-90	191	13.21	2.53	2.90	3.12	14.99	13.77	16.32	17.52	16.66
12-Jul-90	192	13.28	2.43	2.46	4.44	14.67	13.96	17.72	17.10	16.42
13-Jul-90	193	13.53	6.76	7.25	7.96	19.40	19.07	21.49	26.16	26.31
16-Jul-90	196	14.14	2.55	2.78	4.86	18.29	13.77	19.00	20.84	16.55
17-Jul-90	197	14.26	2.84	2.93	3.87	18.67	15.75	18.13	21.51	18.67
18-Jul-90	198	13.77	2.45	2.26	4.46	17.28	13.99	18.23	19.73	16.25
20-Jul-90	200	14.12	2.32	2.34	4.62	17.44	14.52	18.74	19.77	16.86
23-Jul-90	203	14.01	3.11	4.55	4.85	16.08	13.44	18.86	19.19	17.99
24-Jul-90	204	14.09	2.77	2.64	3.28	15.65	16.66	17.36	18.42	19.30
25-Jul-90	205	10.86	0.27	0.43	3.87	16.50	12.83	14.73	16.78	13.26
27-Jul-90	207	10.97	0.00	0.45	2.36	14.80	15.18	13.32	14.80	15.63

APPENDIX R

A SUMMARY OF THE PILOT SYSTEM ENERGY REQUIREMENTS

Table R.1. A summary of the pilot system electrical useage.

ELECTRICAL USEAGE	Quantity	Hp	Voltage	Amperage	wattage	Average Operation Time (hrs/d)	Operation Months	ENERGY USAGE (kw-hr/d)
Wastewater Transfer Pump								
Feed	1	0.75	115	9.3	560	24	All	13.4
AAFEB Intermediate	1	0.75	115	9.3	560	24	All	13.4
NFT Intermediate	1	0.17	115	5.0	124	9	All	1.1
Effluent	1	0.33	115	7.0	249	4	All	1.0
							TOTAL	29.0
AAFEB Reactor System								
Recycle Pumps	2	0.17	115	5.0	124	24	All	6.0
Paddle Mixers	2	0.03	115	1.4	19	0.20	All	0.01
							TOTAL	6.0
AAFEB and NFT Greenhouse								
Inflation Fans	2	0.04	115	1.5	30	24	All	1.4
NFT Ventilation Fan	1	1.00	115	12.8	746	4	All	3.0
AAFEBR Ventilation Fan	1	0.33	115	5.0	249	4	6, 7, 8	1.0
Heating Furnaces	2	0.33	115	13.0	249	4	1, 2, 3, 11, 12	2.0
							TOTAL	4.4 to 7.4
Other Highly Variable Energy Useages								
Sample Prep Room								
pH Meter	1		115	1.0	58			
Balance	1		115	2.0	115			
Hot Water Heater	1		208	19.0	3952			
Lights	6		115	0.7	75			
Office								
Baseboard Heater	1		208	14.4	3000			
Portable Heater	1		115	13.0	1500			
Air Conditioner	1		115	5.5	600			
Small Refrigerator	1		115	1.5	30			
Large Refrigerator	1		115	6.8	136			
Lights	6		115	0.7	75			

Table R.2.

A summary of the pilot system monthly electrical usages.

DATE	* METER READING	TOTAL	WASTEWATER			
		ENERGY USAGE (kw-hr/d)	AAFEB USAGE (kw-hr/d)	TRANSFER USAGE (kw-hr/d)	GREENHOUSE USAGE (kw-hr/d)	OTHER USAGE (kw-hr/d)
22-Dec-89	6587	114.00	18.3	29.2	19.0	47.5
24-Jan-90	6603	87.27	18.3	29.2	19.0	20.8
23-Feb-90	6620	102.00	18.3	29.2	19.0	35.5
26-Mar-90	6631	63.87	18.3	29.2	16.4	0.0
25-Apr-90	6644	78.00	18.3	29.2	19.0	11.5
24-May-90	6655	68.28	18.3	29.2	11.0	9.7
25-Jun-90	6668	73.13	18.3	29.2	11.0	14.6
25-Jul-90	6676	48.00	18.3	29.2	0.5	0.0
23-Aug-90	6686	62.07	18.3	29.2	13.2	1.4
24-Sep-90	6696	56.25	18.3	29.2	8.7	0.0
24-Oct-90	6706	60.00	18.3	29.2	11.0	1.5
26-Nov-90	6717	60.00	18.3	29.2	11.0	1.5
24-Dec-90	6727	64.29	18.3	29.2	16.8	0.0
24-Jan-91	6742	87.10	18.3	29.2	19.0	20.6
25-Feb-91	6755	73.13	18.3	29.2	19.0	6.6

* - Readings supplied by NYSEG Corporation from a kilowatt meter with a conversion factor of 180.

Table R.3.

A summary of the kerosene fuel usage for maintaining 40 °F in the two greenhouse structures.

NFT Greenhouse area = 362.3 square meters.
 AAFEB Greenhouse area = 35.3 square meters
 Total Greenhouse area = 397.6 square meters.

DELIVERY DATE	DELIVERED VOLUME (gal)	FUEL USAGE (gal/d)
22-Dec-89	221.8	16.6
03-Jan-90	198.4	18.5
22-Jan-90	137.8	10.4
08-Feb-90	144.1	8.1
02-Mar-90	155.9	6.6
30-Aug-90	154.8	0.9
31-Dec-90	128.8	1.3
10-Jan-91	118.9	12.9
28-Jan-91	254.9	6.6
Average fuel consumption for 1990 =		20.5 (gal/ft ² -yr) 7.2 (l/m ² -yr)

APPENDIX S

DESIGN CONSIDERATIONS

The following summarizes designs and comparison of two different size systems, 0.1 and one million gallons per day (379 and 3790 m³/d), for two different levels of treatment, secondary (30 mg/l SS and 30 mg/l BOD) and tertiary (BOD and SS less than five mg/l and total nitrogen less than one mg/l and total phosphorus less than one mg/l). After sizing the systems, capital costs are estimated using construction costs or USEPA costing manuals (see main text). Operation and maintenance requirements are also estimated. Life cycle costs are prepared from these cost estimates by estimating the present value of the treatment system over the design period (20 years). All these values are preliminary and should be used with caution.

The preferable design approach would be to use rational models based on a detailed understanding of pollutant interaction phenomena. Although this is possible with the AAFEB, the understanding of the NFT is not sufficiently developed to support this type of analysis. Also the AAFEB information is more complex because of the two-stage system and inclusion of sludge stabilization in accumulating sludge blanket of the first unit of the AAFEB treatment. Thus the following design is empirical and uses gross parameters such as hydraulic retention times, mass loading rates, and hydraulic loading rates that are correlated to required effluent quality achieved in the pilot system. Various secondary parameters were checked to be sure that they were within the range tested after a unit was sized. For example, after assuming an NFT channel area, a width was chosen. The horizontal velocity was then calculated. If it was in the low regions of the rates tested (20.4 m/d to 402 m/d), it was considered acceptable. If not, the configuration was changed to make all physical parameters conform with the pilot system. Note that no attempt was made to incorporate the impact of root mass on design parameters. Future work should adjust velocities, retention times, etc., based on modified liquid volumes.

Unit processes were selected as required by a conventional secondary and tertiary treatment system (built around an activated sludge facility). The resource recovery facility was designed with an on-site sludge assimilation capability for the desired period and energy production via anaerobic digestion. It was composed of the following unit processes.

- 1) Preliminary treatment
- 2) Primary clarifiers
- 3) Anaerobic treatment AAFEB
- 4) NFT-1
- 5) NFT-2
- 6) NFT-off-line for final residue disposal
- 7) Anaerobic digestion

Processes common to all systems were (1) and (2), Preliminary Treatment and Primary Clarifiers.

I. Empirical NFT Design Considerations Based on Pilot Design and Testing

The following summarizes maximum loadings tested during the pilot program.

Maximum Hydraulic Loading Rates Tested in Total System

Maximum flow divided by surface area (D + S)

10,000 gpd/1400ft² and 10,000 gpd/4ft channel width

First-stage NFT channel (DS) would be 400 ft²/1400ft² = 0.286 or 29 percent of total

Maximum loading would be 3.5 times system's maximum for areal loading; that is, when the total system was loaded at 10 cm/d, the hydraulic loading in the first channel was (10/0.286 = 35) 35 cm/d.

$$A. \text{ Areal Loading} = 10,000 \text{ gpd}/1400 \text{ ft}^2 \times \frac{\text{m}^3}{264 \text{ gal}} \times \frac{10.76 \text{ ft}^2}{\text{m}^2} =$$

$$0.291 \frac{\text{m}^3}{\text{m}^2\text{-d}} \text{ or the maximum total system hydraulic loading rate was}$$

$$29.1 \text{ cm/d}$$

$$\text{Areal loading} = \text{HL}_{\text{SA}} = \frac{\text{gpd}}{\text{ft}^2} (0.0408) = \frac{\text{m}^3}{\text{m}^2\text{-d}}$$

B. Weir Loading

$$\text{HL}_{\text{W}} = \frac{\text{gpd}}{\text{ft width}} \left(\frac{\text{m}^3}{264} \cdot \frac{3.28 \text{ ft}}{\text{m}} \right) = \frac{\text{gpd}}{\text{ft w}} (0.01242) = \frac{\text{m}^3}{\text{m-d}}$$

HL_w range tested = 1,000 to 10,000 gpd per 4 ft wide channel
 or 250 to 2,500 gpd/ft_w
 3.10 to 31.0 $\frac{\text{m}^3}{\text{m}_w\text{-d}}$

C. Horizontal Velocities, V_H

Initial Total Water Depths = 6 inches (15.24 cm)

Minimum Total Water Depth = 3 inches (7.62 cm), some channels operated at lower depths.

$$V_H = \frac{\text{gpd}}{\text{ft}_{\text{wide}}} \left(\frac{1}{\text{Area/depth}} \cdot \frac{\text{ft}^3}{7.48 \text{ gal}} \right)$$

@ 6 in deep, Area = 2.0 ft²

@ 3 in deep, Area = 1.0 ft²

$$V_{H6\text{in}} = \frac{\text{gpd}}{\text{ft}_{\text{wide}}} \left(\frac{1}{3.74} \right) = 66.8 \text{ to } 668 \text{ ft/d (20.4 to } 204 \text{ m/d)}$$

$$V_{H3\text{in}} = 132 \text{ to } 1,320 \text{ ft/d (40.2 to } 402 \text{ m/d)}$$

II. Empirical AAFEB Design Considerations

For the bulk of operation a two-stage AAFEB was used. A sludge blanket was allowed to accumulate on top of the first-stage unit to achieve sludge stabilization. The hydraulic retention time in the first-stage bed (HRT_B) varied from 1.6 to 27.2 hours, and the HRT_B in the second stage varied from 0.5 to 8.1 hours. The relationship between temperature and total system HRT_B showed that winter conditions would require the longest design retention time, and that would be about six to ten hours with about two hours in the first stage, as conservative requirements. A one-hour HRT_B was adequate to achieve good hydrolysis and acidification efficiency in the first stage.

Sludge appeared to stabilize rapidly. A sludge blanket volume equal to four days' accumulation should be sufficient in the first stage AAFEB.

EXAMPLE 1. Resource Recovery Wastewater Treatment to Achieve Secondary Quality Effluent for One MGD (3800 m³/d)

A. Preliminary Treatment and Primary Clarifier

Preliminary treatment composed of bar screen and grit chamber and primary clarifier are similar to a conventional facility and are costed from USEPA manuals (see main text).

B. Secondary Treatment

AAFEB System

Between 6 to 10 hr HRT in bed required to achieve BOD₅ & SS <50 mg/l that is acceptable feed to the NFT.

Use 2 hr HRT first-stage AAFEB, 8 hr second-stage AAFEB

Use expanded bed volume occupancy of 67% total volume

First Stage Total HRT = $2/0.67 = 3$ hr with free board included

Second Stage = $8/0.67 = 12$ hr

First stage for design flow of 3800 m³/d

Volume first-stage AAFEB = $3800 \times 3/24 = 475$ m³

@ Ø = 6 m, ht = 16.8 m, Bed ht = 11.2 m

Operating bed ht = 11.2 m

Static bed ht = 9.3 m

Sludge Storage volume to achieve *in situ* stabilization:

Daily volume = 11,400 l/d @ 4% TS

Daily accumulation rate in reactor

$$\text{Area} = \frac{\pi D^2}{4} = \frac{3.14 (36)}{4} = 28.3 \text{ m}^2$$

$$\text{Daily Sludge Depth Accumulation} = \frac{11.4 \text{ m}^3/\text{d}}{28.3 \text{ m}^2} =$$

$$= 0.4 \text{ m/d}$$

Allow two- to four-day accumulation or allow 1.6 m accumulation sludge blanket on top of bed, gives clarifier zone depth:

Clarifier depth = total unit height - accumulated sludge depth - expanded bed depth

$$\text{Clarifier depth} = 16.8 \text{ m} - 1.6 - 11.2 = 4 \text{ m}$$

This is an acceptable clarifier zone and leaves room for bed expansion and sludge management.

Second Stage for design flow of $3800 \text{ m}^3/\text{d}$ -use 4 units equal to first-stage

$$\text{total volume} = 475 \text{ m}^3 \times 4 = 1900 \text{ m}^3, \text{ total AAFEB volume} = 2375 \text{ m}^3$$

One possible AAFEB system arrangement* is as follows:

*In the pilot study the first stage was followed by a second stage AAFEB.

NFT to Achieve Secondary Quality

Design Parameters From Pilot Operation:

Design Areal Loading Rate = 7.6 gpd/ft^2 ($0.312 \text{ m}^3/\text{m}^2\text{-d}$)

Weir Loading Rate = $4200 \text{ gpd/4 ft width} = 1050 \text{ gpd/ft}$

($13 \text{ m}^3/\text{m-d}$), which is less than maximum loading of $31 \text{ m}^3/\text{m-d}$.

Horizontal Velocity =

@ 6 inch depth $V_H = 280 \text{ ft/d}$ (85 m/d), which is less than the maximum velocity of 204 m/d at a six-inch depth

For 1 M&D, ($3.785 \times 10^3 \text{ m}^3/\text{d}$)

$$\text{Area Required} = \frac{3.785 \times 10^3 \text{ m}^3/\text{d}}{0.312 \text{ m}^3/\text{m-d}} = 12.13 \times 10^3 \text{ m}^2$$

($130 \times 10^3 \text{ ft}^2$ or 3 acres NFT channels)

Check to determine whether weir loading rate or horizontal velocity is limiting at maximum weir loading rate of $31 \text{ m}^3/\text{m-d}$.

$$\text{Total width} = \frac{3790 \text{ m}^3/\text{d}}{31 \text{ m}^3/\text{m-d}} = 122 \text{ m wide}$$

Length of channels at maximum weir loading = $12,130 \text{ m}^2 / 122 \text{ m} = 99 \text{ m}$.

Shorter channels would achieve more effective length/width ratio.

Therefore neither weir nor horizontal velocities will be limiting.

Assume 50 m long channels used, calculate total required width

$$\text{Total NFT channel width} = 12130 \text{ m}^2 / 50 = 242.6 \text{ m}$$

Individual channel dimensions:

Assume 6 m wide channels, 50 m long, are = $300 \text{ m}^2/\text{channel}$

$$\text{Number channels} = 12,130 \text{ m}^2 / 300 \text{ m}^2/\text{channel} = 40.4$$

Use 41 channels

Check Weir Loading and Horizontal Velocities

Assume initial depth of 15 cm

$$\text{Weir Loading} = \frac{\frac{3800 \text{ m}^3/\text{d}}{41 \text{ channels}}}{6 \text{ m}_w} = 15 \text{ m}^3/\text{m}_w\text{-d, which is much less than}$$

maximum of $31 \text{ m}^3/\text{m-d}$.

$$V_H = \frac{3800/41}{6 \times 0.15} = 103 \text{ m/d, which is less than maximum of } 204 \text{ m/d.}$$

Note: Disinfection may be needed to meet secondary effluent requirements.

Hydraulic Retention Time in NFT System

At average channel depth of 0.152 m

$$\text{Liquid Volume per channel} = 0.152 \text{ m} \times 50 \text{ m} \times 6 = 45.6 \text{ m}^3$$

$$\text{HRT} = \text{Vol}/Q = \frac{45.6}{\frac{3800 \text{ m}^3/\text{d}}{41}} = 0.49 \text{ days}$$

Areal Organic and Nutrient Loading Rates

a. BOD $S_0 = 50 \text{ mg/l BOD}_5$

$$\begin{aligned} \text{OLR} &= \text{HLR} \cdot S_0 = 0.312 \text{ m}^3/\text{m}^2\text{-d} \cdot 0.05 \frac{\text{kgBOD}_5}{\text{m}^3} = \\ &= 0.0156 \frac{\text{kgBOD}_5}{\text{m}^2\text{-d}} \\ &= 156 \frac{\text{kgBOD}_5}{\text{ha-d}} \left(139 \frac{\text{lb}}{\text{ac-d}} \right) \end{aligned}$$

This is a low organic loading for oxygenating aquatic plant systems

b. TN Loadings

$$\text{TN} = 40 \text{ mg/l or } 0.04 \text{ kg/m}^3$$

$$\text{LRTN} = \frac{3800 \text{ m}^3/\text{d} \cdot 0.04 \text{ kg/m}^3}{123,500 \text{ m}^2} = 0.0124 \text{ kg/m}^2\text{-d or}$$

12.4 gm TN/m²-d

This is a high TN loading rate and will encourage a high nitrogen removal rate, but the removal efficiency will be low.

c. N Removal Potential

- 1) At minimal plant uptake rates of 1 gm/m²-d

$$\text{Removal eff} = 100 - \left[\frac{12.4 - 1}{12.4} \times 100 \right] = 100 - 92 = 8\%$$

- 2) At high N destruction ratio of 5 gm/m²-d

$$\text{Removal eff} = 40\%$$

Enhancing Nitrogen Removal In First Stage NFT Via Nitrification-Denitrification

Previous work with the NFT has shown encouraging ways of destroying nitrogen by controlling microbial nitrogen conversions. The following illustrates the management options.

Intermittent flooding could be used as a management alternative for first step

- 1) Use 41 channels plus 4 extra for reserve.
- 2) Flood 4 channels at a time.
- 3) Check flow velocities.

Operation mode

Flow to 4 channels for 2.4 hours, remain flooded and recirculated for 15.2 hours (24 - 2.4 on - 2.4 draining - 4 rest in drained mode), drain for 2.4 hours, allow to stand in drained form for 4 hours to encourage nitrification and oxygenation of root zone.

Liquid Volume Standing Treatment System @ d = 0.152 m,

$$\text{Vol} = 6 \text{ m} \times 50 \times 0.152 = 45.6 \text{ m}^3/\text{channel}$$

Recirculate 2 times/15 hr, vol = 45.6 m³/channel x 2 = 91.2 m³/15 hr

$$\text{recirculation rate} = 6.08 \text{ m}^3/\text{hr} \quad (27 \text{ gpm})$$

This is probably not essential for good treatment but may improve nitrification.

Loading velocity when loading only 4 channels

$$3800 \text{ m}^3/\text{d} \times \frac{d}{24 \text{ hr}} = 158 \text{ m}^3/\text{hr}$$

Using 4 channels the loading rate is 39.6 m³/hr-channel

Horizontal velocity

$$V_H = \frac{158 \text{ m}^3/\text{hr}}{4 \text{ channels} \cdot 6 \text{ m} \times 0.152 \text{ m}} = 43.3 \text{ m/hr}$$

This is an acceptably low velocity.

EXAMPLE 2. Resource Recovery Wastewater Treatment to Achieve Secondary Quality Effluent for one-Tenth MGD ($380 \text{ m}^3/\text{d}$)

AAFEB

First stage for $380 \text{ m}^3/\text{d}$ flow rate

Use similar two-stage system as in $3800 \text{ m}^3/\text{d}$ facility

First stage total HRT = 3 hr; second stage = 12 hr

First stage dimension

$$\text{Total Vol} = 380 \times 3/24 = 47.5 \text{ m}^3$$

$$@ \varnothing = 3 \text{ m} \quad \text{ht} = 6.73 \text{ m}$$

Second stage - use quadrouple the size of the first stage

$$\text{Total Vol} = 5 \times 47.5 \text{ m}^3 = 237.5 \text{ m}^3$$

It is likely that only two tanks are necessary for the small flow, but the set-up will be treated as similar to the larger design for consistency.

NFT

For Flow of 0.1 MGD ($3.785 \times 10^5 \text{ l/d}$, $378 \text{ m}^3/\text{d}$)

$$\text{Area Required} = 12.13 \times 10^2 \text{ m}^2 \text{ (0.3 acres)}$$

$$\text{Total NFT width} = \frac{12.13 \times 10^2 \text{ m}^2}{50 \text{ m channels}} = 24.3 \text{ m}$$

with 3 m wide channels,

$$\text{Number channels} = \frac{24.3}{3} = 8.1 \text{ or } 9 \text{ channels}$$

Use 9 channels, each 3 m x 50 m

$$\text{Total Area of channels} = 1350 \text{ m}^2$$

Areal Loading Rate = $0.28 \text{ m}^3/\text{m}^2\text{-d}$, okay for secondary quality effluent

Check weir Loading Rate

$$HL_w = \frac{378 \text{ m}^3/\text{d}}{3 \text{ m} \times 9 \text{ channels}} = 14 \text{ m}^3/\text{m}_w\text{-d} \quad \text{okay.}$$

Horizontal Volume

$$V_H = \frac{378 \text{ m}^3/\text{d}}{3 \text{ m} \times 0.152 \text{ m days} \times 9} = 92 \text{ m/d, okay.}$$

Disinfection may be needed to meet secondary effluent criteria.

EXAMPLE 3 Resource Recovery Wastewater Treatment to Achieve Tertiary Quality Effluent for One MGD (3800 m³/d) -- Less than 5 mg/l BOD, 5 mg/l SS, 1 mg/l TN, 1 mg/l TP, and 40 cfu/100 ml of E. Coli.

Design Parameter From Pilot Operation

The following loadings are taken from empirical design relationships that achieve the above effluent quality.

$$\text{Areal Loading Rate} = 1 \text{ gpd/ft}^2 = 0.04076 \text{ m}^3/\text{m}^2\text{-d}$$

$$\text{Weir Loading Rate} = 1400 \text{ gal/4 ft d} = 350 \text{ gpd/ft}$$

$$\frac{5.3 \text{ m}^3}{1.22 \text{ m-d}} = 4.35 \text{ m}^3/\text{m-d}$$

$$\text{Horizontal Velocity} = \frac{4.35 \text{ m}^3}{\text{m-d} \times 0.152 \text{ m deep}} = 28.6 \text{ m/d}$$

$$\text{TN Loading } S_0 = 25 \text{ mg/l} = 0.025 \text{ kg/m}^3$$

$$\text{TNLR} = 0.04076 \text{ m}^3/\text{m}^2\text{-d} \times 0.025 \text{ kg/m}^3$$

$$= 0.00102 \text{ kg/m}^2\text{-d}$$

$$\text{or } 1.02 \text{ gm/m}^2\text{-d}$$

BOD₅ OLR

$$S_0 \leq 30 \text{ mg/l} = 0.03 \text{ gm/l or } 0.03 \text{ kg/m}^3$$

$$\text{OLR} = 0.04076 \text{ m}^3/\text{m}^2\text{-d} \times 0.03 \text{ kg/m}^3 =$$

$$0.00122 \text{ kg BOD/m}^2\text{-d}$$

BOD₅

$$\text{or } 12.2 \text{ kg/ha-d}$$

This is obviously a very low organic loading rate that enables plants to utilize nutrients.

Channel Dimensions

$$\text{Area} = \frac{3800 \text{ m}^3/\text{d}}{0.04076 \text{ m}^3/\text{m}^2\text{-d}} = 93,230 \text{ m}^2 \text{ or } 9.32 \text{ ha}$$

Use First stage similar to secondary system, deduct Area from total

$$\text{Area Secondary NFT} = 93,230 \text{ m}^2 - 12,130 \text{ m}^2 = 81,100 \text{ m}^2$$

$$\text{Channel Width} = \frac{3800 \text{ m}^3/\text{d}}{4.35 \text{ m}^3/\text{m-d}} = 874 \text{ m total}$$

$$\text{Channel Length} = \frac{81100 \text{ m}^2}{874 \text{ m wide}} = 93 \text{ m long (305 ft)}$$

Use channel length of 100 m

Total width = 811 m

Use 15 m wide channels, need 54 separate channels

Overall channel dimensions: 100 m long, 15 m wide, 54 channels

Liquid volume @ d = 0.152 m

$$V = 228 \text{ m}^3$$

Weir Loading @ 0.152 m days

$$\frac{3800 \text{ m}^3/\text{d}}{15 \text{ m wide} \times 54} = 4.69 \text{ m}^3/\text{m-d, slightly above pilot}$$

value, but acceptable

Horizontal Velocity

$$\frac{3800 \text{ m}^3/\text{d}}{15 \times 0.152 \times 54} = 30.86 \text{ m/d, okay}$$

$$\text{HRT} = \frac{15 \times 0.152 \times 100}{\frac{3800}{54}} = 3.24 \text{ days}$$

$$\text{Areal Loading} = \frac{3800 \text{ m}^3/\text{d}}{54 \times 100 \times 15} = 0.0469 \frac{\text{m}^3}{\text{d-m}^2}$$

EXAMPLE 4 Resource Recovery Wastewater Treatment to Achieve Tertiary Quality Effluent for One-Tenth MGD (380 m³/d)

Channel Dimensions

$$\text{Area} = \frac{380 \text{ m}^3/\text{d}}{0.04076} = 9320 \text{ m}^2$$

Use first stage similar to secondary system, deduct area from total needs:

$$\text{Area Tertiary System} = 9320 - 1350 = 7970 \text{ m}^2$$

$$\text{Channel Width} = \frac{380 \text{ m}^3/\text{d}}{4.35 \text{ m}^3/\text{m-d}} = 87 \text{ m total}$$

$$\text{Channel Length} = \frac{7970 \text{ m}^2}{87 \text{ m wide}} = 92 \text{ m long (305 ft)}$$

Use 100 m long channels

Modified Width = 79.7 m

Using 6 m widths, need 14 channels

$$\text{Total Area} = 14 \times 100 \times 6 = 8400 \text{ m}^2$$

$$\text{Check weir loading} = \frac{380 \text{ m}^3/\text{d}}{14 \times 6} = 4.52 \text{ m}^3/\text{m-d} \quad \text{ok.}$$

$$\text{@ } HL_w = 4.35, 6 \times \text{No channels} = 87.4$$

$$\text{No channels} = 15$$

Use 15 channels 6 x 100 m

$$\text{Area} = 9000 \text{ m}^2$$

$$\text{Areal Loading} = \frac{380}{9000} = 0.0422 \frac{\text{m}^3}{\text{m}^2\text{-d}}$$

Use 15 channels, 6 m wide, 100 m long

$$HL_w = \frac{380}{15 \times 6} = 4.22$$

$$\text{Horizontal Vol.} = \frac{380 \text{ m}^3/\text{d}}{15 \times 6 \times 0.152} = 27.8 \text{ m/d, okay.}$$

Estimating Energy Production Potential and anaerobic Digestion Requirements

In situations when energy generation is of interest the plants can be harvested and mixed with the sludge and digester.

Sludge Volume = 11,350 l/d-3800 m³ sewage @ 4% dry or

Biomass Maximum Production Rate = 90 MT(dry)/ha-yr

Plant biomass characterization = 95% VS, 75% BVS

Daily Total Loading = $0.454 \frac{\text{MT}}{\text{d}}$ (dry) sludge + Biomass

$$\text{Biomass} = 90 \text{ MT/yr-ha} = 0.25 \text{ MT (dry)/ha-d}$$

NFT Treatment System Area, Estimated:

$$1. \text{ Secondary NFT area} = 1.23 \text{ ha}/3800 \text{ m}^3/\text{d}$$

$$2. \text{ Tertiary NFT area} = 1.23 + 8.1 = 9.33 \text{ ha}$$

Daily Biomass Loading

$$1. \text{ Secondary Treatment} = 0.454 \frac{\text{MT}}{\text{d}} \text{ sludge} + 0.25 (1.23)$$

$$= 0.454 + 0.3075 = 0.7615 \frac{\text{MT}}{\text{d}} \text{ Total dry solids}$$

$$\text{Biod. solids} = 0.454 \times 0.4 + 0.3075 \times 0.95 \times 0.75 =$$

$$= 0.18 + 0.22 = 0.40 \text{ BMT/d}$$

$$\text{Gas @ } 0.5 \text{ l CH}_4/\text{gm VS} = 500 \text{ m}^3/\text{MT}$$

$$\text{Gas Prod.} = 0.39 \times 500 = 195 \text{ m}^3 \text{ CH}_4/\text{d}$$

$$\text{or } 300 \text{ m}^3 \text{ biogas/d } (10,600 \text{ ft}^3/\text{d})$$

$$\begin{aligned}\text{Final Effluent Solids} &= 0.7615 - 0.40 = \\ &0.37 \frac{\text{MT}}{\text{d}} \text{ refractory solids or } 136 \text{ MT/yr}\end{aligned}$$

Tertiary Treatment

Total NFT Area = 1st stage NFT + 2nd stage + Offline
Residue NFT

$$\begin{aligned}\text{Total NFT Area} &= 12,300 + 81,000 + 42,000 \text{ m}^2 = \\ &135,300 \text{ m}^2 \text{ or } 13.5 \text{ ha}\end{aligned}$$

Biogas max. yield @ 90 mt/ha-yr

$$\text{Yield} = 1215 \text{ MT/yr}, \quad 3.3 \text{ m ton/d} = 2.2 \text{ Bmt/d}$$

$$\text{Gas prod.} = 500 \text{ m}^3 \text{ CH}_4/\text{mt}$$

$$\text{Total Gas Prod.} = 2.2 \times 500 = 1123 \text{ m}^3 \text{ CH}_4/\text{d}$$

$$(40 \text{ million Btu/d}) \text{ or } \$200/\text{d}, \$73,000/\text{yr}$$

Digester Volume

$$@ 0.5 \text{ V/V-d CH}_4$$

$$\text{Vol} = 2246 \text{ m}^3$$

For Secondary System

Daily Biomass Loading to Digester

Use Biogas production rate of 1 V/V-d for the biomass
digester

$$\text{Digester vol} = 300 \text{ m}^3 (10600 \text{ ft}^3)$$

For Tertiary System

$$\begin{aligned}\text{Biomass} &= 0.454 + 9.33 \times 0.25 = 0.454 + 2.33 \\ &= 2.79 \text{ MT/d dry}\end{aligned}$$

$$\begin{aligned}\text{Biod.} &= 0.454 \times 0.4 + 2.33 \times 0.675 = 0.18 + 1.57 = \\ &= 1.75 \text{ BMT/d}\end{aligned}$$

$$\text{Gas Production} = 1.75 \times 500 = 876 \frac{\text{m}^3 \text{ CH}_4}{\text{d}}$$

$$\text{Biogas} = 1348 \text{ m}^3/\text{d} (47,600 \text{ ft}^3/\text{d})$$

$$\text{Cogeneration capacity} = 94 \text{ Kw at } 500 \text{ ft}^3/\text{d per Kw-d}$$

$$\text{Final Effluent Solids} = 2.79 - 1.75 = 1.04 \text{ MT/d or } 380 \text{ MT/yr}$$

Alternative Residue Disposal Alternative - NFT - Off-Line Non-Discharging Artificial Wetland Using Deep NFT Channels

It may be desirable to eliminate off-site sludge disposal. One alternative would be to dispose of digested slurry in an off-line NFT

system that would be designed to accumulate this material for the design life of the facility, or for about 20 years. Natural degradation processes and evapotranspiration would enable relatively deep channels to accomplish this. The following is an example of this application for a design flow of one MGD (3800 m³/d) of wastewater flow.

For Q = 3800 m³/d

Secondary System

Minimum quantity of stabilized and thickened sludge is 3700 l/3800 m³ at 10% dry matter.

Sludge Slurry Q = 3700 liters/d

contain 370 kg TS/d, 259 kg VS/d

or

135,000 kg TS/yr or 94,500 kg VS/yr

Six months storage (may be required if system is not designed to operate in the winter). Total volume of sludge to storage = $3700 \times \frac{365}{2} = 0.68 \times 10^6 \frac{\text{liters}}{\text{year}}$

Sludge Storage Lagoon @ 3 m deep, Area = 230 m², 16m x 16 m
Design Off-Line NFT

Assume slurry loading rate of 9 cm/year on the NFT channels for complete sludge assimilation.

Loading rate to off-line NFT of 9 cm/yr sludge, @ 10% TS

Resulting dry matter addition rate:

$$90 \text{ l/m}^2 \times 100 \text{ gm TS/l} = 9,000 \text{ gm TS/m}^2\text{-yr}$$

$$\text{Area Off-Line NFT} = \frac{135,000 \text{ kg TS/yr}}{9 \text{ kg TS/m}^2\text{-yr}} = 15,000 \text{ m}^2 \text{ off-line NFT unit}$$

line NFT unit

When water evaporates, remaining solids at density of 200 gm/l, or 200 kg/m³

$$\text{Depth of solids} = \frac{9 \text{ kg TS/m}^2\text{-yr}}{200 \text{ kg TS/m}^3} = 0.045 \text{ m/yr}$$

or 4.5 cm/yr

This is an acceptably low loading.

Off-Line NFT Sludge Assimilation Alternate For Tertiary Treatment

Alternative -- For $Q = 3800 \text{ m}^3/\text{d}$.

Sludge generation includes digested plant matter from NFT.

Total Sludge Slurry, $Q = 10,400$ liters per day

Nondischarging NFT area = $\frac{10,400}{3700} (15,000) =$

$42,200 \text{ m}^2$

Plants harvested from this unit would be added to the digester for additional energy production.

Examination of Relationship of Flow Rates, Hydraulic Velocities, Cross-Sectional Loading Rates and Weir Overflow Rates on the Pilot Plant System

Maximum Flow Rate Total System

$$\text{Total System} = \text{DS} + \text{DN} + \text{SN} + \text{SS}$$

$$\text{Total Area} = 130 \text{ m}^2$$

$$\text{Area channels: D} = 74.37 \text{ m}^2$$

$$\text{S} = 55.63 \text{ m}^2$$

$$\text{D} + \text{S} = 130 \text{ m}^2$$

$$\text{O1} = 8.92 \text{ m}^2, \text{ O2} = 55.76 \text{ m}^2$$

Daily Hydraulic Loading Rate

$$\text{HLR} = \frac{Q_T}{A_T} = \frac{40 \text{ m}^3/\text{d}}{130 \text{ m}^2} = 0.308 \text{ m/d or } 30.8 \text{ cm/d}$$

Horizontal Velocity

$$\text{Depth at Influent to DS} = 15 \text{ cm, channel width} = 1.22 \text{ m}$$

$$\text{Effluent depth assumed at DN} = 5 \text{ cm}$$

$$\text{Average depth} = 10 \text{ cm}$$

$$V_H = \frac{Q_T}{A_x} = \frac{40 \text{ m}^3/\text{d}}{0.15 \text{ m} \times 1.22 \text{ m}} = 219 \text{ m}^3/\text{m}^2\text{-d, or } 219 \text{ m/d}$$

$$\text{horizontal velocity or } 9.11 \text{ m/hr}$$

$$V_H \text{ Avg.} = \frac{15}{10} (9.11) = 13.7 \text{ m/hr}$$

Hydraulic Retention Time

Two approaches

- 1) Estimate based on average horizontal velocity and total system length

$$\text{Total length D} + \text{S} = 61 + 61 = 122 \text{ m}$$

$$\text{HRT}_{\text{Avg}} = 122 \text{ m} / 13.7 \text{ m/hr} = 8.91 \text{ hours}$$

$$\text{HRT} = \frac{\text{Vol. D} + \text{S}}{Q} =$$

$$[4 \times 1.22 \times 15.24 + 2 \times 1.83 \times 15.2] / 0.10$$

$$\times 24 = 7.8 \text{ hours, which is close to } 8.9 \text{ hours}$$

Weir Overflow Rate

$$O \text{ R}_w = \frac{40 \text{ m}^3/\text{d}}{1.22 \text{ m width}} = 32.8 \text{ m}^3/\text{m-d} = 1370 \text{ l/m}_{\text{weir}}\text{-hr}$$

Figure S-1. Overview of NFT treatment systems.

EXAMPLE Condition Number 21. In this condition three main NFT units were operated in series with the total flow treated in the first two units of 15 s/d (m^3/d), but only an average of 212 liters per day fed to the third unit.

The following is the calculation procedure to determine flows and loading ratios in the NFT system modified to reflect split stream additions to the third stage.

Hydraulic Loading Rates

$$DS = \frac{15 \text{ m}^3/\text{d}}{74.37 \text{ m}^2} \times 100 \text{ cm/m} = 20.2 \text{ cm/d}$$

$$DN + DS = \frac{15 \text{ m}^3/\text{d}}{(74.37 + 55.63)} = 11.6 \text{ cm/d}$$

DN + DS + 01 Calculated Area of first stage to enable water quality comparison from sample points 1, 2, and 3 shown above.

Determine by calculating ratio of diverted area to total flow:

$$\frac{\text{Flow to 3rd stage}}{\text{Area 3rd stage}} = \frac{\text{Total Inflow Volume}}{\text{Calculated Area 1st two stages}}$$

$$\frac{Q_3}{\text{NFT-01}} = \frac{Q_T}{\text{Calculated DN \& DS}}$$

$$\frac{0.212 \text{ s/d}}{8.92 \text{ m}^2} = \frac{15 \text{ s/d}}{x}$$

$$x = (631 - 8.92) \text{ m}^2 \text{ required in first two stages}$$

$$\text{HLR} = \frac{Q_T}{\text{Total Area}} = \frac{15 \text{ s/d}}{631} = 2.4 \text{ cm/d}$$