FINAL REPORT

THE ALGAL-BACTERIAL SELENIUM REMOVAL SYSTEM FOR TREATMENT OF IRRIGATION DRAINAGE WATER: DEMONSTRATION FACILITY INTERIM STUDIES

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This is an interim report describing a demonstration-scale Algal-Bacterial Selenium Removal (ABSR) Facility constructed in California's San Joaquin Valley for the purposes of demonstrating the efficacy of the ABSR Technology for selenium removal from subsurface agricultural drainage water, optimizing operational parameters, and determining operational costs and engineering requirements. This information is needed prior to designing large-scale systems for control of selenium levels in the San Joaquin Valley and the Bay-Delta. This report covers activities and results that were obtained during the period January 1997-December 1998.

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FOREWORD AND ACKNOWLEDGMENTS

The demonstration Algal-Bacterial Selenium Removal (ABSR) Facility at the Panoche Drainage District has now been operated for over two years yielding data on the removal of selenium salts from agricultural drainage water. Initial difficulties due the requirement that shallow drain tiles could not be disturbed have been mitigated to some extent by covering the Reduction Ponds, but further improvements will be needed. To review, the shallowness of the drain tiles meant that the Reduction Ponds could not be constructed sufficiently deep to prevent the intrusion of dissolved oxygen into almost all of the reduction zones thus inhibiting selenium removal. To simulate deeper ponds we have now completely covered both Reduction Ponds with black liners to better match the conditions to be expected in deep, protected anoxic zones within the Reduction Ponds to be used in full-scale ABSR Facilities. Although the results to be reported here are favorable, they do not fully represent what might be attained in full-scale ABSR Facilities with sufficiently deep and properly protected reduction zones.

This report brings to a close a phase of the work generously supported by the Water Treatment Technology Program of the U.S. Bureau of Reclamation. The work continues now with covered Reduction Ponds and with continued support of the CALFED Bay Delta Program. Because the Panoche Facility now more closely simulates a full-scale system, more precise and relevant data is forthcoming. We are most grateful to the U.S. Bureau of Reclamation for supporting these interim studies to be described herein, and particularly to the following Bureau personnel for their continuous support and encouragement: Frank Leitz, Stephanie Bartlett, and Stanley Ponce in Denver; Michael Delamore in Fresno; and Joel Zander in Sacramento. Our thanks are also due to Dennis Falaschi, General Manager, and the Board of the Directors and staff of the Panoche Drainage District for their support of the project and for their in-kind and cash contributions. Marcos Hedrick, Chase Hurley, Carl Westbrook, and Michael Gardener of the Panoche Drainage District were instrumental in the construction and operation of the ABSR Facility.

DISCLAIMER

Opinions or hypotheses expressed in this document are those of the Applied Algae Research Group authors and do not necessarily reflect those of the personnel of the U.S. Bureau of Reclamation or the University of California, Berkeley. Mention of trade names or commercial products does not constitute endorsement or recommendation.

CONTENTS

List of Tables iv
List of Figures v
Project Team and Responsibilities vii
Project Participants viii
Glossary ix
Abbreviations x
Executive Summary xi

1.0 Background 1
1.1. Drainage Water Treatment in the San Joaquin Valley 1
1.2. Selenium Reduction 2
1.3. Full-scale Experience with Algal-Bacterial Technologies 3
1.4. Mechanisms of the ABSR Process 4
1.5. Flow Modes 5
1.6. Wildlife Considerations 7
1.7. Objectives of the Research 7

2.0 Conclusions and Recommendations 11

3.0 Methodology 12
3.1. The Panoche Drainage District ABSR Facility 12
3.2. Operations 14
3.3. Sample Collection, Preservation, and Preparation for Analysis 16
3.4. Water and Sediments Analyses 17
3.5. Algal Identification 20

4.0 Results 22
4.1. Quality Assurance and Quality Control 22
4.2. Drainage Water Composition 22
4.3. Substrate Efficiencies and Substrate Treatment 22
4.4. Bacterial Reduction of Dissolved Oxygen 23
4.5. Nitrate Removal and Algal Productivity in the High Rate Ponds 24
4.6. Denitrification Rates and Substrate Efficiencies 25
4.7. Selenium Removal 26
4.8. Ratios of Nitrate to Selenate 27
4.9. Selenium in ABSR Pond Sediments 27
4.10. Algae Identification 28

5.0 Discussion 29
5.1. Algal Substrate Treatment and Algae Harvesting 29
5.2. Bacterial Reduction of Dissolved Oxygen 29

CONTENTS, CONTINUED

5.3. Nitrate Removal and Algal Productivity in the High Rate Ponds 30
5.4. Selenium Removal 32
5.5. Ratios of Nitrate to Selenate 33
5.6. Selenium in ABSR Pond Sediments 33
5.7. Algae Identification 34
5.8. Preliminary Cost Estimates for a 10-AF/d ABSR Facility 34

References 36

Tables 39

Figures 54

Metric Conversion Table 69

Appendix: Water Quality Data Record 70

LIST OF TABLES

Table 1. Oxidation-reduction potential in drainage water when in equilibrium with various redox couples.

Table 2. Volume and surface area of the ponds of the ABSR Facility at the PDD.

Table 3. Operational timeline for the ABSR Facility at the PDD..

Table 4. Constituent analysis of molasses.

Table 5. Nutrient application rates to the HRPs at the ABSR Facility.

Table 6. Water quality analytical methods used for ABSR Facility samples.

Table 7. Summary of quality control results for April-December 1998

Table 8. Influent drainage water quality at the Panoche ABSR Facility.

Table 9. Effect of substrate type on nitrate removal efficiency.

Table 10. Nitrogen removal by the North Reduction Pond.

Table 11. Nitrogen removal by the South Reduction Pond.

Table 12. Sediment selenium concentrations in the ABSR Facility at the PDD.

Table 13. Dominant algal genera in the HRPs of the ABSR Facility at the PDD.

Table 14. Preliminary design and cost estimate for a Mode 1 ABSR Facility in the PDD

Table 15. Preliminary design and cost estimate for a Mode 2 ABSR Facility in the PDD

LIST OF FIGURES

Figure 1. Schematic of the Mode 1 System at the ABSR Facility at the PDD.

Figure 2. Schematic of the Mode 2 System at the ABSR Facility at the PDD.

Figure 3. Plan view of the ABSR Facility at the Panoche Drainage District

Figure 4. Dissolved oxygen concentrations in the North Reduction Pond of the ABSR Facility at the PPD.

Figure 5. Dissolved oxygen concentrations in the North Reduction Pond at the PDD.

Figure 6. Dissolved oxygen concentrations in the South Reduction Pond of the ABSR Facility at the PDD.

Figure 7. Dissolved oxygen concentrations in the South ABSR System at the PDD.

Figure 8 . Volatile suspended solids concentrations in the North ABSR System at the PDD.

Figure 9. Volatile suspended solids concentrations in the South ABSR System at the PDD.

Figure 10 . Nitrate+nitrite concentrations in the North ABSR System at the PDD.

Figure 11. Nitrate+nitrite concentrations in the South ABSR System at the PDD.

Figure 12. Temperature in the North ABSR System at the PDD.

Figure 13. Temperatures in the South ABSR System at the PDD.

Figure 14. Selenate concentration in the North ABSR System at the PDD.

Figure 15. Selenate-Se mass removal in the North ABSR System at the PDD.

Figure 16. Cumulative selenate-Se mass flow in the North ABSR System at the PDD

Figure 17. Selenate concentration in the South ABSR System at the PDD.

Figure 18. Selenate-Se mass removal in the South ABSR System at the PDD

Figure 19. Cumulative selenate-Se mass flow in the South ABSR System at PDD.

LIST OF FIGURES, CONTINUED

Figure 20. Comparison of residual nitrate and selenate in the North RP effluent of the ABSR Facility at the PDD.

Figure 21. Comparison of residual nitrate and selenate in the South RP effluent of the ABSR Facility at the PDD.

Figure 22. Correlation of effluent nitrate-N concentration to selenate-Se removal rate in the North RP effluent of the ABSR Facility at the PDD.

Figure 23. Correlation of effluent nitrate-N concentration to selenate-Se removal rate in the South RP effluent of the ABSR Facility at the PDD.

Figure 24. Correlation of nitrate-N to selenate-Se concentrations in the North RP effluent of the ABSR Facility at the PDD.

Figure 25. Correlation of nitrate-N to selenate-Se concentrations in the South RP effluent of the ABSR Facility at the PDD.

Figure 26. Levels of pH in the North ABSR System at the PDD.

Figure 27. Phenolphthalein alkalinity concentrations in the North ABSR System at the PDD.

Figure 28. Levels of pH in the South ABSR System at the PDD.

Figure 29. Phenolphthalein alkalinity concentrations in the South ABSR System at the PDD.

Figure 30. Monthly wholesale price history for black strap molasses at the Port of Stockton (USDA, 1999).

PROJECT TEAM AND RESPONSIBILITIES

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GLOSSARY

assimilation	Incorporation of nutrients or trace elements into living organisms
atomic absorption	Spectrometric analytical method for selenium determination
denitrification	Reduction of nitrate (NO_3^-) ultimately to nitrogen gas (N_2).
dissolved air flotation	Method to remove suspended particles from water. Air, dissolved in water under pressure, is released at atmospheric pressure. Bubbles form and attach to suspended particles causing them to float to the surface where they are skimmed off.
elemental selenium	Selenium in the 0 oxidation state; a solid under natural conditions.
High Rate Pond	A pond specially designed to grow microalgae at a high rate.
oxidation	Change in the chemical oxidation state of an atom by the loss of one or more electrons; the reverse of reduction.
reduction	Change in the chemical oxidation state of an atom by the gaining of one or more electrons; the reverse of oxidation.
Reduction Pond	A pond specially designed to reduce oxygen, nitrate, selenate, and selenite.
selenium	A metalloid that, depending on its concentration in the body, can be beneficial or toxic to humans and to certain plants and animals.
selenite	Selenium in the 4+ chemical oxidation state; Se IV.
selenate	Selenium in the 6+ chemical oxidation state; Se VI.
substrate	An energy and/or carbon source necessary for the growth or metabolism of microorganisms; a substance upon which an enzyme acts.
supernatant	Clarified water overlying a strata containing a high concentration of solids.

ABBREVIATIONS

ABSR	Algal-Bacterial Selenium Removal
AF	acre-foot
AIWPS®	Advanced Integrated Wastewater Pond Systems
ASP	Algae Settling Pond
atm	atmospheric pressure
BOD	biochemical oxygen demand
CIMIS	California Irrigation Management Information System
d	day
DAF	dissolved air flotation
DI	deionized water
DO	dissolved oxygen
EEHSL	Environmental Engineering and Health Sciences Laboratory of the University of California, Berkeley
ft	feet
gal	gallon
K	degrees Kelvin
kJ	kilojoule
kWh	kilowatt hours
HP	horsepower
HRP	High Rate Pond
in	inches
L	liter
LBNL	Lawrence Berkeley National Laboratory
lbs	pounds
M	molar; moles per liter
mil	one thousandth of an inch thickness
mV	millivolt
N	nitrogen; as nitrogen
O&M	operations and maintenance
P	phosphorus; as phosphorus
PDD	Panoche Drainage District
psi	pounds per square inch
QA/QC	quality assurance/quality control
RP	Reduction Pond
s	second(s)
Se	selenium
Se IV	selenium in the 4+ oxidation state representing selenite
Se VI	selenium in the 6+ oxidation state representing selenate
TSS	total suspended solids
VS	volatile solids
VSS	volatile suspended solids
yr	year

EXECUTIVE SUMMARY

This is an interim report describing a demonstration-scale Algal-Bacterial Selenium Removal (ABSR) Facility constructed in California's San Joaquin Valley for the purposes of demonstrating the efficacy of the ABSR Technology for selenium removal from subsurface agricultural drainage water, optimizing operational parameters, and determining operational costs and engineering requirements. This information is needed prior to designing large-scale systems for control of selenium levels in the San Joaquin Valley and the Bay-Delta. This report covers activities and results that were obtained during the period January 1997-December 1998.

Previous treatment efforts sought to reduce selenium concentrations to less than 2-5 μg/L. The Panoche ABSR Facility demonstration focuses on providing the means to economically reduce the mass loading rate of selenium that is discharged to the San Joaquin River.

During treatment, the high levels of nitrate in the drainage water must be reduced to nitrogen gas or converted to nitrogen-rich algae in order to achieve extensive biological selenium reduction. Initial data from the ABSR Facility show nitrate reduction of over 95% and sustained reduction in total soluble selenium mass of 86%. Algae productivity has reached 13 tons per acre per year (30 tonnes per hectare per year). Preliminary total cost estimates for ABSR treatment are less than $200 per acre-ft for 10 acre-ft per day facilities ($162 per 1000 m^3 for 12,000 m^3/d facilities). Facilities treating 30 acre-ft per day are expected to cost less than $100 per acre-ft ($81 per 1000 m^3 for 37,000 m^3/d facilities). Excessive use of nitrogen fertilizers in the San Joaquin Valley could be somewhat mitigated if dried microalgae grown on excess nitrate could be adopted as fertilizer by growers. Future studies should include a preliminary desk study of this possibility.

1. BACKGROUND

1.1. DRAINAGE WATER TREATMENT IN THE SAN JOAQUIN VALLEY

Depending on location and season, agricultural drainage water in the western San Joaquin Valley contains between 100 μg/L and 1,400 μg/L of naturally-occurring selenium, predominantly in the highly soluble selenate form (SeO_4^{2-}, Se VI). Selenium bioaccumulates in aquatic ecosystems such as wetlands and estuaries and can cause teratogenesis in fowl feeding in these waters (Ohlendorf *et al.*, 1986). The California State Water Resources Control Board and the U.S. Environmental Protection Agency have set 5 μg/L as the maximum mean monthly selenium concentration in discharges to rivers (SWRCB, 1989; U.S. EPA, 1987), but the combined drainage discharges from water districts in the Grasslands Basin exceed this concentration on a regular basis. During 1997 and 1998, the total Se concentration in the drainage water discharged to the San Joaquin River via Mud Slough ranged from 17 μg/L to 120 μg/L in flows of 24 to 273 AF/d (29 to 377 m^3/d) (CVRWQCB, 1999).

Selenium is regulated on a mass basis in addition to a concentration basis. Beginning in late 1996, the Grasslands Bypass Agreement allowed the combined drainage discharge from 97,000 acres (39,000 ha) in the western San Joaquin Valley to be released to the San Joaquin River through a single outlet, Mud Slough, with the limit of 6,660 lbs (3,027 kg) of selenium for the 1997-1998 water year (Quinn, 1998). This load limit will decrease each year reaching 5,661 lbs (2,573 kg) in the 2000-2001 water year. At that time, the success of the Bypass program for selenium load reduction and wildlife protection will be assessed, and the Bypass permit may be extended with decreasing selenium load allowances. The eventual goal for discharge to Mud Slough is 5 μg/L. Improved timing of drainage releases can improve the consistency of compliance with the selenium concentration limit, but the most reliable, long-term method for meeting concentration and load objectives is by reducing the load of selenium in the drainage flows.

The process now known as the Algal-Bacterial Selenium Removal (ABSR) Process was invented, developed, and applied by W.J. Oswald for nitrate* removal in 1968 (Goldman *et al.*, 1969a, b) and was later adapted for selenium removal (Oswald, 1985). A 760-gal/d (2.8 m^3/d) pilot ABSR Facility was operated from 1987-1989 near Mendota, California, and its ability to remove high concentrations of selenium and nitrate from agricultural drainage water was proven. Reductions in total selenium concentration from 400 μg/L to less than 10 μg/ L were achieved. A detailed economic analysis conducted in 1988 indicated that ABSR facilities with capacities of 3, 30, and 300 acre-feet per day would have total costs of $272,

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* Nitrite concentrations were usually at least five times lower than nitrate concentrations throughout the ABSR Facility. Both species were routinely determined simultaneously with a single analytical method, and as such, their concentrations are conflated. Throughout this report, the word nitrate will refer to NO_3^- $+NO_2^-$.

$103, and $68 (1988 dollars) per acre-foot (AF), respectively (Gerhardt and Oswald, 1990). These costs are equivalent to $220, $83, and $55 (1988 dollars) per 1000 m^3.

The Mendota studies elucidated several key microbiological and physico-chemical mechanisms for selenium and nitrate removal and laid the foundation for the current 10,000 to 30,000 gallon per day demonstration project (Gerhardt and Oswald, 1990; Gerhardt *et al.*, 1991; Lundquist *et al.*, 1994). In 1995-1996, the ABSR Facility was built near Firebaugh in the Panoche Drainage District to demonstrate on a larger scale the feasibility and economy of nitrate and selenium removal from irrigation drainage water and to develop basic information for the design of full-scale systems.

1.2. SELENIUM REDUCTION

Dissimilatory selenate reduction by bacteria is strongly inhibited by the presence of high nitrate concentrations when the reaction is carried out in well-mixed laboratory reactors containing ABSR pond sediments (Gerhardt and Oswald, 1990). The inhibition of selenium reduction by oxygen and nitrate can be explained by the fact that dissimilatory selenate reduction provides less energy than oxygen respiration or denitrification. The amount of energy an organism can obtain from its carbon/energy source is related to the reduction potential of the electron acceptor (Table 1). The higher the redox potential of an electron acceptor pair, the more energy will be transferred. When molecular oxygen (O_2) is absent, and both nitrate and selenate are present, well-mixed facultative heterotrophic microbial cultures tend to utilize the nitrate before the selenate because they can obtain more energy through the reduction of nitrate to nitrogen gas. Even if nitrate and selenate are reduced by different bacteria, nitrate should diminish first due to the competitive energy advantage of the nitrate-reducers over the selenate-reducers.

Some types of bacteria *can* reduce selenate in the presence of nitrate or dissolved oxygen (DO) (Gerhardt and Oswald, 1990; Macy, 1994; Losi and Frankenberger, 1998), but maintaining the dominance of these organisms in pilot treatment systems is expensive (Macy, 1994).

A simultaneous assimilatory selenium reduction mechanism may exist as well as a dissimilatory one. Such a process might explain nitrate-independent removal of soluble selenium observed in laboratory-scale ABSR experiments (Gerhardt, *et al.*, 1991) and the presence of organic selenium in the ABSR pond sediments at the PDD (Tokunaga, 1997). Sulfate-assimilating bacteria could perform selenate assimilation due to the chemical similarities of selenium and sulfur. This phenomenon has been reported by Shrift (1953) who found that *Chlorella* algae in which selenium replaced sulfur in their DNA could not divide and rather grew to sizes 100-fold normal.

Empirical Reactions

Given that the ABSR Process appears to promote primarily dissimilatory reduction of selenate (Se VI) to selenite (Se IV) and elemental selenium (Se°), empirical chemical reactions can be proposed. In the reactions below, acetate is shown as the electron donor.

$$CH_3COO^- + 4\ SeO_4^{2-} + 5\ H^+ \dashrightarrow 2\ CO_2 + 4\ HSeO_3^- + 2\ H_2O \quad (1)$$

$$2\ CH_3COO^- + 4\ HSeO_3^- + 6\ H^+ \dashrightarrow 4\ CO_2 + 4\ Se^\circ + 8\ H_2O \quad (2)$$

$$3\ CH_3COO^- + 4\ SeO_4^{2-} + 11\ H^+ \dashrightarrow 6\ CO_2 + 4\ Se^\circ + 10\ H_2O \quad (3)$$

The overall reaction, equation (3), is similar to dissimilatory sulfate reduction, except that selenium is reduced only to the elemental state (Se°) instead of the selenide state (Se -II).

The Gibbs free energy change for the reactions shown in equations (1), (2), and (3) are -1024, -884, and -930 kJ/mole acetate, respectively. These values were calculated for pH 8 from thermodynamic data (Wagman, *et al.*, 1982) using concentrations of 200 mg/L acetate ($3.3 \cdot 10^{-3}$ M), 10^{-3} M CO_2, and equimolar concentrations of all selenium species shown. More energy can be obtained in acetate oxidation using Se VI rather than Se IV as an electron acceptor. Organisms would, therefore, tend to utilize Se VI first, converting much of it to Se IV before further reducing it to Se°.

1.3. FULL-SCALE EXPERIENCE WITH ALGAL-BACTERIAL TECHNOLOGIES

The ABSR Process is a specialized application of an effective and economical wastewater treatment technology known as the Advanced Integrated Wastewater Pond Systems (AIWPS®) Technology developed by Professor William J. Oswald and his co-workers at the University of California, Berkeley over the past five decades. AIWPS® facilities with algae-producing High Rate Ponds have provided reliable municipal wastewater treatment for many California cities including St. Helena, Hollister, and Delhi for 30, 19, and 2 years, respectively. AIWPS® facilities without High Rate Ponds, so called Type 2 AIWPS® facilities, have also provided municipal wastewater treatment for many California cities including Bolinas, Esparto, Napa, and Modesto, each for more than 25 years. Numerous AIWPS® facilities provide industrial wastewater treatment for wineries and food processing plants. Two algae farms in the Imperial Valley of California and another in Hawaii produced algae in High Rate Ponds for pharmaceutical, food dye, and health food markets. Accordingly, large-scale algae production is a mature technology.

The chemical transformations involved in the reduction of selenium are different than those required for municipal and industrial wastewater treatment or for food-grade algae production, but many of the treatment steps and reactor designs are similar. Thus, the design, construction, and costs of proposed large-scale ABSR facilities will be similar to the AIWPS® facilities for which many years of experience have been accumulated by Dr. Oswald, his co-workers, and the owners and operators of AIWPS® facilities.

1.4. MECHANISMS OF THE ABSR PROCESS

The basic concept of the ABSR Process is to grow microalgae using drainage water nitrate as the nitrogen source, and then to use the algal biomass, together with supplements as needed, for the carbon sources for native nitrate- and selenium-reducing bacteria such as *Pseudomonas* and *Bacillus*. In the near absence of oxygen and nitrate, the bacteria use soluble selenate as an electron acceptor, reducing it to selenite and insoluble forms of selenium (Gerhardt and Oswald, 1990; Oswald *et al.*, 1995). The selenite combines readily with polyvalent cations to form insoluble precipitates that remain in the sediment on the floor of the treatment pond. If needed, further selenium removal, mainly particulate selenium removal, and clarification can be accomplished by dissolved air flotation (DAF) and sand filtration. Supplemental carbon sources such as molasses and other organic wastes can be employed as reductants in addition to algal biomass. In applying organic substrates for nitrate and selenium reduction and selenite-metal precipitation, it is important not to use excessive loadings that could create acidic conditions that re-solubilize selenium.

Past and current studies show a clear need to reduce DO and nitrate to low levels before selenate is reduced. In the ABSR Process, DO and nitrate are reduced during respiration by microorganisms at the bottom of Reduction Ponds (RPs) which are sufficiently deep or covered to exclude atmospheric oxygen. Since nitrate concentrations in drainage water are often as high as 90 mg/L as N compared to <0.5 mg/L for selenium, the carbon requirement for nitrate reduction far exceeds that for selenium reduction. At 2,000 to 4,000 mg/L (as SO_4^{2-}), sulfate is even more concentrated than nitrate and could divert carbon substrate to sulfate reduction. However, sulfate reduction has been found to be only a minor reaction in the ABSR Process, and it does not appreciably interfere with nitrate or selenium reduction (Gerhardt *et al.*, 1990).

Nitrate is also removed by assimilation into algal biomass in High Rate Ponds (HRPs). HRPs are shallow, continuously-mixed raceways designed to maximize algal productivity and bacterial oxidation of dissolved organic matter (Oswald, 1988). In HRPs, algal productivities typically range from 15 to 30 tons dry weight per acre per year (34 to 67 tonnes/ha/yr). In comparison, the productivity of crops such rice, wheat, corn, and soybeans is rarely in excess of 2 to 3 tons/acre/yr (4.5 to 6.7 tons/ha/yr). Continuous low-speed paddle wheel-mixing of HRPs requires only 5 to 10 kWh/acre/d (12 to 24 kWh/ha/d). Beyond promoting high productivity, the gentle mixing of HRPs enhances the selection of algal species that tend to settle when introduced into quiescent Algae Settling Ponds (ASPs). In an ASP, algae settle to form a 3% to 4% solids slurry that can be removed (harvested) by pumping into the anoxic zone of the RPs where the algae eventually decompose contributing to reduction reactions.

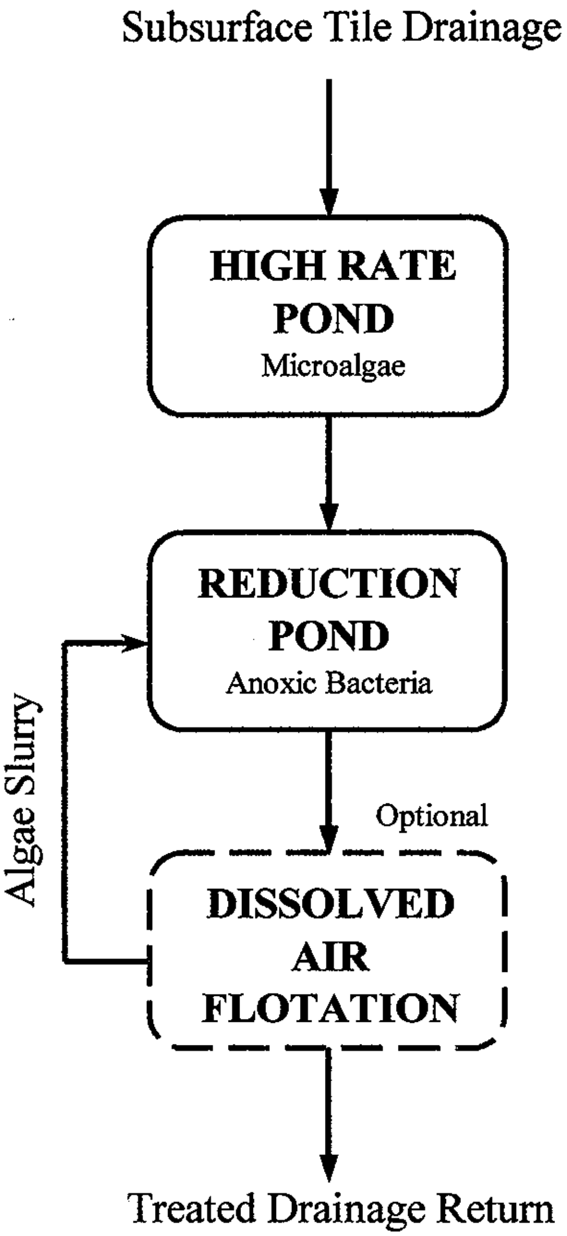
Although algae can utilize carbon from natural alkalinity, the algal growth rate in HRPs is enhanced by addition of carbon dioxide. There are at least two practical carbon dioxide sources for HRPs treating drainage water: (1) CO_2 and bicarbonate produced during bacterial respiration in the RPs and (2) sparging of exhaust gas from on-site power or heat generation units. Sparging of pure CO_2 has been used since 1983 as a carbon source in HRPs used for commercial algal cultivation in the Imperial Valley in southern California (Naylor, 1993).

It has been assumed that in order for nitrate- and selenium-reducing bacteria to readily use algae as a carbon and energy source, the algal cell walls must either be ruptured initially or disintegrated during long periods in anoxic zones. Heating or drying have been used in the laboratory and at the ABSR Facility to disrupt algal cells; however, our recent work indicates that pretreatment may only improve the denitrification rate when older algal biomass is used as a carbon source. "Older" algae are those that have collected in ASPs over weeks before harvesting. More recent studies indicate that if the algae are collected, harvested, and fed to the RPs in a cycle of days, rather than a cycle of weeks, denitrification rates are equal to or higher than those for pretreated older algae (Zárate *et al.,* 1998a; Zárate *et al.,* 1998b). The explanation for this result is presumably that the dark respiration of living algal cells in the RPs quickly removes dissolved molecular oxygen. After DO is removed to low levels, the reaction with the highest energy yield is the combination of oxygen atoms extracted from nitrate with reduced carbon. Also as noted above, the algae eventually die in the RPs, and their cells are degraded leading to denitrifying and selenium-reducing reactions. The alkalinity created and the soluble nutrients released from algal decomposition in the RPs can be recycled to the HRP to enhance algal growth. The key to using the full reducing potential of microalgae for nitrate and selenium reduction is to prevent oxygen intrusion into the reducing zone of the RPs. This protection of the reducing zone can be achieved with an engineering design for Fermentation Cells recently patented by the University of California, Berkeley.

Insoluble selenium removed from the water column accumulates in settled algal-bacterial biomass and inert materials on the floor of the RPs. This biomass is continuously undergoing anaerobic decomposition, so the volume of solid residues increases only slowly over many years. Removal and disposal of the solids in a landfill should not be required for many years, if not several decades. Alternatively, the dried inert solids which contain nitrogen, phosphorus, as well as selenium, could be useful as a soil amendment and fertilizer in the eastern Central Valley where the soils are selenium deficient. The reduced selenium in the algal biomass appears to be in the following forms: Se^0, organic selenium or Se -II, and sorbed selenite. The organic form is likely to be the most available to selenium-deficient crops (Meyer, 1998).

1.5. FLOW MODES

The ABSR Process can be operated in two flow modes each having potential cost advantages due to nitrate removal mechanism and internal nutrient recovery. In Mode 1 (assimilation-denitrification; Figure 1), drainage water is brought into a HRP where 15 to 30 mg/L of nitrate-nitrogen is removed through assimilation by algal cells. The HRP effluent having elevated concentrations of DO flows into the RP where oxygen is depleted, the remaining nitrate is denitrified, and selenium is reduced by bacteria using substrates liberated



1) Carbon dioxide and trace nutrients are added.
2) Nitrate is assimilated by growing algae.
3) Some selenium and additional nitrate is removed, probably by bacteria.

1) Algae settle and decompose.
2) Oxygen depleted. Carbon dioxide increases.
3) Nitrate is reduced to nitrogen gas.
4) Selenate is reduced to selenite or organic Se; selenite adsorbs to cationic particles or is reduced to elemental Se.

1) Residual algae, if any, are harvested.
2) Water is further clarified.
3) Residual selenite and particulate Se are removed.

Figure 1. Schematic of the ABSR Technology operated in Mode 1.

from decomposing algae or supplemental carbon-rich substrates. By removing some nitrate through assimilation, the denitrification process requires less algal biomass as a carbon source. The disadvantage of this mode is that carbon dioxide and iron must be added to the drainage water to increase algal growth in the HRP and high DO levels in the HRP effluent must be reduced in the RP or a separate pond. Some carbon dioxide and nutrients can be provided to the algae by recirculation of RP effluent or by methane capture, combustion, and diffusion of combustion gases into the HRP.

In Mode 2 (primary denitrification; Figure 2), the drainage water, with organic substrate added, passes through the RP where the oxygen is depleted and most of the nitrate is removed by denitrification followed by selenium reduction. The RP effluent containing metabolites of denitrification such as ammonium, phosphate, and dissolved carbon dioxide passes to the HRP. The metabolites become fertilizer for algae growth thereby reducing the need for supplemental carbon dioxide and nutrients.

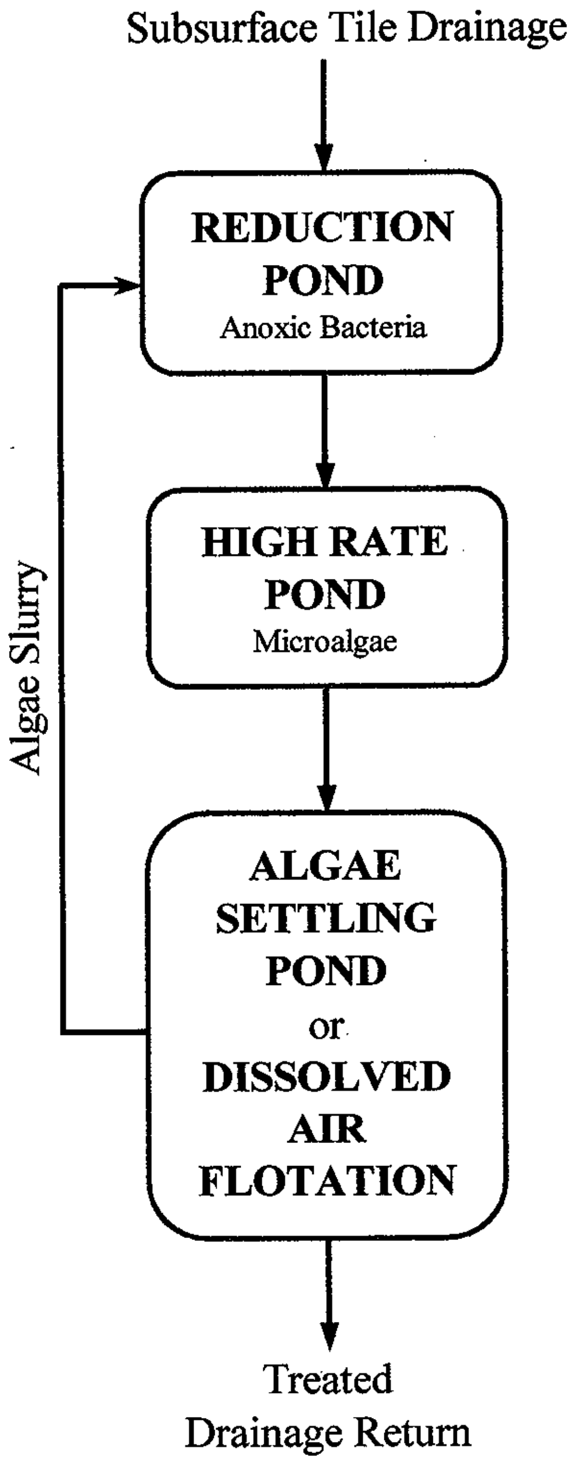
In Mode 2, the nitrate is removed strictly by denitrification which requires more bacterial substrate than Mode 1. However in Mode 2, the RP influent is drainage water containing 8-10 mg/L of DO. This DO concentration is two to three times lower than in the HRP effluent pumped to the RP under Mode 1 operation. The lower DO level requires less substrate for DO removal. Some operational programs may utilize the diurnal cycle of low DO characteristic of HRPs during the hours between midnight and sunrise.

1.6. WILDLIFE CONSIDERATIONS

Large-scale ABSR Facilities are expected to pose much less hazard to wildlife than the surrounding drainage channels, evaporation ponds, or drainage-contaminated wetlands. The concentration of selenium in the shallow HRPs will be similar to or less than that of the drainage channels themselves, and HRPs are continuously mixed by paddle wheels to minimize formation of sediment that could attract invertebrates. Concentrated selenium is sequestered in the anaerobic depths of the RPs. At 16- to 20-foot depth, the anaerobic RP floor could not support invertebrate life and would not attract waterfowl since there is nothing to forage even if those depths could be reached by diving water fowl. It will, of course, be vital to maintain such ponds at full depth at all times.

1.7. OBJECTIVES OF THE RESEARCH

As noted before, the interim studies reported herein have moved us further toward understanding and optimizing the performance of the ABSR Facility at the PDD (Figure 3). Information was gained toward demonstrating the use of inexpensive substrates and combinations of substrates for nitrate and selenium reduction and for algae production. Data were produced to show the selenium reduction efficiency of the Facility and the extent to which the Facility can internally recycle nutrients required for algal and bacterial growth, particularly when full anaerobiosis is attained. The specific objectives of the research were



1) Organic carbon is added.
2) Oxygen is depleted. Carbon dioxide increases.
3) Nitrate is reduced to nitrogen gas.
4) Selenate is reduced to selenite or organic Se; selenite adsorbs to cationic particles or is reduced to elemental Se.

1) Algae grow by assimilating carbon dioxide, ammonium, and phosphate.
2) Soluble organic carbon is removed.

1) Algae are harvested.
2) Water is clarified.
3) Residual selenite and particulate Se are removed.

Figure 2. Schematic of the ABSR Technology operated in Mode 2.

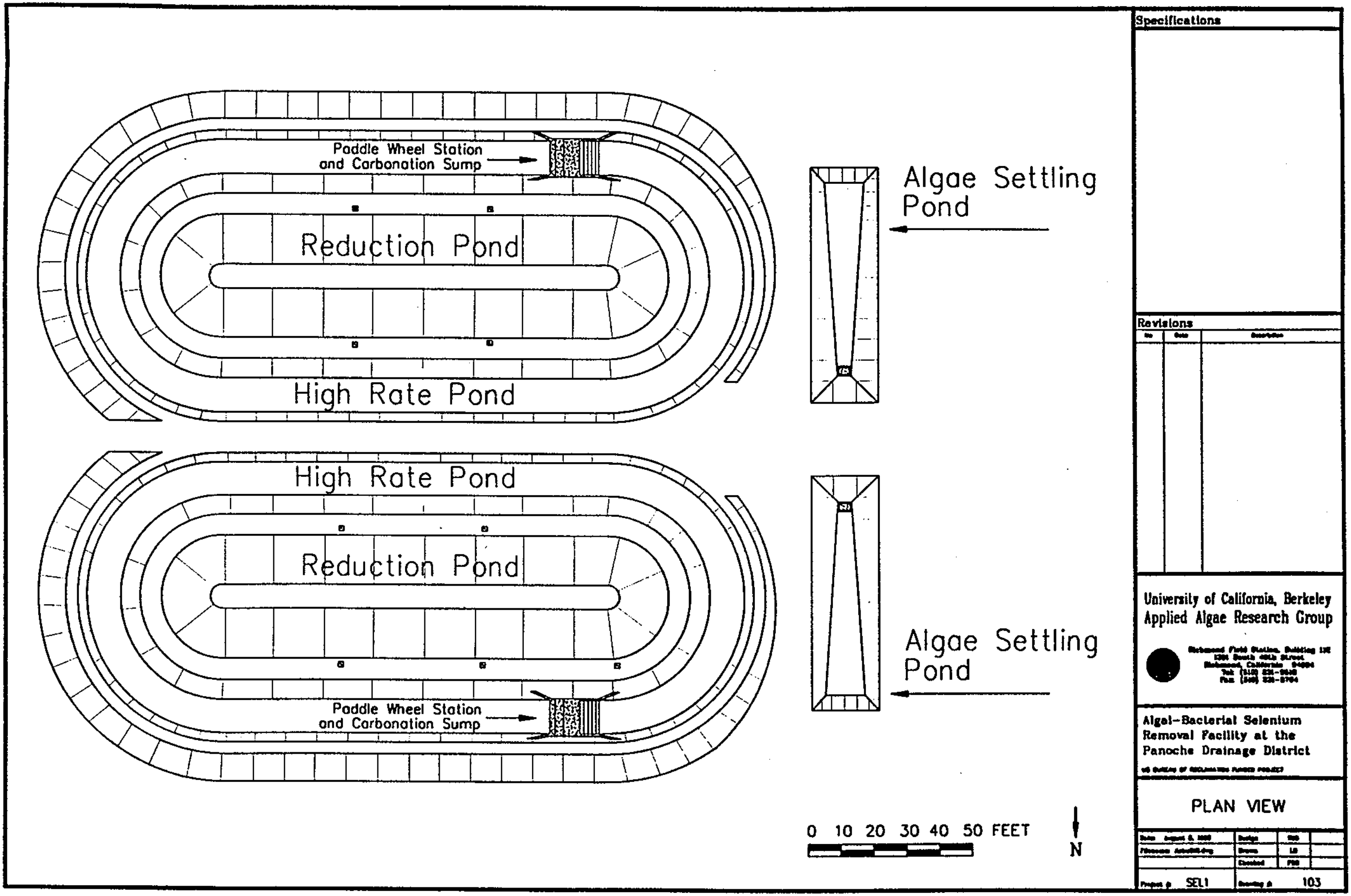


Figure 3. Plan view of the ABSR Facility at the Panoche Drainage District

the following:

- Continue to collect the data from the existing Facility required to perform selenium mass balances and to validate the removal performance;
- Determine as well as possible during the short-term research, the steady-state selenium concentrations in the algal-bacterial solid residuals;
- Determine the substrate feed rates that most efficiently remove selenium mass;
- Continue to collect the data required to perform nutrient mass balances on the systems and adjust operational parameters (HRP depth, pH control) to most efficiently use the nutrients;
- Explore the use of food processing waste as an alternative or supplemental substrate for nitrate and selenium reduction; and,
- Use the data collected to better estimate the capital and operational costs of full-scale ABSR facilities.

For this research further insights may be gained from using climatological and substrate controls in which the major controllable variables are held constant in one system and varied in the other system. In any pond system the major controllable variables are depth, residence time, and inorganic and organic loading. Variables beyond operational control in outdoor systems are temperature, light, and influent water quality. Orthogonal squares experiments, including evaluation of seasonal food processing wastes for substrate, have not yet been conducted at the Panoche ABSR Facility due to the ongoing need to determine the relative merits of Mode 1 and Mode 2 operation in the two identical ABSR Systems at the Panoche Facility. Evaluating the modes has required long-term experiments due to the strong effect of seasonal temperature and hydraulic loading rate on treatment performance. These sophisticated orthogonal squares studies are scheduled for the final year of the ongoing investigation.

2. CONCLUSIONS AND RECOMMENDATIONS

This study has confirmed the following characteristics of the ABSR Process:

- Average total soluble selenium mass removal of 80% can be maintained over at least 24 months when animal feed-grade molasses is used as a substrate supplement to algae biomass grown on site;
- Algae grown in the Mode 1 High Rate Pond consistently settled in the Reduction Pond leaving less than 40 mg/L total suspended solids residual. The settled algae were effective in reducing nitrate and selenate during the months most critical to meeting selenium load limits, July - September;
- The land required for 10 AF/d facilities is likely to be between 40 and 60 acres (16 and 24 ha) assuming Reduction Pond water depths of 15 feet (4.6 m);
- The operations personnel requirement for a 10 AF/d facility is likely to be less than 2 person-days per week; and
- Total costs for 10 AF/d facilities of either Mode 1 or Mode 2 design are likely to be below \$200 per AF treated (\$162 per 1000 m^3 for 12,000 m^3/d facilities) over 20 years.

Future research will attempt to reduce costs by the following:

- Increasing the efficiency of imported substrate use by reducing the substrate dosing level;
- Improving contact between algal substrate and drainage water in order to improve nitrate and selenium reduction rates;
- Study minimization of iron fertilizer use in controlled experiments with the two identical High Rate Ponds at the ABSR Facility in the Panoche Drainage District; and.
- Estimate the impact of algae fertilizer on drainage water nitrate levels.

The risk that full-scale ABSR Facilities, both in Mode 1 and Mode 2, may pose to water birds is currently being assessed with support from the CalFed Bay Delta Program. This determination will indicate the direction future research should take at the ABSR Facility.

3. METHODOLOGY

3.1. THE PANOCHE DRAINAGE DISTRICT ABSR FACILITY

The Panoche ABSR Facility (Figure 3, Table 2) consists of two parallel systems each having a covered Reduction Pond (RP); a paddle wheel-mixed High Rate Pond (HRP) designed to maximize algae production; and an Algae Settling Pond (ASP). A control system is essential to normalize the inevitable changes in drainage composition and climatic conditions. Using two systems also allows side-by-side evaluation of various bacterial substrates, substrate treatments, and flow regimes. Dates of major operational changes are shown in Table 3.

Reduction Ponds

The 0.1-acre (0.04-ha) RPs were designed to promote the growth of nitrate and selenate reducing bacteria. These organisms require the absence or near absence of DO in order to transform nitrate and selenate to insoluble forms. Consequently, the RPs were constructed as deep as the underdrained, agricultural site allowed in order to help prevent significant oxygen concentrations in the reaction zone near the floor of the pond. Floating covers on the RPs were also used to reduce wind-induced mixing of oxygenated surface water to the pond floors.

The RPs had a V-shaped cross section and a 4:1 length to width ratio. For their construction, the RPs were excavated to depth of 6 ft (1.8 m). This shallow cut was chosen to avoid groundwater and to prevent damage to the existing subsurface drain lines. The RP berms were built up with an excavator and compacted with a vibrating roller compactor to achieve a final basin depth of 11 ft (3.6 m), corresponding to a 10-ft (3.0-m) maximum water depth. The RPs were lined with 40 mil high density polyethylene (HDPE). HDPE was selected for its long-term resistance to UV degradation and its low cost. The influent pipelines delivered drainage water to 8 in (20 cm) above the RP floor at the west ends of the RPs. Effluent was taken at mid-depth from the east end of the RPs.

On October 30, 1997, two vertical baffle walls constructed of scrim-reinforced plastic were installed in each of the RPs. The baffles divided the RPs into three cells with equal volume. The baffles were supported at the top with floats and weighted along the bottom and sides with galvanized chain inserted in a hem in the baffle. Three 2-in (5-cm) diameter holes in each baffle allowed water to pass between cells.

In order to simulate a deeper pond, a temporary surface cover was installed on the South RP on December 19, 1996 to prevent wind mixing and decrease photosynthetic oxygenation. The cover was constructed of 8-ounce nonwoven geotextile. A temporary surface cover of 10 mil polyethylene sheeting was installed on the North RP on March 4, 1997. Both covers were removed on September 22, 1997. Permanent covers were installed on the South and North Reduction Ponds on November 21, 1997 and October 9, 1998, respectively. The permanent covers were constructed of 36-mil, scrim-reinforced polypropylene supported by floats. A 1-ft (30-cm) long skirt of cover material descended into the pond to prevent wind from blowing under and displacing the cover. The cover skirt was weighted at the edge with a chain.

High Rate Ponds

The 0.1-acre, paddle wheel-mixed HRPs were designed to cultivate microalgae in high concentrations and at high productivity. The HRP floors were laser leveled to ±0.5 inch (13 mm) and compacted to 95% of optimum. Level HRP floors were required to improve the efficiency of the paddle wheel mixing. The HRPs were lined with a 36-mil, scrim-reinforced, vinyl-based liner, known as XR5, which was manufactured by Seaman Corporation.

The HRPs were operated at depths of 8 in to 24 in (20 cm to 61 cm) and were mixed by eight-bladed, 10 ft-long (3 m) paddle wheels which maintained a mean surface velocity around the pond circuit of 0.5 ft per second (15 cm/s). This velocity is sufficient to keep microalgae in suspension. The paddle wheels were driven at 3.0-3.5 rpm by 0.33 HP (0.25 kW) motors with variable frequency speed controllers.

Carbon dioxide was diffused into the HRP water providing carbon for algal growth and pH control. Each HRP had a carbonation sump that crossed the width of the HRP channel at the paddle wheel station. The sumps were 2 ft wide by 4 ft deep by 10 ft long (0.6 m by 1.2 m by 3.0 m). The horizontal water flow was directed downward into the sump by a corrugated fiberglass baffle which formed a vertical wall across the length of the sump. Upon reaching the bottom of the sump, the flow reversed direction upward and then continued horizontally around the HRP circuit. A carbon dioxide diffuser (0.25" diameter or 6 mm, plastic, Aquatic Ecosystems, Inc.) lay on the floor of each sump releasing carbon dioxide bubbles against the downward water flow. The counter current flow lengthened the time the carbon dioxide bubbles were held in suspension improving their dissolution into the water.

Algae Settling Ponds

ASPs provided a quiescent zone for the algae grown in the HRPs to settle. ASPs clarified the HRP effluent and provided a simple means to harvest algae for use as bacterial substrate. The ASPs were excavated to a depth of 6.5 ft (2.0 m) at the deep end and 3.3 ft (1.0 m) at the shallow end. A 2 ft by 2 ft by 3 ft (61 cm by 61 cm by 91 cm)concrete sump was installed into the floor at the deep end. During the harvesting of the algae slurry, a pump was used in this sump. The sloped floor aided the flow of the algae slurry to the sump. The ASP influent was discharged by gravity to 1.5 ft (0.5 m) above the floor the deep end. ASP effluent was collected in a launder (surface trough) at the shallow end of the ASPs. The purpose of the launders was to improved algae sedimentation by removing supernatant from the surface of the pond at a low overflow velocity.

Final Clarification

Following the last pond in the ABSR series, additional clarification and algae harvesting could be performed as necessary by chemical flocculation followed by dissolved air flotation (DAF) and sand filtration (SF). Final clarification has not been used to date.

The ponds of full-scale installations of ABSR ponds will be lined with clay, rather than plastic, to retard percolation at a lower cost. In the ABSR Facility at the PDD, any percolation would have interfered with the input-output analyses and the performance evaluation. Therefore, all ponds were lined with plastic.

3.2. OPERATIONS

Two modes of operation were evaluated for nitrate removal at the PDD Facility. The North System was operated in Mode 2 during the entire study period while the South System was operated in Mode 2 from startup until June 27, 1997 when it was switched to Mode 1 operation. These configurations continue to be evaluated under the CALFED program.

Water Flow

The influent source was the tile drainage sump, Discharge Point 25. At approximately 15-minute intervals a float switch activated a sump pump which discharged drainage water to a waste ditch. A portion of the pumped flow was shunted into an 8,000-gal (30-m^3) translucent plastic tank which served as the constant head tank for the ABSR Facility. The constant head tank fed the influent splitter box through a 3-in (76-mm) pipe. Two V-notch weirs in the influent splitter box divided the flow between the North and South ABSR Systems. The V-notch weirs were marked at 5-mm intervals, and a flow vs. gage curve was developed. One or two times per weekday, PDD personnel recorded the influent gage reading and adjusted the flow as needed. Periodically the flow checked with a bucket and stopwatch.

RP effluent flows were typically measured twice per month using the bucket and stopwatch method. These measurements were used to verify effluent flows calculated from influent flow measurements plus precipitation and evaporation data. The primary source of evaporation and precipitation data was the California Irrigation Management Information System (CIMIS) weather station located at the PDD office ten miles (16 km) from the ABSR Facility and maintained by the California Department of Water Resources.. These data were periodically verified with an evaporation pan at the ABSR site.

Substrates Used For Denitrification And Selenium Reduction

Beginning July 11, 1996, algae harvested at the AIWPS® Facility at University of California, Berkeley Environmental Engineering and Health Sciences Laboratory (EEHSL) in Richmond were fed to the RPs. The AIWPS® Facility treated 27,000 gal/d (102 m^3/d) of domestic sewage. During the dry season the algae harvested from the AIWPS® Facility were sun-dried and pulverized in a hammer mill, and during the wet season the algae were heat-treated or steam-treated to >60°C while in slurry form. Algae grown at the ABSR Facility were periodically harvested to the RPs without treatment.

Animal feed-grade molasses (Table 4) was used to supplement the algal substrate in the North ABSR System beginning February 20, 1997. From February 20, 1997 to November 27, 1997, the molasses was Type #116 black strap (Liquid Sugars Inc., Emeryville, Calif.). After November 27, 1997, the molasses was supplied by distributors of Westway Trading Corporation of Stockton, California (cane feeding molasses, brix 79.5% min., moisture 27% max., sugar (TSI) 48% min.). Laboratory tests confirmed the equivalency of the two brands for denitrification efficiency.

To avoid inconsistent dosing rates due to temperature changes and hose clogging, low-rate pumping of molasses to the RP was not attempted. Instead, the appropriate quantity of molasses was poured from pails into the North RP influent weir box three times per week by PDD personnel.

Algae harvested on a one-month cycle from the Richmond AIWPS® Facility ASPs and by dissolved air flotation from the City of Sunnyvale wastewater treatment ponds were fed to the South RP beginning April 14, 1997. When the South System was switched to Mode 1 operation on June 28, 1997, the algae grown in the South HRP were pumped directly into the RP with the RP influent. Retention of the algae by the RP was almost complete as indicated by low RP effluent volatile solids concentrations.

High Rate Pond Operations

To promote rapid algal growth, carbon, nitrogen, phosphorus, and trace nutrients such as iron must be present in the water. In the Mode 1 South System, influent tile drainage water was the medium for algae growth. Nitrogen was plentiful in the drainage water, but phosphorus in the form of triple super phosphate fertilizer (Northern California Fertilizer Co., Shasta, 0-45-0, monobasic calcium phosphate, $CaH_4(PO_4)_2$), chelated iron (Monterey Chemical Co., Fresno, Sequestar 7%, $FeNa_2DTPA$), and carbon dioxide (University of California, Berkeley storehouse) were added. Carbon dioxide was continuously sparged into the HRPs, and the other nutrients were added once per week.

The Mode 2 North System, the HRP influent was the RP effluent which was rich in dissolved carbon dioxide, phosphorus, and iron from decomposing molasses and algae.

However, nitrogen was often limited in the North RP effluent due to denitrification. Ammonium phosphate or urea were added to provide nitrogen. Despite the carbon-rich influent, algal growth was often so vigorous in the North HRP that carbon dioxide had to be supplemented. Carbon limitation was assumed when the HRP pH rose above 8.5. Sparging carbon dioxide into HRPs with pH levels lower than this is inefficient due to a poor dissolution rate. Triple super phosphate was also added to be certain that phosphorus would not limit algal growth. Fertilizer and carbon dioxide application rates are shown in Table 5.

3.3. SAMPLE COLLECTION, PRESERVATION, AND PREPARATION FOR ANALYSIS

In order to maintain quality control and ensure that data was as accurate as possible, a strict sampling regimen was implemented. The following procedures ensured that the collected data in this report is as free as possible from error induced by inconsistent sampling methods. The remote location of the ponds required special attention to sample treatment. Grab samples were the main method of sampling. Periodically diurnal samples were collected at four or six hour intervals to assure that the concentrations of elements in the ponds remained fairly constant over the course of the day and that grab samples were representative of average daily concentrations.

Both the North and South Systems were sampled at least once a week usually on Tuesday or Wednesday. Routine samples were collected between 12:00 PM and 5:00 PM. The following samples were routinely collected: drainage water influent, RP effluents, HRP effluents, and ASP effluents. In addition, the internal cells of the RPs were sampled periodically at three depths--surface, 5 ft below the surface, and at the floor. The drainage water waste channels adjacent to the ABSR Facility were also sampled regularly in order to develop a water quality data set on the aggregate of several high selenium sumps in the PDD. Ponds were sampled before any maintenance or substrate feedings were performed in order not to confound the samples.

All samples were collected in 500 mL polyethylene bottles. Prior to sampling, all sample bottles were washed and scrubbed with phosphorus-free detergent and hot water, then rinsed three times with deionized water and allowed to dry completely. When sampling, the sample bottle was rinsed three times with the pond water being sampled, then filled with sample. A sampling device was used to obtain discrete samples at different depths in the RPs. This device consisted of a 20-ft long PVC pipe with a 500-mL bottle holder at one end. A butyl stopper with two 0.25-in holes was placed in the bottle mouth. The 0.25-in holes were blocked with smaller glass stoppers attached to a string. When the sample bottle was brought to the correct depth, the string and the attached glass stoppers were pulled, and water entered the sample bottle. The stoppers were thoroughly rinsed with DI water between samples. Surface and mid-depth samples were collected before the floor samples.

Typically 30 minutes were required for sampling. Immediately after all the samples were taken, pH, DO, and temperature were measured in each of the samples. The sample bottles were then capped and placed in refrigeration for 3 to 4 hours until they were transported on ice to EEHSL for further analyses. At EEHSL, an aliquot of the sample was acidified immediately to pH<2 with sulfuric acid (metal analysis grade). This aliquot was tested for total phosphorus, total Kjeldahl nitrogen, and ammonia. Another aliquot was filtered through a 0.22 μm filter and acidified to pH<2. This aliquot was tested for soluble phosphorus and nitrate. A third aliquot was filtered through a 0.22 μm filter and left unfiltered, this aliquot was tested for total soluble selenium. The remaining, unaltered sample was tested for solids, alkalinity, and algae identification. All samples were stored in the dark at 4°C until testing.

3.4. WATER AND SEDIMENTS ANALYSES

The monitoring program designed and executed by the personnel of the Applied Algae Research Group at EEHSL required the determination of selenium in water and sediments taken from the ABSR Facility. Except for selenium, all other parameters for water quality determination were performed at EEHSL. Sample preparation for selenium analyses in water were performed at EEHSL. Sample preparation for selenium determination in sediments were performed at EEHSL and the Lawrence Berkeley National Laboratory's Environmental Measurement Laboratory (EML/LBNL). All selenium analyses, from water and sediments, were performed at the EML/LBNL. A list of the standard methods used are shown in Table 6. Analytical accuracy was assured by a quality assurance/quality control (QA/QC) program consisting of matrix spikes, standards, blanks, split samples, and duplicates. These QA/QC samples consisted of 10% to 15% of the samples analyzed. Out of control sample sets were re-analyzed.

Quality Assurance and Quality Control

The Algae Group QA program sets operating procedures for data collection, sampling, and analysis resulting in reliable data and defensible results. The internal Algae Group quality control (QC) is part of the QA program and fulfills the requirements for the credibility of the results. Below is a list of the QC components and their purpose:

(1) Certification of analyst competence, provided by the EML/LBNL

(2) Recovery of known additions or spikes to gauge interference

(3) Analysis of standards to gauge accuracy

(4) Analysis of blanks to gauge contamination

(5) Calibration with standards to gauge precision

(6) Analysis of duplicates or splits to gauge accuracy and precision with the natural matrix

Selenium Analysis in Water

The common forms of selenium found in natural waters are selenate (SeO_4^{2-}), selenite (SeO_3^{2-}), and various forms of organic selenium (Benson *et al.*, 1990). Also, selenopolysulfide ions (SSe^{2-}) may occur in the presence of hydrogen sulfide in or nearby waterlogged, anoxic soils or sediments, and methylated selenium is also prossible (APHA, 1995). In the case of the ABSR Facility at the PDD, we determined that filtered samples contained selenate and selenite.

Selenium analyses of water samples were performed by hydride generation atomic absorption spectrometry (HGAAS) following guidelines of the *Standard Methods for Analysis of Water and Wastewater* (APHA, 1995). APHA Method 3500-Se-C was adapted to analyze water samples from the ABSR Facility. Analyses were performed at the EML/LBNL.

Alkaline digestion using hydrogen peroxide and sodium hydroxide is recommended by the APHA 3500-Se method as one of the ways to determine selenium in natural matrixes. This method recommends the digestion of unfiltered samples using suitable preparatory steps to convert other selenium species to selenite. We adapted the alkaline digestion method to validate results for total soluble selenium determination digested with concentrated hydrochloric acid and different additions of 2% ammonium persulfate, $(NH_4)S_2O_8$.

Procedures to adapt this method for validation purposes are explained below with more detail.

During the first nine months of operation, the samples from the ABSR Facility had very low turbidity and color, then samples from both the South and North ABSR systems started to present color, presumably caused by the continuing additions of algal slurry and molasses substrates to the RPs. Some samples from the South System were cloudy and had a hydrogen sulfide odor. Samples from the North System were transparent but lightly colored yellow-brown presumably from molasses residuals. Color and odor characteristics may indicate the presence of soluble selenium compounds other than selenite and selenate (APHA, 1995). In addition, those characteristics of the samples may also imply that organic matter is present that could interfere with analytical determinations (Fio and Fujii, 1990).

Ammonium persulfate was used in the digestion of samples in order to remove interference from reducing agents and to oxidize labile organic selenium compounds such as seleno-amino acids. Total soluble selenium concentrations using ammonia persulfate were significantly higher when compared to concentrations in the same samples digested with peroxide according to APHA 3500-Se-C method. This result confirmed that the presence of soluble organic matter interfered with the analytical determinations of these samples and that ammonium persulfate addition was necessary.

To validate these findings, the same samples were (1) analyzed following alkaline hydrogen peroxide digestion (method APHA 3500-Se A), and (2) spiked to gauge interference and measure recovery. The results of alkaline digestion validated additions of 0.2 -0.4 mL of 2% ammonium persulfate solution to 2.5 mL of sample. The addition of known standards (spikes) also validated variations to the analytical procedures recommended by method APHA 3500-Se C.

The variations introduced to the APHA 3500-Se C method for total soluble Se determinations were the following:

Sample Preparation

Centrifuge 40 mL of sample at 15,000g for 30 minutes prior to filtration

Digestion for Total Soluble Selenium:

1. Place 2.5 mL of samples into 40-mL glass test tubes
2. Add 2.5 mL of concentrated HCl
3. Add 0.1-0.4 mL 2% $(NH_4)S_2O_8$ solution (w/v)
4. Heat glass test tubes containing samples at 96-98°C for 30 minutes in block heater or water bath
5. Let sample test tubes cool, make dilutions as needed, and analyze samples.

In spite of the procedures performed to validate our results, further selenium determinations through both persulfate and alkaline digestions are planned. This validation should incorporate the addition of known organic soluble Se standards. Determinations of soluble organic Se compounds in the natural matrix will be important to assess its variability over time.

Selenium Determination in Sediments

Samples for selenium determination in sediments were handled and prepared as follows: Any supernatant in the samples was drained. The sediments were homogenized, split into two sets, and air-dried or oven-dried at 45 ± 5 °C within 48 hours after samples were collected. After sediments were dried, they were milled. Milling was performed either manually, using a mortar and a pestle, or using a ball mill. Ground samples were sieved through a 150-μm mesh and dried again at 45 ± 5 °C to constant weight and stored in 60-mL polyethylene bottles prior to selenium determination. Selenium determination in sediments followed the method of Martens and Suarez (1997). The following steps are recommended for total acid digestion (TAD) in accordance with this method:

- Place 0.2-5.0 g of prepared sample into a 100 mL teflon beaker
- Add 5 mL of *aqua regia* (3:1 conc.HCl:conc.HNO_3, vol:vol)
- Add 2 mL of hydrofluoric acid, cover beaker with teflon watch "glass"
- Heat beaker for 2 h at 110-120 °C in sand bath
- Dilute samples to 25, 50, or 100 mL with DI water and transfer into a 100-mL polyethylene wide-mouth bottle
- Store the sample at 4 °C and analyze within one week by hydride generation atomic absorption spectrometry (HGAAS) including the alkaline digestion or concentrated HCl digestion step
- Estimate concentration in original sample by considering all dilution factors and the sediment mass used for the determination.

Standard and blank controls were analyzed. Standard sediments NIST No. 1646a and NBS No. 1646 obtained from EML/LBNL were used for this purpose. Initial validation of the total selenium results using the standard sediments and blank background checks were consistently within $\pm$ 15% of their values. Further validation of this method is in progress.

3.5. ALGAL IDENTIFICATION

Algae genera were identified in the HRPs on a regular basis with the aid of references (Prescott, 1978; Nakamura, 1963; and APHA, 1995). Algal identification helped monitor the effects of changing parameters such as nutrients, sunlight, and temperature on part of the algal consortia in the HRPs. Algal identification was also important since algae are the primary substrate for nitrate reduction. A Pasteur pipet was used to transfer an aliquot of fresh sample to a normal microscope slide with a cover slip. The slide was examined under 40x to 1,000x magnification using a phase contrast filter. The quantification of algal species was conducted with a relative abundance scale explained below.

Relative Abundance Scale

A relative scale was used to enumerate both quantity and dominance of algal species in the samples. Each algal species or type identified on the slide was assigned a number: 5 indicated complete number dominance of the species and a large population of the species relative to earlier samples; 1 was used if one or two cells of the species was seen in the sample; 2, 3, and 4 were assigned to species whose population numbers fell between the 1 and 5 extremes. During the course of the project, two analysts performed the identification and enumeration. The second analyst was trained by the first over the course of three months ensuring consistency.

4. RESULTS

4.1. QUALITY ASSURANCE AND QUALITY CONTROL

Results of the Applied Algae Research Group QC in 64 sample sets, covering the period April-December 1998 are summarized in Tables 7a-7d . The quality of the results was assessed through the inclusion of standards, blanks, splits or duplicates, and spikes in the sample sets. Analytical results for selenite indicate that 90.63% of the sets of samples were in control after the first analysis. Less than 10% of the sets (6 out of 64) required reanalysis for selenite determination. For total soluble selenium, the overall results shown a slightly better performance than for selenite (92.20% vs. 90.63%) after the first analysis. This indicates that 5 out of 64 sample sets were reanalyzed for total soluble selenium determinations. All reanalyses were in control but not reported in the Tables 7a-7d.

Tables (7a-7d) show QC results in terms of accuracy and precision percentage (standards), contamination (blanks), accuracy and precision with the natural matrix percentage (splits), and interference percentage (spikes). Table 7a shows results for selenite and total soluble selenium analysis. Selenite results indicate that the percentage of precision ranged 99.1±5.9% as standards measurements. Precision for total soluble selenium as standard measurements ranged 100.5±6.0%. Table 7b, show that blanks for both selenite and total soluble selenium are within acceptable range readings to control for contamination, 0.08±0.03% and 0.17±0.11% respectively. Results obtained to control precision and accuracy with the natural matrix through splits analysis are shown in Table 7c. Selenite and total soluble selenium splits present the narrowest ranges for this type of control indicating that the measurements are representative of the natural matrix. Splits percent replicable measurements for selenite ranged 100.8±2.7% while for total soluble selenium ranged 99.1±2.3%. Finally, results to control interference through spikes or addition of known standards ranged 98.2±5.0% recovery for selenite and 99.7±5.0% recovery for total soluble selenium. Thus, the QC results of analytical selenium determinations produced reliable and defensible results that fulfilled the aims of the Applied Algae Research Group QA program.

4.2. DRAINAGE WATER COMPOSITION

A sample from the drainage water influent was submitted to the analytical laboratory of the University of California, Davis Department of Agriculture and Natural Resources for mineral analyses. The drainage water had low concentrations of some trace nutrients important to algae and bacteria, namely Fe, Zn, Mn, Mo, and Co (Table 8). Concentrations of the other elements were typical of San Joaquin Valley drainage water. Sulfate, Na, Ca, Mg, and B were present in high concentrations.

4.3. SUBSTRATE EFFICIENCIES AND SUBSTRATE TREATMENT

During the first six months of operation in 1996, DO and NO_3^--N removal was poor in both systems. The cause of the poor removal appears to have been the recalcitrant nature of the algae used as feed and vigorous photosynthetic oxygenation by algae growing at the surface of the RPs coupled with wind-mixing of the surface water to the RP floors.

The RPs were fed algae harvested from the Algae Settling Basins of the Richmond AIWPS® Facility. This algal biomass had accumulated over approximately six months before harvesting and treatment by drying or heating. Subsequent laboratory studies suggested that during the accumulation period most of the algal carbon that was readily available to nitrate-reducing bacteria was lost due to anaerobic degradation in the Settling Basins. However, algae not allowed to settle and accumulate but instead harvested directly from the Panoche and Richmond HRPs had good reducing capacity. In laboratory tests, these fresh algae reduced ten times more nitrate than the Richmond Settling Pond algae that had been fed to the Panoche RPs previously (Table 9). Heat treatment of the older algae reduced this advantage to about three times more effective. Recently-grown algae harvested directly from the HRP at either Richmond or Panoche were about half as effective as molasses. Regardless of substrate, once nitrate was reduced in the laboratory cultures, total soluble selenium was typically reduced from an initial level of 375 μg/L to 25 μg/L in eight days, equal to greater than 90% removal.

4.4. BACTERIAL REDUCTION OF DISSOLVED OXYGEN

As noted before, denitrification and dissimilatory selenium reduction are inhibited by the presence of DO. As such, DO levels in the RPs were monitored under various conditions of substrate addition and sunlight blocking with floating covers.

North Reduction Pond

After the start of molasses dosing at 0.59 g/L in late February 1997 and installation of the cover on the North RP in early March 1997, DO levels dropped from 8 to 9 mg/L to less than 2 mg/L at the floor and mid-depth of the North RP (Figure 4, points A and B), however, the effluent did not reach <2 mg/L until late July 1997 after an increase in the molasses dose to 0.78 g/L (Figure 5, point C). The temporary RP cover was removed in September 1997 (point D) and the DO level in the RP rose again to between 2 mg/L to 6 mg/L. DO increased to a maximum of 8 mg/L in February 1998, but by April DO was again <2 mg/L. The influent flow increases in July appeared to have little influence on effluent DO concentration in the RP which remained <1 mg/L. North RP effluent rose to 3 mg/L after the November 1998 increase in flow (point G), but decreased bacterial activity and increased oxygen solubility due to cooler weather probably also contributed to the rise.

South Reduction Pond

The South RP was covered in December 1996 and received algae as its sole substrate. Despite the cover, the substrate loading and decomposition rate were not high enough to eliminate DO. The DO levels varied between 1 and 10 mg/L averaging 6 mg/L prior to the switch to Mode 1 in June 1997 (Figure 6 and Figure 7, point A). Consequently nitrate and selenium removals were poor (<50%).

After the switch to Mode 1, the influent to the South RP was South HRP effluent which had DO levels of 20 mg/L to 35 mg/L during the day. Despite the high influent DO, during July through September, DO in the South RP dropped reaching <1 mg/L in September.

The removal of the temporary cover in September 1997 (point B) resulted in DO levels in the South RP effluent to reach nearly the influent concentrations, but with the installation of the permanent cover, about 10 mg/L of DO was removed in the RP. It is unclear whether the improvement in DO removal after March 1998 was due to warmer conditions or due to the beginning of FeDTPA addition. The chelated iron addition was meant to cause an indirect drop in DO levels by increasing algae (bacterial substrate) production, which it did. The increased algae production did not increase DO levels as these were already supersaturated before FeDTPA addition. The FeDTPA also could have directly improved oxygen reduction by stimulating bacterial activity.

4.5. NITRATE REMOVAL AND ALGAL PRODUCTIVITY IN THE HIGH RATE PONDS

North High Rate Pond

The North RP effluent to the North HRP was generally so low in nitrate that there was little opportunity to measure nitrate removal in the North HRP. An occasional removal peak of 0.2 to 0.4 kg/d was seen during 1997 and 1998. In Mode 2, the purpose of the HRP was to remove soluble BOD and nutrients from the RP effluent and to recapture carbonates as organic carbon in the form of algae. These algae are then harvested and placed in the RP as bacteria substrate.

Prior to the start of molasses dosing of the North RP (August 6, 1996 to February 20, 1997), the North HRP algal productivity was 436 g/d as VSS or about 1.0 $g/m^2/d$. The addition of molasses to the RP increased the alkalinity of the HRP influent and improved algal productivity to 1,605 g/d as VSS or 3.6 $g/m^2/d$. The North system flow was increased to 6,650 gal/d on July 8, 1998 resulting in a further increase in productivity to 3,787 g/d VSS or 8.5 $g/m^2/d$. After molasses addition began to January 1999, the concentration of algae as volatile solids averaged 172 mg/L (Figure 8).

South High Rate Pond

While operating in Mode 2, the South HRP removed residual nitrate in the South RP effluent. During February 20, 1997 until the mode switch on June 27, 1997, the influent nitrate-N to the South HRP averaged 62.0 mg/L and the effluent averaged 43.0 mg/L. The N mass removal averaged 0.28 kg/d, equivalent to 0.59 g/m^2/d or 3.2 mg/L/d. During the same period, algal productivity averaged 0.46 kg/d or 1.0 g/m^2/d or 5.4 mg/L/d.

Two and a half months after to the switch to Mode 1 operation, the South HRP nitrate mass removal stabilized. During September 16, 1997 to February 17, 1998, when FeDTPA addition to the South HRP began, the drainage water influent to the South HRP averaged 79.9 mg/L nitrate-N while the effluent averaged 63.2 mg/L corresponding to a removal of 0.38 kg/d or 0.79 g/m^2/d or 3.0 mg/L/d of N. During the same period, algal productivity averaged 0.71 kg/d or 1.5 g/m^2/d or 5.6 mg/L/d as VSS. The ratio of NO_3^--N removed to VSS produced was 0.38 kg/d divided by 0.71 kg/d or 54%.

The nitrate mass removal then increased and remained fairly constant to the end of 1998. From February 17, 1998 to December 31, 1998, nitrate-N concentration dropped from 74.4 mg/L to 32.5 mg/L during treatment in the South HRP, equivalent to a nitrate-N removal of 0.60 kg/d or 1.22 g/m^2/d or 4.6 mg/L/d. During the same period, algal productivity averaged 0.99 kg/d as VSS or 2.0 g/m^2/d or 7.6 mg/L/d. The ratio of NO_3^--N removed to VSS produced was 0.60 kg/d divided by 0.99 kg/d or 61%.

The algal VSS concentration from February 17, 1998, the start of FeDTPA addition, to the end of December 1998 averaged 100 mg/L. Prior to FeDTPA addition the VSS concentration was typically was 40 mg/L to 50 mg/L (Figure 9).

A considerable mass of nitrogen is unaccountable in the South HRP during March to December 1998. The organic nitrogen (ON) in the South HRP effluent averaged 9.9 mg/L (median 9.1 mg/L) during March 3, 1998 to December 31, 1998, and both influent and effluent ammonia averaged <0.2 mg/L. The drainage water influent was low in organic nitrogen at 0.12 mg/L on average, 0.02 mg/L median. The ON:VSS ratio in the South HRP effluent during this period averaged 0.10 (median 0.10) which is typical of microalgae. The ON production rate was thus (0.10)(2.0 g/m^2/d VSS) = 0.20 g/m^2/d ON. The nitrate+nitrite-N removal rate was 1.22 g/m^2/d, leaving 1.0 g/m^2/d unaccounted for.

Ratios of Carbon Dioxide Added to Nitrogen Removed during Assimilation

No correlation was found between the level of carbon dioxide addition and the nitrate removal seen in HRP*s*.

4.6. DENITRIFICATION RATES AND SUBSTRATE EFFICIENCIES

In the North RP, the water and nitrate loading rates and the molasses feeding rate are the predominate variables for both the nitrate removal rate and the substrate efficiency (Table 10). Covering the North RP appeared to have no effect on the substrate efficiency, whereas covering the South RP did improve the substrate efficiency (Table 11). Seasonal variations in nitrate removal are discernable (Figure 10 and Figure 11). Presumable with the RPs covered, temperature, which was lowest near the end of each year (Figure 12 and Figure 13), was the only weather parameter affecting the RPs. Nitrate concentration and nitrate loading to the RPs also dropped during January to April making it difficult to separate the temperature dependency of the field denitrification rates. However, the threshold between the summer nitrate mass removal rate and the winter rate appears to be about 20°C.

4.7. SELENIUM REMOVAL

Selenate Reduction in the North ABSR System

More significant selenium removal began in the North RP after molasses addition began on February 20, 1997 (Figure14, point A). Selenate removal averaged 4.8 g/d during February 26, 1997 to October 30, 1997, peaking at about 11 g/d in October 1997 (Figure 15). The North HRP removed an average of 0.1 g/d during this period. Cumulative mass removal of total soluble selenium for 1997 through 1998 was 84% (Figure 16).

From April to October 1997, the molasses-fed system consistently reduced nitrate nitrogen to less than 10 mg/L NO_3^--N and total soluble selenium 70% to 80% from a mean of 413 μg/L in the influent down to a mean of 87 μg/L. The lowest effluent total soluble selenium concentration was 31 μg/L.

From October 1997 to the beginning of March 1998, selenate removal in the RP averaged 3.0 g/d, falling briefly to zero removal on February 24, 1998. During this period, selenate removal in the HRP increased to 0.8 g/d. Selenate removal in the RP then rose steadily to a peak of 12.8 g/d on October 9, 1998. The average removal during the 7.5 months from March 3, 1998 to October 14, 1998 was 5.9 g/d, and removal in the HRP remained constant at 0.8 g/d. Selenate removal increased through the end of the year to 6.3 g/d in the RP and 0.9 g/d in the HRP. Selenate removal in the North Algae Settling Pond was less than 0.1 g/d from February 26, 1997 to October 14, 1998. However, removal rose to average 0.1 g/d from October 27, 1998 to the end of the year.

Selenate Reduction in the South ABSR System

During December 30, 1996 to June 27, 1997 under Mode 2 operation, the South RP removed an average of 0.7 g/d of selenate, and the South HRP removed 0.2 g/d (Figure 17 and Figure 18). After treatment stabilization following the switch to Mode 1 operation to the end of 1998 (September 22, 1997 to December 22, 1998), the South HRP removed an average of 1.1 g/d of selenate from the influent drainage, and the South RP removed an average of 2.5 g/d from the HRP effluent. Cumulative mass removal for the two years 1997 and 1998 was 46% (Figure 19).

Ratio Carbon Added to Selenium Removed

Since a majority of the organic carbon added to the RPs is expended on nitrate removal, the ratio of carbon added to selenium removed is not as relevant as the carbon:nitrate removed, presented in the section above. Instead, the ratio of nitrate removed to selenium removed or nitrate remaining to selenium remaining is more significant. These results are presented below.

4.8. RATIOS OF NITRATE TO SELENATE

Laboratory experiments have shown that nitrate-N concentrations must fall to less than about 5 mg/L before significant selenium reduction occurs (Lundquist *et al.*, 1994). In the RPs, selenium reduction was greater when nitrate was removed to low levels. The selenate-Se removal rate was maintained above 1 g/d only when the nitrate-N concentration was less than 6 mg/L to 8 mg/L. However, some selenium was reduced even in the presence of 10 to 20 mg/L nitrate-N (Figure 20 and Figure 21). Selenate removal did not track effluent nitrate concentration well (Figure 22 and Figure 23). The effluent nitrate concentration correlated to selenate mass removal with an r^2 of only 0.44 (North RP) and 0.17 (South RP) even when samples with undetectable nitrate concentrations were excluded.

However, effluent selenate concentration correlated to effluent nitrate concentration with an r^2 of 0.80 (North RP) and 0.60 (South RP) (Figure 24 and Figure 25). Also in the North RP, selenate mass removal tracked nitrate mass removal, yielding an r^2 value of 0.73 and a slope of 4.2 = (g/d selenate removal) ÷ (kg/d NO_3^--N removed). In the South RP, the correlation of nitrate-N mass removal and selenate-Se mass removal had an r^2 of 0.54 and a slope of 4.0 = (g/d selenate removal) ÷ (kg/d NO_3^--N removed) which is close to the slope for the North RP.

4.9. SELENIUM IN ABSR POND SEDIMENTS

Preliminary results indicate concentrations of total selenium in the ABSR pond sediments ranged from 41 μg/g to 204 μg/g (Table 12). The higher concentrations were found in the RP sediments, although considerable selenium appears to have accumulated in the HRP and ASP sediments, too.

All samples contained elevated levels of total selenium. Interpretation of these results requires some caution since validation of the method is still in progress. Samples taken on November 24 showed levels of selenium within the range 40.92 ± 3.63 to 203.60 ± 18.55 μg/g. Sediments accumulated in the carbonation sump of the South HRP have shown the lowest concentration (40.92 μg/g) of total selenium. On the other hand, sediments taken from the floor of the third cell of the South RP had the highest concentration of selenium accumulation, 203.60 μg/g. Sediment selenium at the east end of the South HRP showed levels of 54.95 ± 4.94 μg/g while levels of selenium in sediments from the floor of the first cell of the South RP averaged 92.35 μg/g.

Results for samples collected on December 29, 1998 show both expected and surprising results. On one hand, levels of selenium in sediments from the South HRP were 52.29 ± 4.70 μg/g, which are similar to the levels found for these sediments on November 28. On the other hand, sediments taken from the floor of the third cell of the South RP had levels of 103.06 ± 9.03 μg/g. This level represents one half of what was found for samples taken on November 28. Levels of selenium in sediments coming from the floor of the North ASP were 71.03 ± 7.07 μg/g. Total selenium in samples taken from the South HRP were 216.79 ± 19.55 μg/g.

Validation of the digestion method is important in order to report reliable results. Currently, validation of the method is in progress and initial results indicate that the method of Martens and Suarez (1997) has proven reliable. This information is, of course, essential if significant mass balance data are to be maintained.

4.10. ALGAE IDENTIFICATION

As expected, there were marked differences in the populations of the South HRP with its drainage water influent and the North HRP which received RP effluent. In the South HRP, the dominant algal species were commonly centrale-type diatoms, the green alga *Scenedesmus*, and the diatom *Chaetoceros*. In the North HRP, the most dominant genera were *Nannochloris*, *Westella*, and centrale-type diatoms. In addition, the diatoms *Navicula* and *Nitzschia* were found in small numbers throughout the study period in both HRPs.

Flagellated green algae (e.g., *Euglena)* were dominant in the start up periods (to March 1997) of both HRPs. Then diatoms (centrale, *Nitzschia, Chaetoceros, Navicula)* dominated during the rest of 1997 and 1998. Green algae were also often present or co-dominant in both HRPs. *Scenedesmus, Nannochloris,* and a green flagellate, perhaps *Mesostigma,* were the most prevalent green algae in the South HRP; while green algae such as *Nannochloris, Micractinium,* and *Westella* often shared dominance with the diatoms in the North HRP.

5. DISCUSSION

5.1. ALGAL SUBSTRATE TREATMENT AND ALGAE HARVESTING

Laboratory studies showed that recently-grown algae harvested directly from the HRP are more immediately effective as denitrifying substrate compared with algae that accumulated in an ASP before being used as substrate. This result was not expected since past research has shown that microalgae grown in AIWPS® Facilities are initially resistant to microbial degradation. For example, the methane yield from anaerobic digestion of microalgae nearly doubled after heat treatment to 100°C (Chen, 1987) suggesting that bacteria could ferment the cells far more completely after the algae cells walls were disrupted.

It is well known that algae deprived of light demonstrate the highest respiration rate during the first hours of deprivation. It also appears, judging from the laboratory and field studies on the ABSR Process, that when there is no free molecular oxygen, respiring algae can obtain oxygen from nitrate and possibly selenate at rates greater that those of their bacterial analogs.

Frequent harvesting and immediate utilization of algae should preserve labile algal carbon for use by nitrate- and selenium-reducing bacteria. Continuous harvesting was implemented in the South ABSR System by switching to Mode 1 operation and using the South RP as the settling unit. The algae carried by the HRP effluent settled in the RP and rapidly reduced the level of DO. DO concentrations in the South RP effluent remained below 5 mg/L between July and October 1997 even though the influent DO concentration rose from 9 mg/L to about 27 mg/L due to the switch in mode of operation (i.e., the RP influent switched from drainage water to oxygen-rich HRP effluent) (Figure 7, point A to point B).

In the North ABSR System operated in Mode 2, algae grown in the HRP settled in the ASP. This biomass was not harvested and added to the North RP in order to avoid confounding determination of the effectiveness of the molasses substrate. The algae biomass collected in the North ASP was harvested and added to the South RP on September 1, 1998. After that harvest, algae were allowed to accumulate in the North ASP.

5.2. BACTERIAL REDUCTION OF DISSOLVED OXYGEN

After the first several months of operation in 1996, it became apparent that the thermal stratification of the RPs due to solar insolation was insufficient to prevent wind from mixing surface water with high DO concentrations to the RP floor. As would be expected, the abundance of DO inhibited the reduction of nitrate and selenium. Full-scale ABSR facilities will have RPs two to three times deeper than the 10-ft (3-m) deep RPs at the demonstration ABSR Facility. The additional depth will hinder DO from reaching the pond floor and thereby promote a greater anoxic volume where nitrate- and selenium-reduction will occur.

As we were clearly unable to attain anoxic conditions with open water surfaces, temporary surface covers were installed on the RPs. The covers prevented wind mixing and production of DO by algae in the RP surface water. DO levels dropped dramatically in the covered RP and nitrate reduction improved. When the temporary covers were removed, DO levels rose, especially in the lightly loaded South RP. DO then decreased when the permanent cover was installed on the South RP (Figure 7, point B to point C). The effect of the surface cover on DO in the North RP apparently was obscured by the high oxygen demand of the molasses substrate.

5.3. NITRATE REMOVAL AND ALGAL PRODUCTIVITY IN THE HIGH RATE PONDS

North High Rate Pond

Before molasses addition to the North RP commenced, the algal productivity of the North HRP was only about 1.0 $g/m^2/d$. The decomposition of molasses in the RP provided inorganic carbon for algae growth in the HRP. Phenolphthalein alkalinity rose from about 250 mg/L as $CaCO_3$ in the influent to 350 mg/L to 900 mg/L in the RP effluent. This alkalinity was then reduced to <100 mg/L as $CaCO_3$ presumably by algal assimilation and carbonate precipitation in the high pH HRP (Figure 26 and Figure 27). After molasses addition to the RP was started, algae productivity increased to 8.5 $g/m^2/d$ during the summer of 1998. The hydraulic residence time the North HRP averaged 7 days whereas maximum algae productivity often is achieved at residence times of 3 to 5 days. Shorter hydraulic residence times are likely to further increase the productivity.

South High Rate Pond

Under Mode 2 operation (RP→HRP→ASP), the South HRP also had algal productivity of only about 1.0 $g/m^2/d$, even though under summer conditions many full-scale HRPs are able to produce as much as 25 $g/m^2/d$ when nutrients and inorganic carbon are not limiting growth. The high pH, usually between 8.5 and 10 (Figure 28), and low phenolphthalein alkalinity levels, usually less 100 mg/L as $CaCO_3$ (Figure 29), in the South HRP during this period indicate that carbon limited the algae productivity. Despite the low productivity, nitrate removal was better than expected. Green microalgae typically contain 8%-10% nitrogen dry weight. The organic nitrogen content of the algae grown in the South HRP during Mode 2 operation ranged from 7% to 11%, averaging 10%. With this nitrogen content, nitrate removal by assimilation should have been (10%)(0.46 kg/d algal VSS)=0.046 kg/d N removal. Instead, the NO_3^--N removal rate was 0.28 kg/d or six times higher than expected. Denitrification was not expected in the HRPs due to their high DO concentrations which typically remain above zero overnight. This excess removal of nitrate persisted throughout the operation of the South HRP, possibly indicating denitrification in the biofilms on the pond floor or aerobic nitrate reduction (Carter *et al.*, 1995).

With the switch to Mode 1 (HRP→RP) operation and an increase in chelated iron addition to the South HRP, algae productivity improved to 5.6 $g/m^2/d$. Algal productivity was probably limited by low substrate alkalinity and long hydraulic residence time. Nitrate removal increased by 37% and was 5.4 times higher than would be expected if assimilation were the only path of nitrate-N removal.

It appears that sedimentation creates a sink for organic nitrogen in the HRPs. The depth of the sediment in the South HRP ranged from <1 cm to 25 cm depending on location within the continuous raceway. Algal sediment in the HRP had a 4% VS content, TS containing 45% VS, a specific gravity of 1.05, and a 10% N content. Had all the missing nitrogen settled in the HRP as algae, the sediment depth would have been about 14.5 cm deep. These sediment depths are comparable to the measured depths indicating that sedimentation is a major N sink in the South HRP.

Denitrification is also a likely means for NO_3^--N removal in the HRP. In the deeper sediment areas of the South HRP, the settled algae was black and had a slight hydrogen sulfide odor indicating intense reducing conditions. In the areas of deeper sediment approximately half the depth of sediment was not consolidated. Due to paddle wheel mixing, the overlying pond water mixed through the unconsolidated sediment providing contact between reducing sediment and the overlying water. The combination of sedimentation and denitrification in the HRP often removed more NO_3^- than the same processes in the South RP despite its much greater algae sediment mass. This phenomenon can be applied in a full-scale system through special designs for the HRPs.

Ratios of Carbon Dioxide Added to Nitrogen Removed

In the carbon-limited algae cultures at the ABSR Facility, one would expect nitrate assimilation by the algae to increase with an increase in carbon dioxide sparged into the culture. The apparent lack of correlation between carbon dioxide addition to the HRPs and nitrate removal was probably due to the denitrification apparently occurring in the South HRP and by a lack of nitrate in the North HRP influent.

Denitrification Rates and Substrate Efficiencies

In the North RP, the nitrate removal rate and the substrate efficiencies rose when the hydraulic loading rate was increased. Presumably with ever higher hydraulic loadings a break through point exists where nitrate and selenium mass removal per volume of pond would decrease and the cost per mass of selenium removed increase. Future studies will explore higher hydraulic loadings in an attempt to find the break through point under summer and winter conditions.

The breakpoint between the rapid summer nitrate removal rates and the much lower winter rates appears to be about 20°C. Earlier studies (Brown, 1975) indicate that denitrification ceases near 17°C. Full-scale ABSR Facility might elevate pond temperatures and nitrate removal rates by capturing waste heat from on-site electrical generating equipment using methane captured from the anaerobic zones of the ponds. The onset of cold temperatures coincides with the period of reduced irrigation and drainage flows. In the case of sewage ponds with fermentation zones, there is some evidence of exothermic heating in dense sludges.

Laboratory Studies

The molasses substrate efficiency in laboratory shaking flask experiments averaged 0.22 kg N removed/kg molasses VS added, but the efficiency in the North RP ranged from 0.10 to 0.16 kg N removed/kg molasses VS. The result was the opposite for the algae substrate. The shaking flask tests showed efficiencies of 0.01 to 0.13 kg N removed/kg VS added, whereas the South RP removed between 0.09 to 0.21 kg N removed/kg VS added. The reduced molasses efficiency may be due to the agitation present in the laboratory but not the ponds. The increased efficiency of the algal substrate is likely the result of the essentially infinite residence time of the algae settled in the South RP. With years to degrade, more of the reducing potential of the algae may be exerted. Continuing laboratory studies are expected to indicate methods of improving substrate efficiency for nitrate and selenium removal.

5.4. SELENIUM REMOVAL

Selenium Reduction in the RPs

Clearly the addition of molasses to the North RP provided the reduced carbon needed to reduce DO, nitrate, and selenate. Prior to the molasses addition, algae addition to the RP and the algae's decomposition was not sufficient to reduce the DO brought into the system with the influent (7-10 mg/L) or produced by algae growth at the pond surface. Even after installation of the RP covers some algae photosynthesis occurred in the 30-cm to 90-cm peripheral gap between the cover and the berm of the pond.

A plateau of selenium reduction can clearly be seen (Figure 14). The increase in molasses dose from 0.59 g/L to 0.78 g/L on June 12, 1997 brought total soluble selenium levels from 100 μg/L down to 26 to 45 μg/L but never lower. Effluent selenate concentration was not affected by the increase in molasses application. The algae-fed South RP was able to achieve effluent concentrations as low as 20 μg/L selenate. The algae-fed Mendota ABSR pilot plant reached a total soluble selenium concentration of less than 10 μg/L but only after addition of 20 mg/L ferric chloride (Gerhardt and Oswald, 1990). Measures to remove the final 70 μg/L to 100 μg/L Se may not prove be cost effective on a mass removal basis, but we will continue strive for the lower selenium concentrations.

Further selenium reduction was seen in the HRP and ASP of the North System. This could have been caused by reduction in anoxic zones of these ponds or by uptake of the selenium by algae and bacteria. The selenium content of the algae sediment in the HRPs will be investigated further.

In further studies of molasses supplements on July 8, 1998 and November 4, 1998, the flow to the North RP was increased 64% and then an additional 20% without increase in the molasses dose. The increase of flow and the onset of cooler weather had little effect on the selenate reduction of the North RP. Higher flow rates will be evaluated in the future until selenium removals fall below 70%. Then the molasses dose will be increased to attempt to bring the selenium removal above 70%. In this way, both the sensitivity of selenium removal to hydraulic residence time and molasses dose should be determined with greater accuracy.

Selenate reduction in the South RP was poor until a sufficient mass of algae had accumulated in the RP by July 1997. However, this effect was short-lived. Cooler weather beginning in October 1997 corresponded to higher effluent selenium concentrations. Selenate concentrations remained high until the following August through October 1998. The water temperature at these transitions was near 20°C.

5.5. RATIOS OF NITRATE TO SELENATE

Laboratory experiments have shown that nitrate-N concentrations must fall to less than about 5 mg/L before significant selenium reduction occurs (Lundquist *et al.*, 1994). In the RPs, selenium reduction was greater when nitrate was removed to low levels, however, in the RPs some selenium was reduced in the presence of 10 to 20 mg/L nitrate-N. If the nitrate-N concentration was less than 6 mg/L to 8 mg/L, the selenate-Se removal by the RPs was consistently maintained above 1 g/d. A nitrate threshold of 5 mg/L is used as the target concentration in the scale-up design.

The apparent correlations of nitrate removal to selenate removal and nitrate concentration to selenium concentration suggest that the unmixed RPs have extensive zones, probably near the sediment on the slopes and floors, where nitrate is reduced to low levels and selenate reduction follows despite the presence of nitrate in the bulk RP water column. Despite the use of very different substrates in the North and South RPs, the ratio of nitrate mass removal to selenium mass removal in the RPs was close, 4.2 and 4.0, respectively. This similarity is evidence that the relationship between nitrate and selenium reduction is nearly constant regardless of organic substrate.

5.6. SELENIUM IN ABSR POND SEDIMENTS

Recalling that there are three cells in series in each RPs, preliminary results indicate that more selenium is reduced in the third cell of the South RP than the first. This could be due to the presence of DO and nitrate in the drainage water discharged to the first cell of the RPs. The presence of selenium in the South HRP sediment is not surprising since considerable selenium mass loss was seen in the HRP. The South HRP sediments, however, are only 25% to 50% as rich in selenium as the RP cell 3 concentrations. Analyses of North RP sediments have not been conducted yet due to the difficulty in obtaining samples of the minimal sediments.

5.7. ALGAE IDENTIFICATION

Algal identification helped monitor the effects of changing parameters such as nutrients, sunlight, and temperature on the biological community in the HRPs. The typical species of algae found in HRPs treating municipal wastewater are green algae belonging to genuses such as *Scenedesmus*, *Chlorella*, *Microactinium*, and *Pediastrum*. However, at the ABSR Facility many different types of algae were identified, including diatoms, green algae, and flagellates.

As might be expected since drainage water is low in organic matter, diatoms were the most numerous algae type over the course of the study. This may also be due to the salinity or TDS in the water being more favorable to diatoms. Soluble silica which is required for diatom frustule growth was abundant in the drainage water with concentrations near 39 mg/L.

5.8. PRELIMINARY COST ESTIMATES FOR A 10-AF/DAY ABSR FACILITY

Numerous selenium removal technologies have been successfully demonstrated on the pilot scale during the last 15 years, but estimated costs for full-scale treatment have generally been in the range of \$200 to \$400 per AF treated (\$160 to \$320 per 1000 m^3) and thus considered too expensive to implement. A detailed economic analysis conducted in 1988 indicated that ABSR facilities with capacities of 3, 30, and 300 acre-feet per day would have total costs of \$272, \$103, and \$68 per AF (or \$220, \$83, and \$55 per 1000 m^3), respectively (Gerhardt and Oswald, 1990).

A considerable amount of experience has been gained during the past decade with the ABSR process and the related AIWPS® Technology. For example, some unit processes and treatment steps in the 1988 cost study have been eliminated in the Panoche ABSR Facility. In order to update the ABSR cost estimates, construction and O&M cost information was acquired for the 2-year-old Delhi County Water District AIWPS® Facility located 50 miles (80 km) from the PDD. Ten years of bulk molasses price data for the Port of Stockton was also obtained (USDA, 1999; Figure 30). This information, in combination with nitrate and selenium removal relationships and substrate requirements developed at the Panoche ABSR Facility, were used to estimate costs for a 10-AF/d ABSR Facility located in the PDD. After analyzing PDD sump data, a 10-AF/d facility was selected since a facility with this capacity could treat the flow of the PDD sumps that produce the greatest selenium load.

These new cost estimates do not include any consideration of disposal of Se-laden solids. The quantity of solids and the disposal costs are not well enough known at this point.

Although they are continuously decomposing, residual algal-bacterial biomass will accumulate in the RPs. If the RPs are cleaned out frequently enough, perhaps once every two years, the solids will have a low enough selenium concentration to allow their reuse as a nitrogen-, phosphorus-, and selenium-rich fertilizer. The biomass might be desirable to alfalfa growers on the east side of the San Joaquin Valley where soils are selenium deficient. Alternatively, the RP sediments could be allowed to decompose to their minimum volume and then be disposed of in a hazardous waste land fill.

Design and cost estimates were prepared for both Mode 1 and Mode 2 operation (Table 14 and 15). These estimates are subject to large revisions resulting from the ongoing research at the ABSR Facility. The base cost for the Mode 1 system is \$180/AF (\$146/1000 m^3) or \$346/lb (\$755/kg) of Se removed. This cost assumes that carbon dioxide for algal growth will be available at no cost in the form of boiler exhaust gas from the DeFrancesco and Sons, Inc. food dehydration facility located in the PDD. The operational costs most likely to decrease with further research is the cost for iron fertilizer. The iron application rate at the Panoche ABSR Facility has yet to be optimized and the iron dose might be reduced considerably without significantly diminishing the treatment performance. With a 90% reduction in iron consumption, the Mode 1 cost decreases to \$122/AF (\$99/1000 m^3) or \$235/lb (\$517/kg) of Se removed

The Mode 2 facility base cost assumes that residual substrate in the RP effluent amounting to perhaps 30 to 40 mg/L BOD_5 (5-day biochemical oxygen demand) can be discharged to drainage channels within the PDD without causing harm to Mud Slough the eventual receiving water for the Grasslands Bypass drainers. Under this assumption, a Mode 2 facility would cost approximately \$151/AF (\$122/1000 m^3) or \$275/lb (\$605/kg) Se removed. HRPs and ASPs may be recommended to remove BOD and nutrients in the RP effluent and to produce algae substrate for nitrate and selenium reduction. In this case the Mode 2 facility would cost approximately \$180/AF (\$146/1000 m^3) or \$328/lb (\$722/kg) Se removed. The greatest potential for cost savings under Mode 2 operation is reduction in the cost of imported substrate and increased efficiency of substrate use. Assuming a 50% saving on imported substrate and no requirement for HRPs and ASPs, the cost estimate drops to \$126/AF (\$102/1000 m^3) or \$230/lb (\$506/kg) Se removed.

Experience with wastes from tomato canneries and wineries in advanced ponding systems is that added nutrients are often recycled internally, and new additions can be decreased over time. This phenomenon is beginning to appear now in the ABSR Facility and may be a significant savings in full-scale systems.

Costs for both modes of operation will be reduced if drainage water nitrate concentration and/or drainage water flow rates drop. Growers have some control over both of these parameters through nitrogen fertilizer and irrigation application rates. Combined cost analysis of crop production and drainage water treatment could optimize the overall expenditures for agricultural operations within the PDD and its neighboring water districts.

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Table 1. Oxidation-reduction potential[1] in drainage water when in equilibrium with various redox couples.[2]

Redox Couple	Equilibrium Oxidation-Reduction Potential[3], (mV)
O_2/H_2O^*	+750
NO_3^-/N_2^*	+670
SeO_4^{2-}/SeO_3^{2-}	+380
SeO_3^{2-}/Se^o	+180
SO_4^{2-}/S^o	-280
SO_4^{2-}/HS^-	-280
CO_2/CH_4^*	-290
CO_2/CH_3COO^-	-340
N_2/NH_4^+	-350

[1] Calculated from Gibbs free energy of formation data in Wagman *et al.*, 1982.

[2] Source: Gerhardt *et al.*, 1990.

[3] Equilibrium Eh referenced to the standard hydrogen electrode when the molar ratio of the indicated redox couple is unity, unless otherwise indicated. T = 298 K, pH = 8.

*Concentrations: O_2 = 0.21 atm, N_2 = 0.79 atm (concentrations in air); NO_3^- = 150 mg/L as N; CH_4 = 0.75 atm, CO_2 = 0.2 atm (concentration expected in pond biogas).

Table 2. Volume and surface area of ponds of the ABSR Facility at the PDD.

	Volume m^3 gallons	Surface Area m^2 sq. ft.
Reduction Ponds (10 ft deep)	758 200,000	435 4680
High Rate Ponds @ 8 in depth	90 23,700	471 5,070
High Rate Ponds @ 12 in depth	140 36,850	501 5,390
High Rate Ponds @ 16 in depth	193 50,830	532 5,720
Algae Settling Ponds (4.9 ft deep)	100 26,510	112 1210

Table 3. Operational Timeline.

1996	
July 12	All ponds full; Facility operation begins with both systems in Mode 2
December 19	Temporary cover installed on the South RP
1997	
February 20	Molasses feeding at 0.59 g/L to the North RP begins
March 4	Temporary cover installed on the North RP
June 9	Carbonation sump baffles installed
June 12	Molasses feeding to the North RP increases to 0.78 g/L
June 27	South system switched to Mode 1
September 22	Temporary RP covers removed
October 30	Both RPs divided into three cells with baffles
November 21	Permanent cover installed on South RP
1998	
February 17	Switched to DTPA-chelated iron supplement for Mode 1 HRP
July 8	Influent flow to North System increased to 6,650 gal/d
October 9	Permanent cover installed on North RP
November 4	Influent flow to North System increased to 7,950 gal/d

Table 4. Feed grade molasses constituent analysis (from Liquid Sugar, Inc.) with resulting mass of constituent added per liter of drainage water treated at molasses feed rate of 1.0 g/L.

Constituent	Per 100 g of molasses	Units	Per liter of water treated	Units
Water	21.3	g	0.213	g/L
Calories	297	kcal	2.97	kcal/L
Protein	0.26	g	2.6	mg/L
Ash	8.50	g	85	mg/L
Total Carbohydrates	74.2	g	0.742	g/L
Total Fat	0.09	g	0.90	mg/L
Sodium	216	mg	2.16	mg/L
Calcium	64	mg	0.64	mg/L
Potassium	150	mg	1.50	mg/L
Copper	0.020	mg	0.20	µg/L
Iron	10.5	mg	0.105	mg/L
Magnesium	16.2	mg	0.162	mg/L
Phosphorus	4.7	mg	0.047	mg/L
Selenium	non detect	mg	non detect	mg/L
Zinc	0.050	mg	0.50	µg/L

Table 5. Nutrient application rates to the HRPs at the ABSR Facility.

Pond	Carbon Dioxide (g/d as C) (g/m^2/d as C)	Ammonia (g/d as N) (g/m^2/d as N)	Phosphorus (g/d as P) (g/m^2/d as P)	Chelated Iron (g/d as Fe) (g/m^2/d as Fe)
N. HRP	388 0.77 February 21, 1997 to August 10, 1998	none January 1, 1997 to July 19, 1997	33 0.066 January 1, 1997 to October 20, 1997	none January 1, 1997 to December 31, 1998
N. HRP	576 [1] 1.2 August 11, 1998 to November 16, 1998	125 0.25 July 20, 1997 to September 15, 1998	181 0.36 October 21, 1997 to December 31, 1998	NA
N. HRP	386 [2] 0.77 November 17, 1998 to December 31, 1998	250 0.50 September 16, 1998 to December 31, 1998	NA	NA
S. HRP	370 0.74 February 21, 1997 to June 30, 1998	none January 1, 1997 to December 31, 1998	34 0.068 January 1, 1997 to November 20, 1997	12 0.024 February 17, 1998 to December 31, 1998
S. HRP	NA	NA	115 0.23 November 21, 1997 to June 8, 1998	NA
S. HRP	856 1.7 July 1, 1998 to December 31, 1998	NA	184 0.37 June 9, 1998 to December 31, 1998	NA

[1] 190 g/d gas CO_2-C + 386 g/d urea CO_2-C

[2] 386 g/d urea CO_2-C

Table 6. Water quality analytical methods used for ABSR Facility samples. Methods taken from APHA (1995).

Parameter	Method of Analysis	Equipment Required
	Major Organics	
Total & volatile suspended solids, and total dissolved solids	Filtration, oven drying, and ashing (Methods 2540-B, 2540-E, 2540-C, and 2540-F)	105°C and 180°C ovens, 550°C furnace, filter apparatus, vacuum pump, analytical balance, hood
Total and soluble biochemical oxygen demand	Incubation at 20°C for five days with checks using glucose-glutamic acid (Method 5210-B)	Orion dissolved oxygen probe, 20°C incubator, aerator, filter apparatus, vacuum pump
	Nutrients	
Total Kjeldahl and ammonia nitrogen	Distillation with titrimetric finish (Methods 4500-N-N_{org}-B and 4500-NH_3-C)	12-flask digestion and distillation unit, pH probe
Ammonia nitrogen	Ion selective electrode (Method 4500-NH_3)	Electrode, meter, mixer
Nitrate-nitrogen with microplate reader	Polyscience NAS Szechrome reagent	Dynatech MRX microplate reader
Nitrite	Colorimetry (Method 4500-NO_2^--B)	Dynatech MRX microplate reader
Total phosphorus and soluble reactive phosphorus	Sulfuric acid-nitric acid or persulfate digestion or 0.45 μm filtration for SRP (Method 4500-P-B) followed by ascorbic acid colorimetry with spectrophotometer (Method 4500-P-E) or vanadomolybdophosphoric acid colorimetry with microplate reader (Method 4500-P-C)	Hot plates, hood, macro-Kjeldahl units, Milton Roy spectrophotometer, Dynatech MRX microplate reader
Dissolved carbon dioxide	Titration (Methods 4500-CO_2-C and -D)	Potentiometer
	Minerals and Metals	

Parameter	Method of Analysis	Equipment Required
Selenate, selenite, arsenate, and arsenite	Continuous hydride generation/atomic absorption spectrometry (Method 3114-C)	Atomic absorption spectrometer with hydride generator, hot plates, hood
Hardness	EDTA titration (Method 2340-C)	sublit magnetic stirrer
Alkalinity	Acid titration (Method 2320-B)	pH meter, magnetic stirrer
Conductivity	Method 2510-B	Conductivity cell
	Biological Components	
Soluble protein	BioRad kit	Spectrophotometer or microplate reader
Chlorophyll	Methanol extraction (Method 10200)	Spectrophotometer
Bioassays on algal growth, denitrification, selenium reduction, methane production, etc.	Various methods	Chemostats, heated shaker bath, light boxes, anaerobic glove box, hood
Microorganism identification and enumeration	Microscopic examination	Phase contrast optical microscope, camera adapters, haemocytometer
	Other Parameters	
Hydrogen ion concentration (pH)	Potentiometry (Method 4500-H^{+}-B)	Fisher Accumet 925 potentiometer, gel-filled glass electrodes with internal reference
Turbidity	Light dispersion (Method 2130-B)	Nephelometer
Oxidation-reduction potential	Platinum electrode potential (adaptation of Method 2580-B)	Millivolt meter, electrodes
Dissolved oxygen	Membrane potential and iodometric method (Methods 4500-O-G and -B)	Oxygen electrode, potentiometer

Table 7a. Summary of quality control results for standards, April-December 1998

	Se IV			Total Se		
Total	n	Mean (%)	S.D.	n	Mean (%)	S.D.
12	10	99.1	5.9	11	100.5	6.0

Table 7b. Summary of quality control results for blanks, April-December 1998

	Se IV			Total Se		
Total	n	Mean (%)	S.D.	n	Mean (%)	S.D.
4	4	0.08	0.03	4	0.17	0.11

Table 7c. Summary of quality control results for splits, April-December 1998

	Se IV			Total Se		
Total	n	Mean (%)	S.D.	n	Mean (%)	S.D.
16	16	100.7	2.7	16	99.1	2.3

Table 7d. Summary of quality control results for spikes, April-December 1998

	Se IV			Total Se		
Total	n	Mean (%)	S.D.	n	Mean (%)	S.D.
32	28	98.2	5.0	28	99.7	5.1

Table 8. Influent drainage water quality at the Panoche ABSR Facility. December 4, 1998 sample; all values in mg/L.

SO_4 as sulfate	1,974
Na	1,380
Ca	556
Mg	237
Cl	174
Total Si	43
Soluble Si	39
B	17.8
Soluble K	8.01
V	0.8
Se	0.252
Fe	0.19
Zn	0.04
Mn	0.03
Mo	0.03
Cu	0.02
Ni	<0.1
Co	<0.1
As	<0.02

Table 9. Effect of substrate type on nitrate removal efficiency.

Substrate		Substrate Efficiency g NO_3^--N removed per g substrate VS
Algae from ABSR HRP		
	No treatment	0.11*
	Steam treatment	0.11*
Algae from Richmond HRP		
	Steam treatment	0.13
Algae from Richmond ASP		
	No treatment	0.01
	Heating to 60°C	0.01
	Heating to 90°C	0.02
	Steam treatment	0.04*
Molasses		0.22

* Minimum substrate efficiency; nitrate concentration was reduced below detection limit.

Table 10. Nitrogen removal by the North Reduction Pond.

Period	Conditions	Days in Period	Effluent Temperature (°C)	Areal Removal ($g/m^2/d$)	Volumetric Removal (mg/L/d)	Molasses Feed Rate		Substrate Efficiency (kg N removed/ kg molasses)	Nitrate Removal
						(g/L water)	(g/g NO_3^--N introduced)		
Mar. 4, 1997 to Dec. 29, 1998	Mean HRT 45 days	665	20.3	2.8	1.6	0.59	8.50	0.10	94%
Mar. 4, 1997 to Sep. 22, 1997	Covered 63-day HRT	202	23.9	2.2	1.3	0.67	7.99	0.12	95%
Sep. 23, 1997 to Jul. 7, 1998	Uncovered 53-day HRT	289	17.2	2.3	1.3	0.74	9.18	0.10	88%
Jul. 8, 1998 to Oct. 9, 1998	Uncovered 31-day HRT	93	26.1	4.3	2.5	0.59	7.77	0.13	>99%
Oct. 10, 1998 to Nov. 4, 1998	Covered 30-day HRT	26	18.9	3.8	2.2	0.41	6.20	0.16	>99%
Nov. 5, 1998 to Dec. 29, 1998	Covered 25-day HRT	55	11.9	4.5	2.6	0.51	7.64	0.13	96%

Table 11. Nitrogen removal by the South Reduction Pond.

Period	Conditions	Days in Period	Effluent Temperature (°C)	Areal Removal ($g/m^2/d$)	Volumetric Removal (mg/L/d)	Algal VS Feed Rate		Substrate Efficiency (kg N removed/ kg algal VS)		Nitrate Removal
						"A" (g VS[1]/ g NO_3^--N introduced)	"B" (g VS[2]/ g NO_3^--N introduced)	"A"	"B"	
Aug. 9, 1996 to Dec. 16, 1998	Mean HRT 45 days	859	NA	0.73	0.42	1.54	1.54	0.24	NA	36%
Aug. 9, 1996 to Dec. 19, 1996	Uncovered Mode 2 45-day HRT	132	NA	0.85	0.49	1.27	1.27	0.21	0.21	27%
Dec. 20, 1996 to Jul. 25, 1997	Covered Mode 2[3] 59-day HRT	218	17	1.02	0.59	2.19	2.19	0.21	0.21	47%
Sep. 22, 1997 to Nov. 21, 1997	Uncovered Mode 1[4] 27-day HRT	60	16.2	1.15	0.66	1.03	1.79	0.28	0.16	29%
Nov. 22, 1997 to Dec. 16, 1998	Covered Mode 1 53-day HRT	389	18.6	0.40	0.23	1.52	3.21	0.20	0.09	30%

[1] g volatile solids imported from offsite for South RP.

[2] g volatile solids imported from offsite for South RP plus volatile solids produced in South HRP that flowed into South RP.

[3] Mode 2 ended on June 27, 1997, but data until July 25, 1997 is used here since the RP had a 1-month HRT.

[4] Baffle walls were installed in the RPs on October 30, 1997. Any effects caused by the baffle installation appear to be minimal compared with other conditions such as loading rates and season.

Table 12. Sediment selenium concentrations in the ABSR Facility at the PDD determined using AA (dry weight).

Sample	n	Concentration (µg Se/g TS)	Standard Dev. (µg Se/g TS)	S.D./Concentration (%)
November 24, 1998				
South RP cell 1	4	92	8.5	9
South RP cell 3	4	204	18.6	9
South HRP carbonation sump	4	41	3.6	9
South HRP east end	4	55	4.9	9
December 29, 1998				
South HRP east end	4	52	4.7	9
South RP cell 3	4	103	9.0	9
North ASP	4	71	7.1	10

Table 13. Dominant algal genera in the HRPs of the ABSR Facility at the PDD.

South HRP	
January to March 1997	green flagellate, *Euglena, Navicula*
April to July 1997	*Chaetoceros, Nitzschia, Navicula*
August to September 1997	*Chaetoceros, Nitzschia*, green flagellate, *Navicula*
October to November 1997	*Chaetoceros*
December 1997 to March 1998	centrale diatoms, *Scenedesmus, Nannochloris*
April to October 1998	*Chaetoceros*, centrale diatoms
November to December 1998	centrale diatoms, *Scenedesmus, Nannochloris*
North HRP	
January to March 1997	green flagellates, *Euglena, Chlorella, Tabellaria, Navicula*
April 1997	*Chaetoceros*, centrale diatoms, *Nitzschia*
May to July 1997	green flagellate, *Nitzschia*
August to September 1997	*Nitzschia, Nannochloris*
October 1997	centrale diatoms, *Micractinium*
November 1997 to February 1998	centrale diatoms, *Nannochloris*
March to December 1998	centrale diatoms, *Westella*

Table 14. Preliminary design and cost estimate for a Mode 1 ABSR Facility in the PDD treating 10 AF/day.

Contaminant Reductions			
Nitrate			
	Influent	85	mg/L as N
	Effluent	5	mg/L as N
Selenium			
	Influent	440	ug/L
	Effluent	117	ug/L
	Mass removal	1,900	lbs/year
High Rate Pond			
Depth		3	ft
Area		18	acres
Hydraulic residence time		6	days
Reduction Pond			
Depth		15	ft
Area		43	acres
Hydraulic residence time		65	days

Capital Costs		
Land @$2500/acre	$ 168,000	
Construction	$ 2,686,000	
Total Capital (7% over 20 years)	$ 69	per AF treated
O&M Costs		
Personnel @$50/hour	$ 5	per AF treated
Fertilizers & coagulant	$ 72	per AF treated
Electricity @$0.12/kWh	$ 4	per AF treated
Total	$ 81	per AF treated

Total Costs including 20% contingency

per AF	per lbs Se removed	
$ 180	$ 346	Mode 1 ABSR Facility
$ 122	$ 235	assumes fertilizer iron dose reduced by 90%

Note: Periodic reuse or disposal of solids not included. Disposal at Waste Management, Inc. landfill (Kettleman Hills) is estimated to cost $20 to $30 per AF.
Assumes carbon dioxide available in exhaust gas from the food dehydration facility located near the proposed site.

Table 15. Preliminary design and cost estimate for a Mode 2 ABSR Facility in the PDD treating 10 AF/day.

Contaminant Reductions			
Nitrate			
	Influent	85	mg/L as N
	Effluent	5	mg/L as N
Selenium			
	Influent	440	ug/L
	Effluent	104	ug/L
	Mass removal	2,000	lbs/year
Reduction Pond			
Depth		15	ft
Area		30	acres
Hydraulic residence time		45	days
High Rate Pond			
Depth		3	ft
Area		10	acres
Hydraulic residence time		3	days
Algae Settling Pond			
Depth		10	ft
Area		2	acres
Hydraulic residence time		2	days
Dissolved Air Flotation Unit			
Area		500	sq. ft.
Hydraulic residence time		5	minutes

Capital Costs RP and DAF only			
Land @$2,500/acre	$	83,000	
Construction	$	1,833,000	
Total Capital (7% over 20 years)	$	46	per AF treated
O&M Costs RP and DAF only			
Personnel @$50/hour	$	6	per AF treated
Substrate @$80 per ton & chemicals	$	66	per AF treated
Electricity @$0.12/kWh	$	7	per AF treated
Total O&M	$	79	per AF treated

Total Costs including 20% contingency

per AF	per lbs Se removed	
$ 151	$ 275	RP and DAF only; assumes residual organic substrate is permitted to be discharged to drains
$ 180	$ 328	HRPs and ASPs added for removal of residual organic substrate
$ 126	$ 230	assumes 50% reduction in molasses requirement and no HRPs and ASPs

Note: Periodic reuse or disposal of solids not included. Disposal at Waste Management, Inc. landfill (Kettleman Hills) is estimated to cost $10 to $18 per AF.

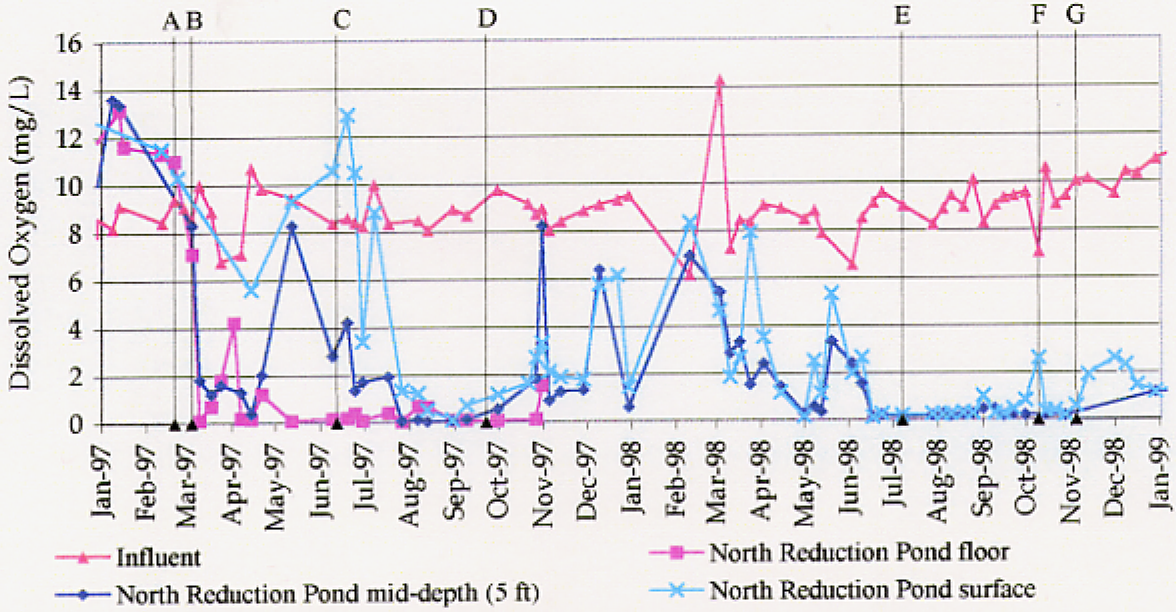

Figure 4. Dissolved oxygen concentrations in the North Reduction Pond of the ABSR Facility at the PPD. A) start molasses at 0.59 g/L; B) temporary cover installed; C) molasses increased to 0.78 g/L; D) cover removed; E) influent increased to 6,650 gal/d; F) permanent cover installed; G) influent increased to 7,950 gal/d.

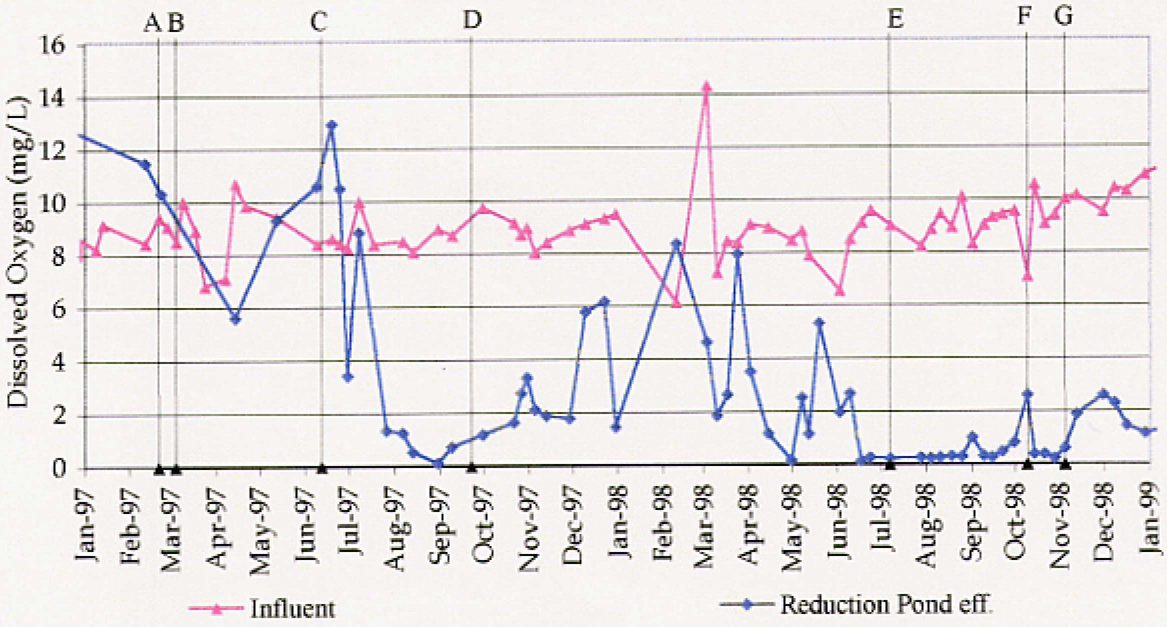

Figure 5. Dissolved oxygen concentrations in the North RP at the PDD. A) start molasses at 0.59 g/L; B) temporary cover installed; C) molasses increased to 0.78 g/L; D) cover removed; E) influent increased to 6,650 gal/d; F) permanent cover installed; G) influent increased to 7,950 gal/d.

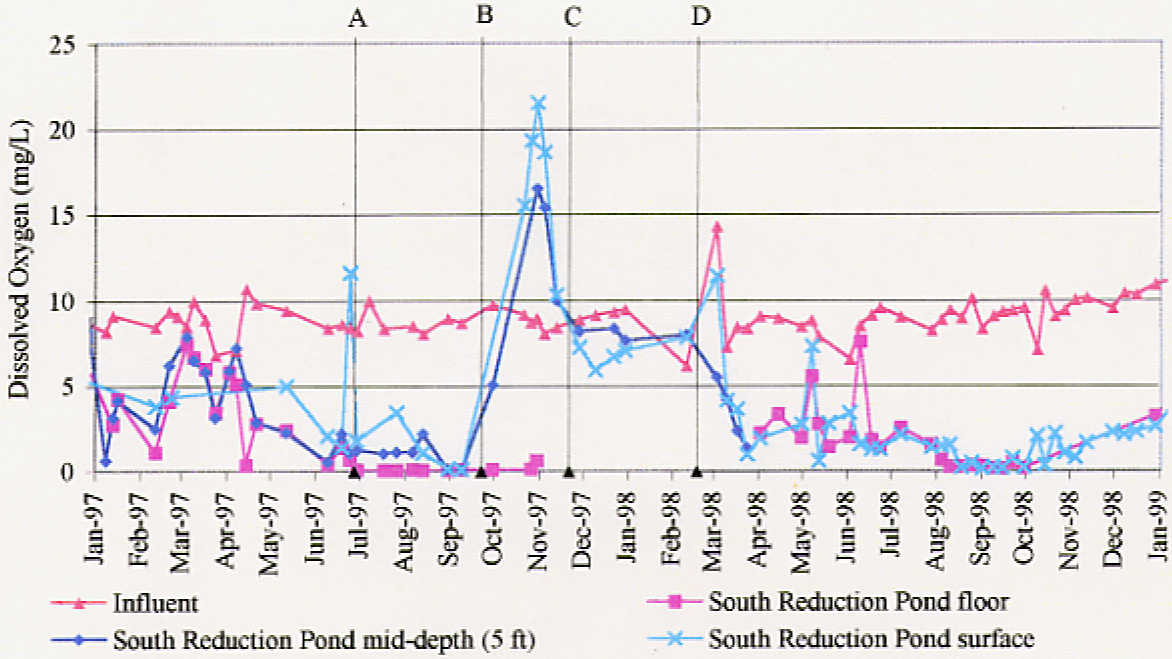

Figure 6. Dissolved oxygen concentrations in the South Reduction Pond of the ABSR Facility at the PDD. A) switched to Mode 1; B) temporary cover removed; C) permanent cover installed; D) started FeDTPA.

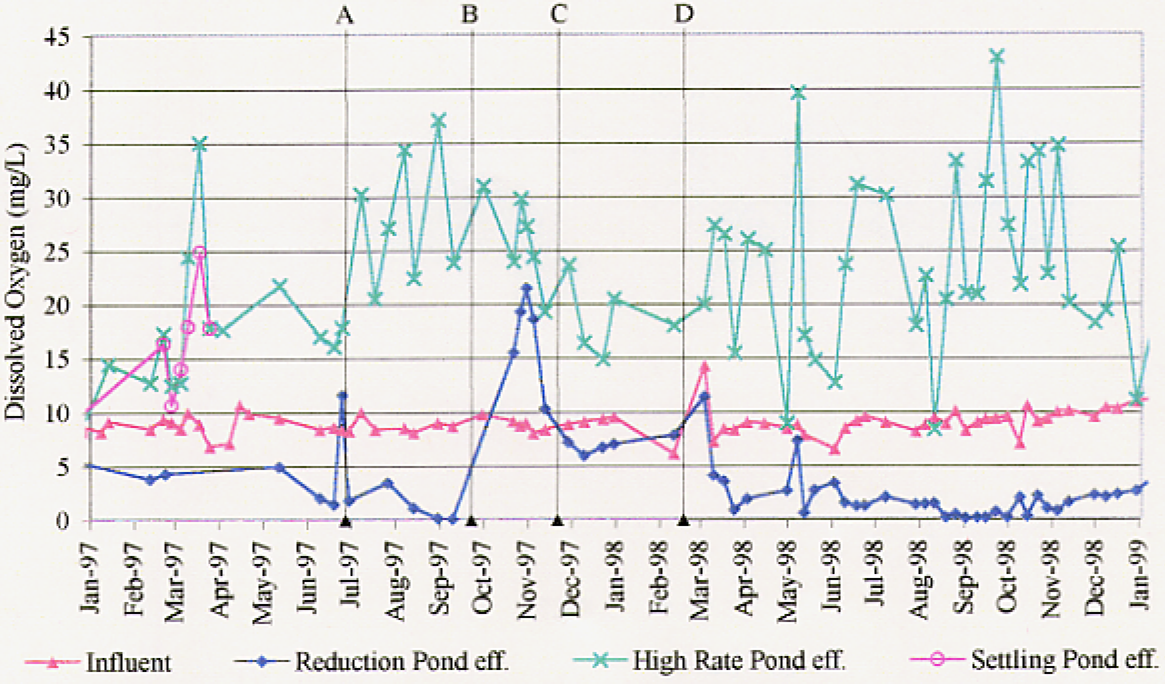

Figure 7. Dissolved oxygen concentrations in the South ABSR System at the PDD. A) switched to Mode 1; B) temporary cover removed; C) permanent cover installed; D) started FeDTPA.

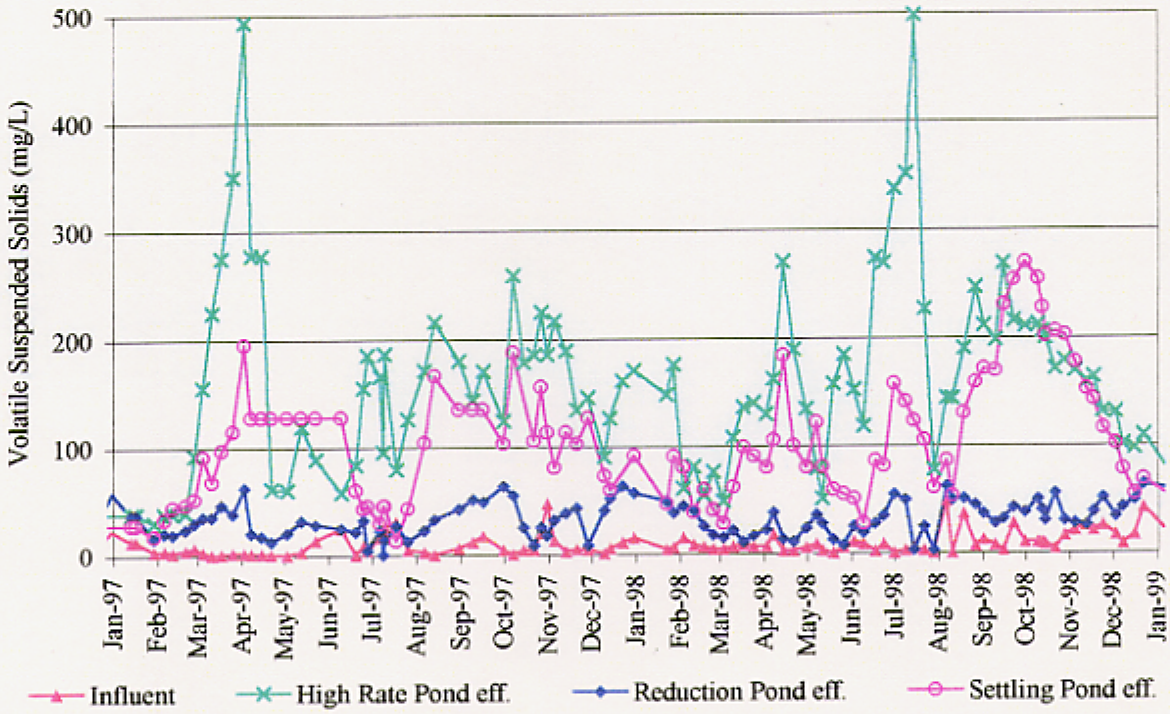

Figure 8. Volatile suspended solids concentration in the North ABSR System.

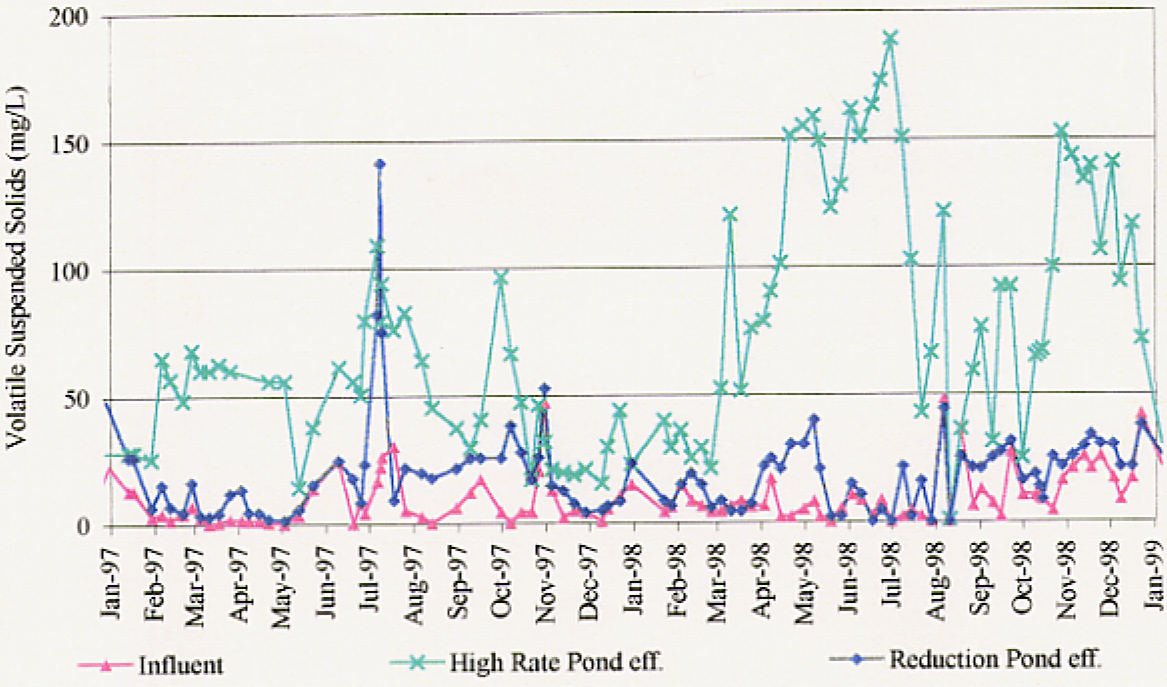

Figure 9. Volatile suspended solids concentration in the South ABSR System at the PDD.

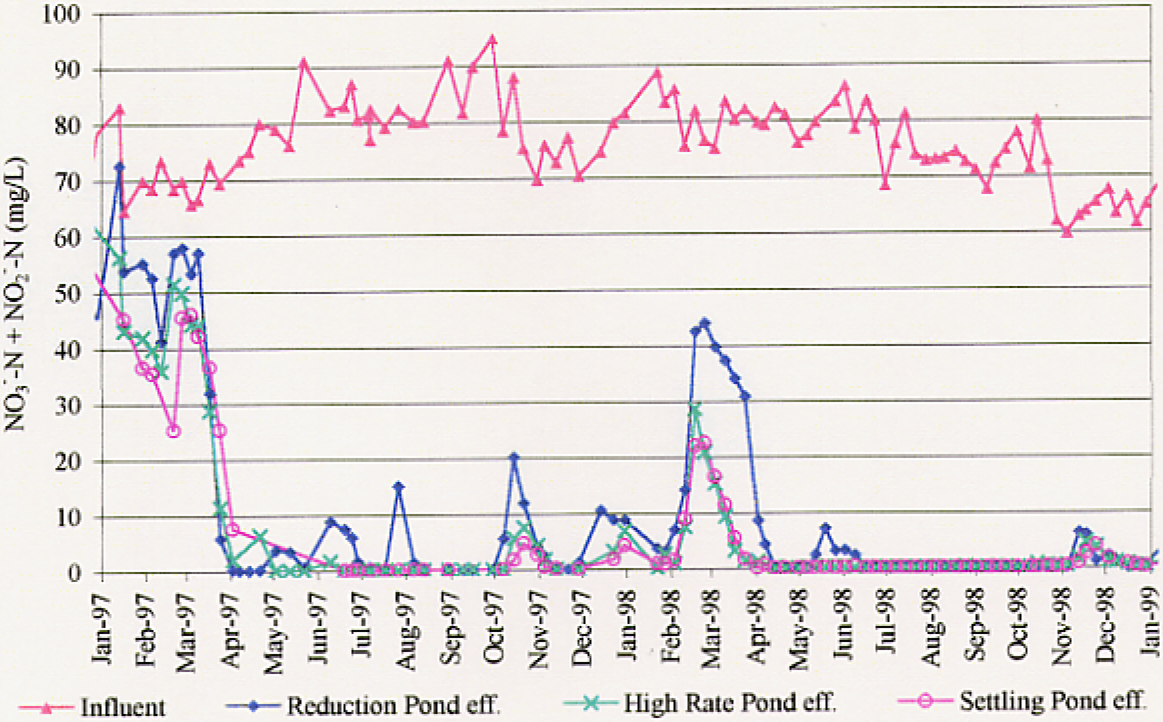

Figure 10 . Nitrate+nitrite concentrations in the North ABSR System at the PDD.

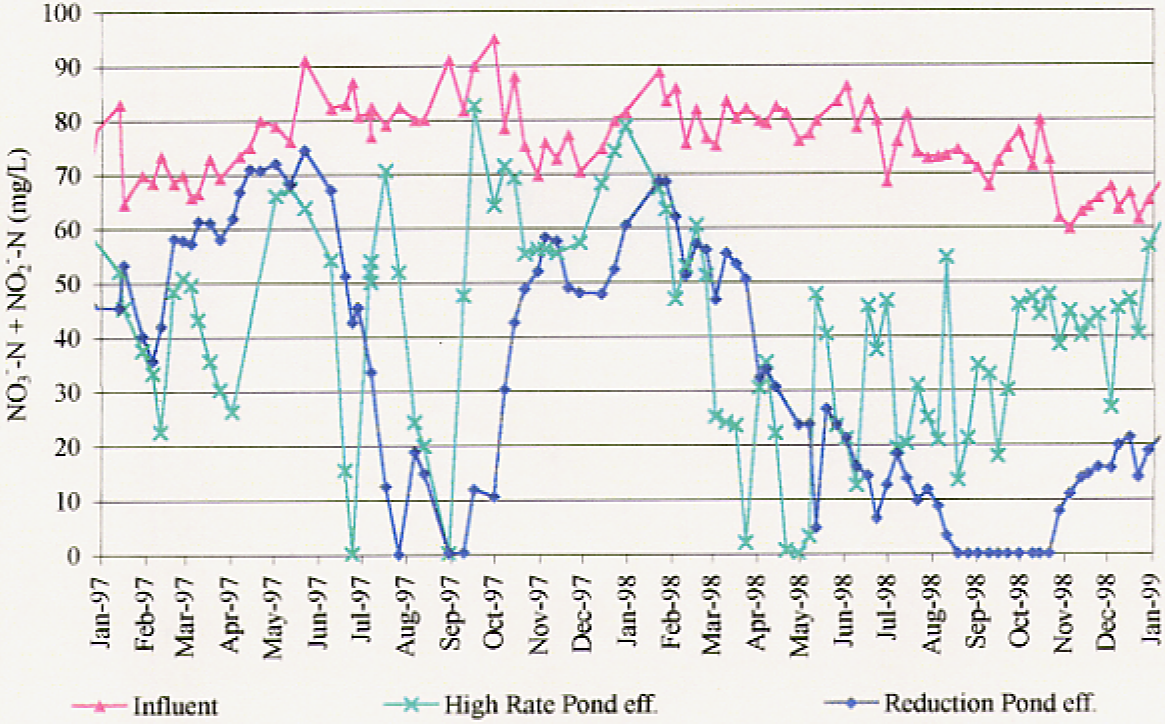

Figure 11. Nitrate+nitrite concentrations in the South ABSR System at the PDD.

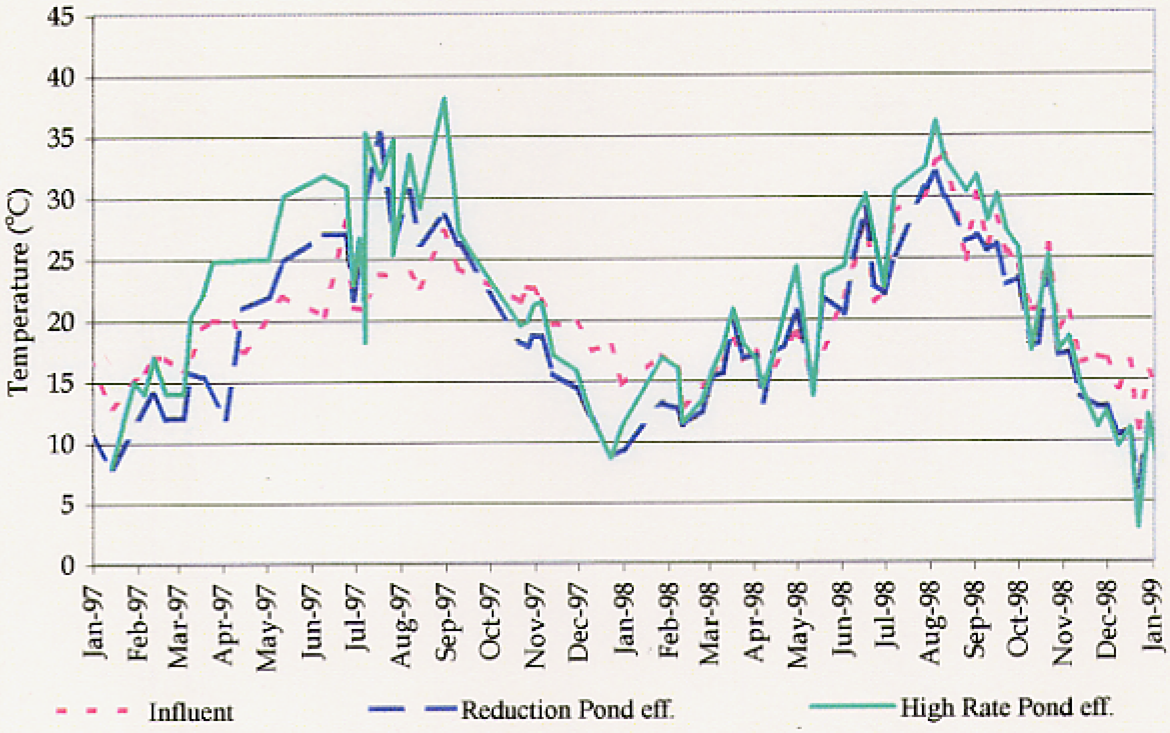

Figure 12. Temperature in the North ABSR System at the PDD.

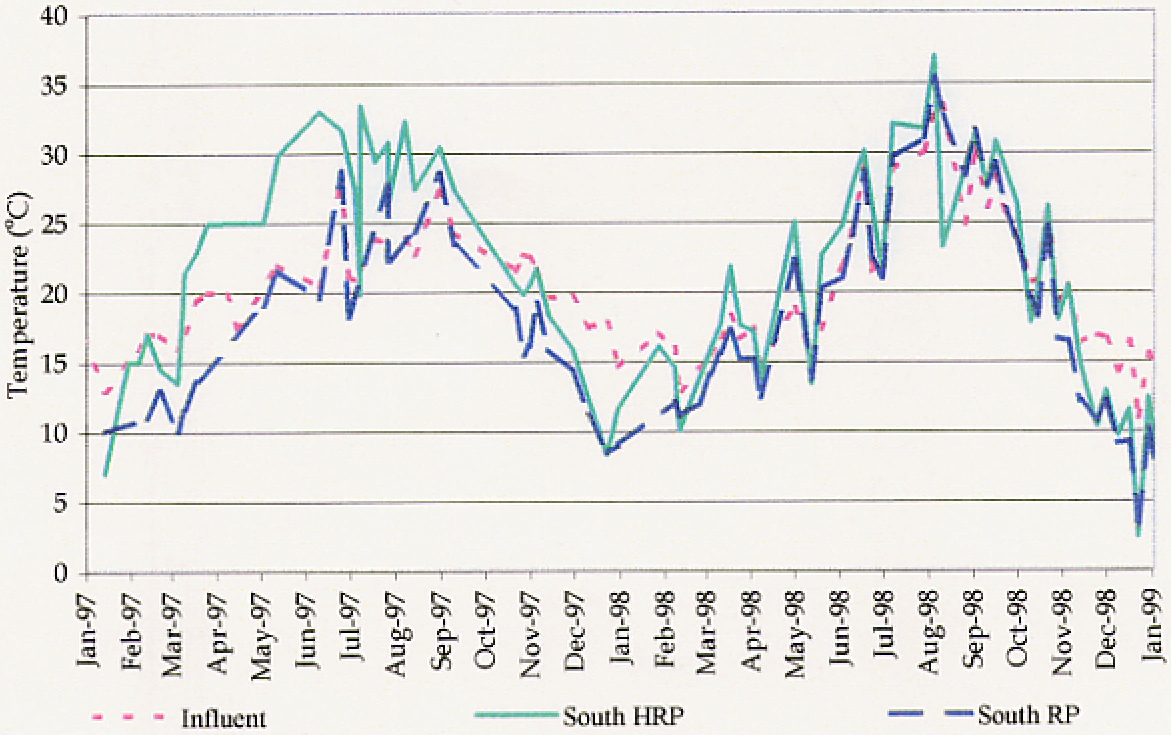

Figure 13. Temperatures in the South ABSR System at the PDD.

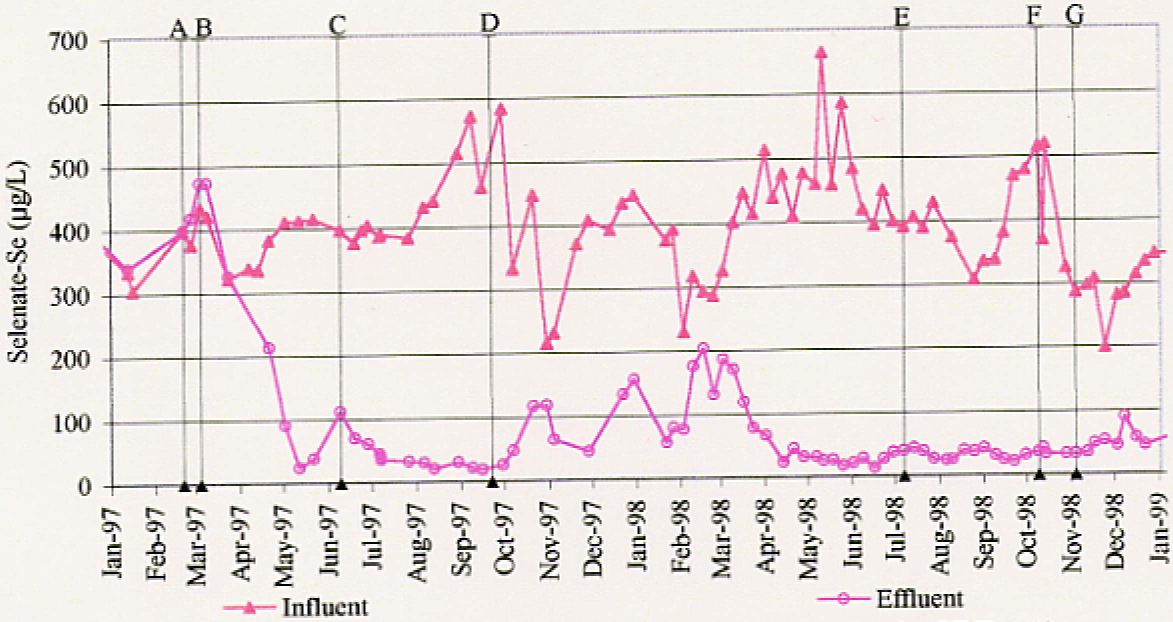

Figure 14. Selenate-Se concentration in the North ABSR System at the PDD. A) start molasses at 0.59 g/L; B) temporary cover installed; C) molasses increased to 0.78 g/L; D) cover removed; E) influent increased to 6,650 gal/d; F) permanent cover installed; G) influent increased to 7,950 gal/d.

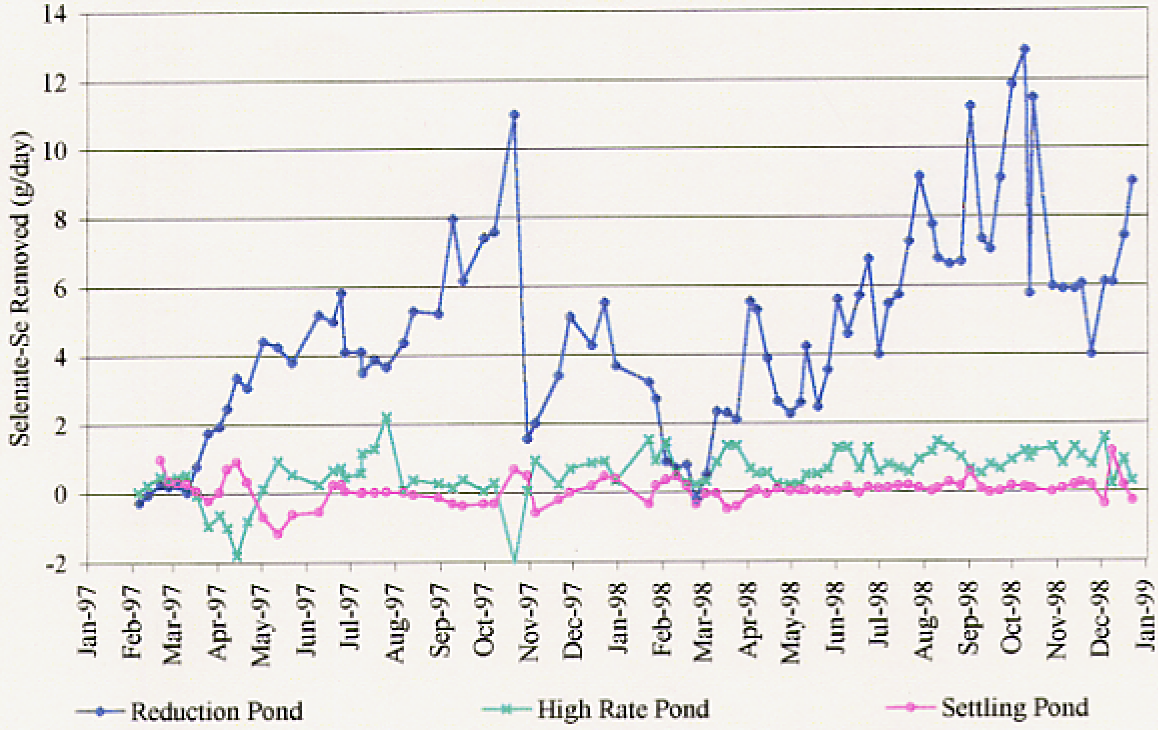

Figure 15. Selenate-Se mass removal in the North ABSR System at the PDD.

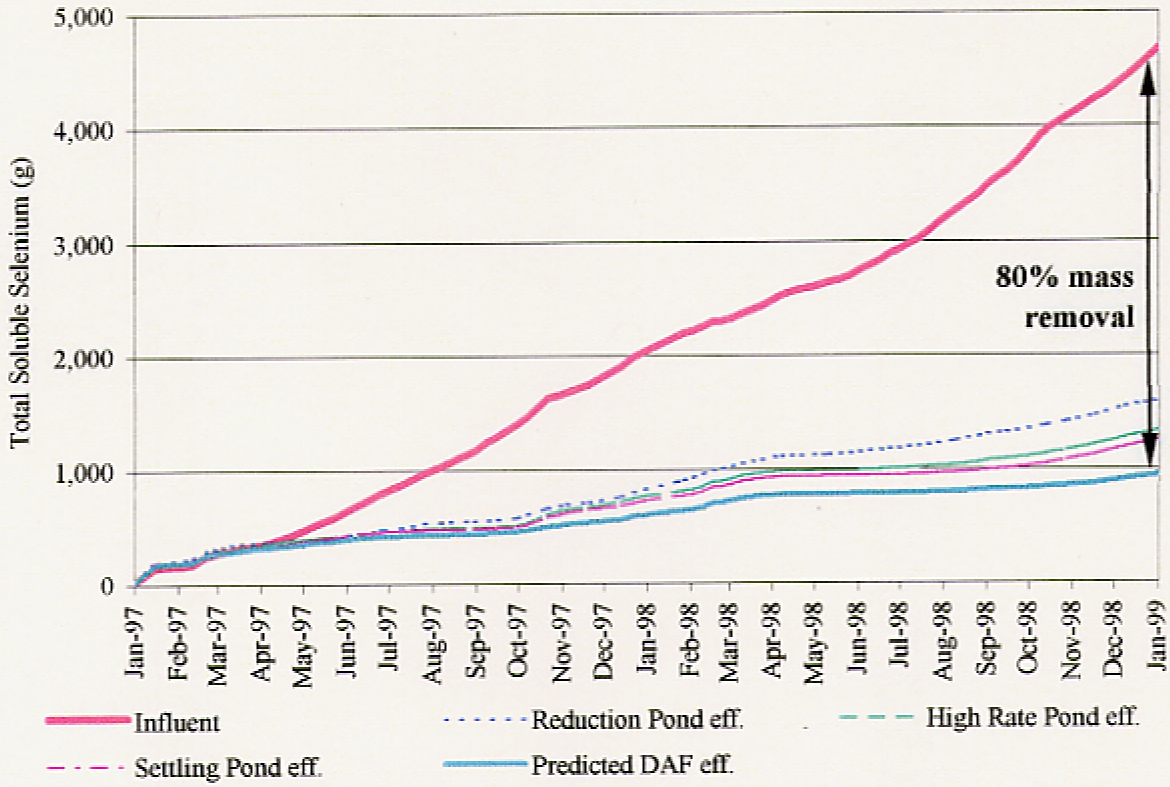

Figure 16. Cumulative total soluble selenium mass flow in the North ABSR System at the PDD.

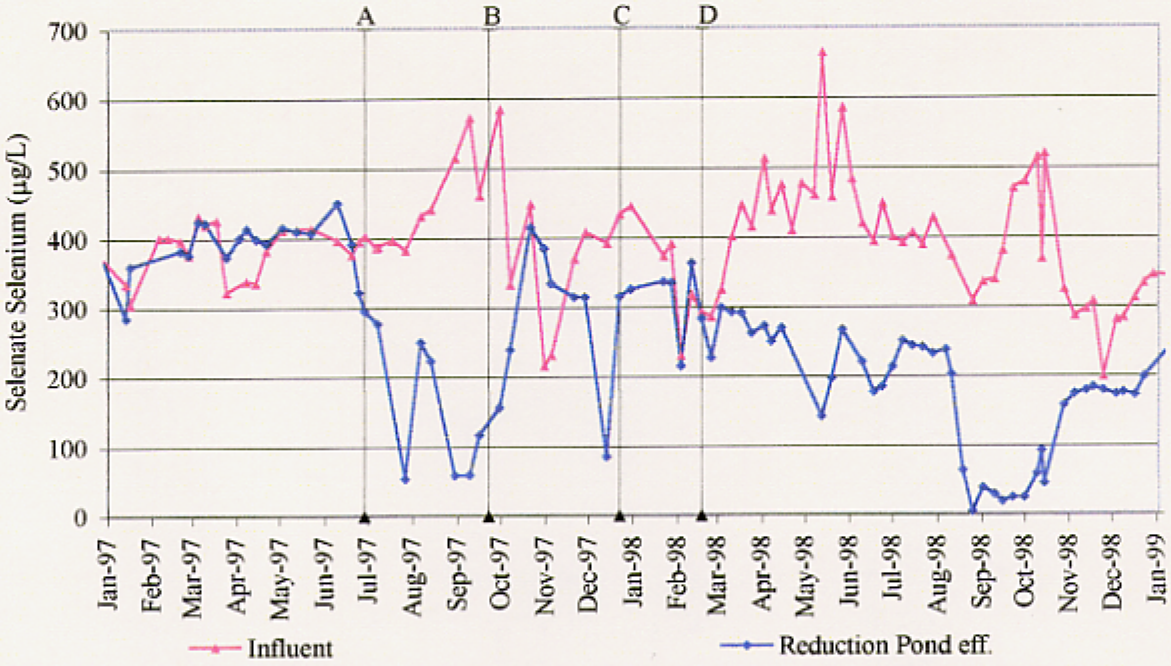

Figure 17. Selenate-Se concentration in the South ABSR System at the PDD. A) switched to Mode 1; B) temporary cover removed; C) permanent cover installed; D) started FeDTPA.

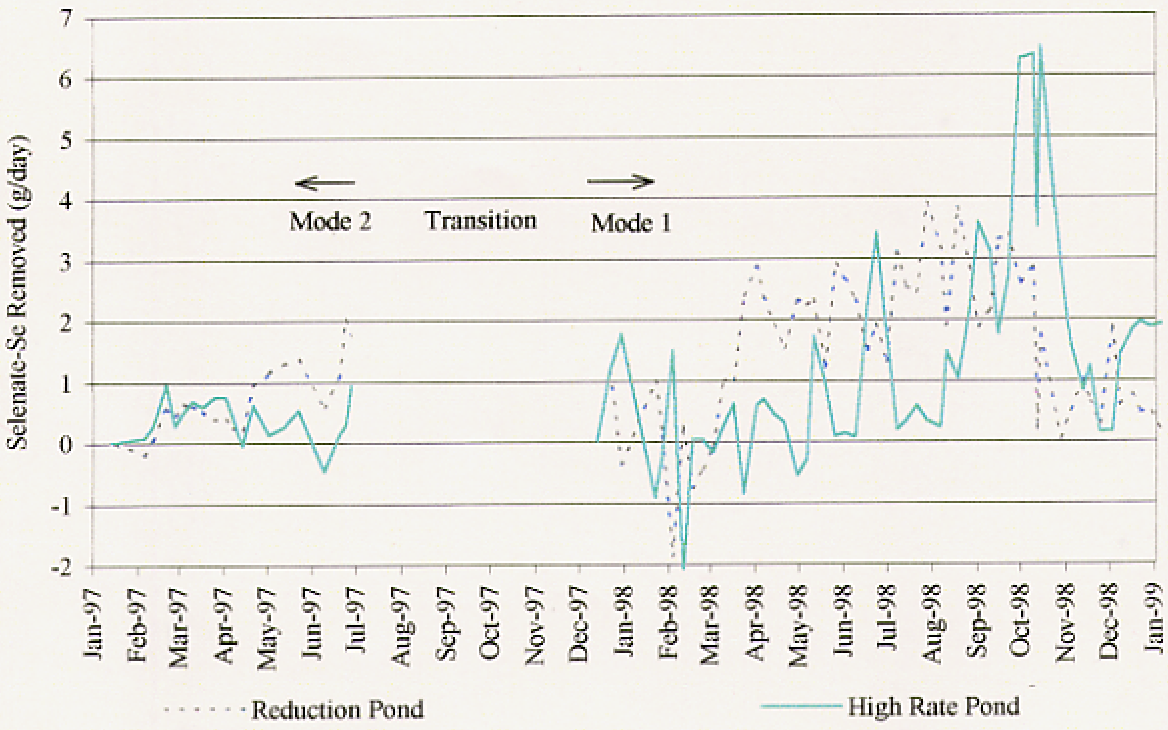

Figure 18. Selenate-Se mass removal in the South ABSR System at the PDD.

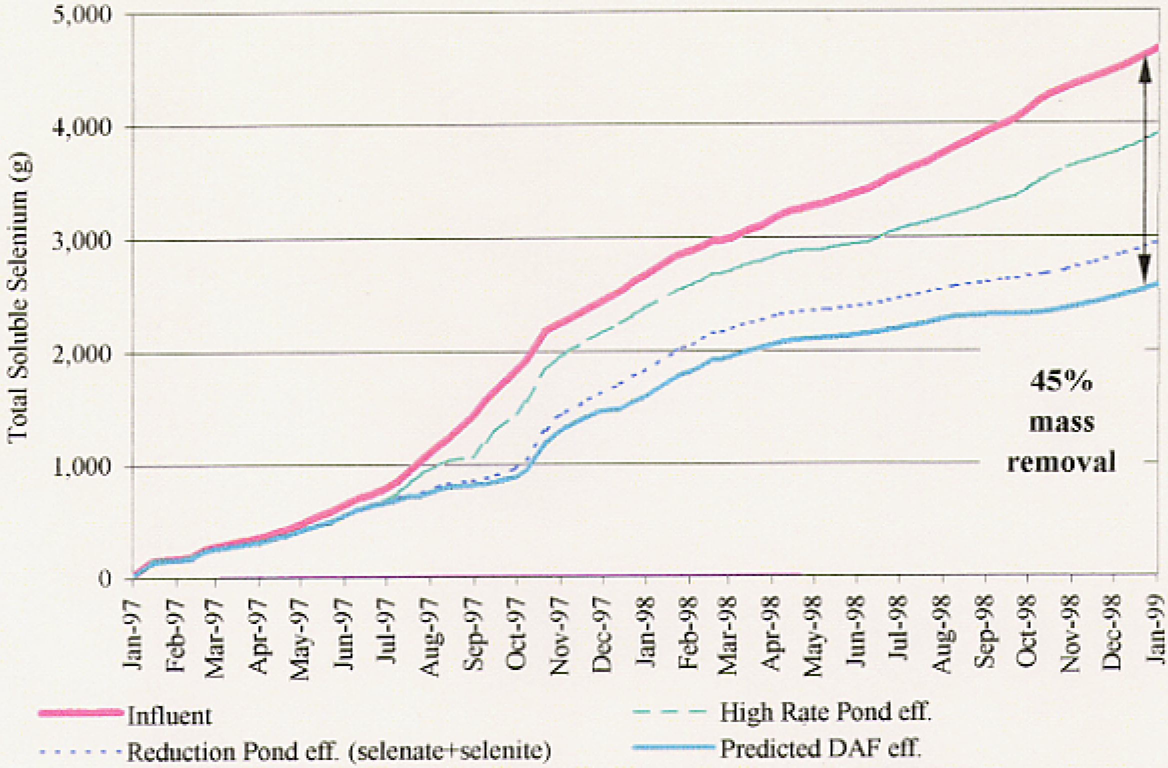

Figure 19. Cumulative total soluble selenium mass flow in the South ABSR System at PDD.

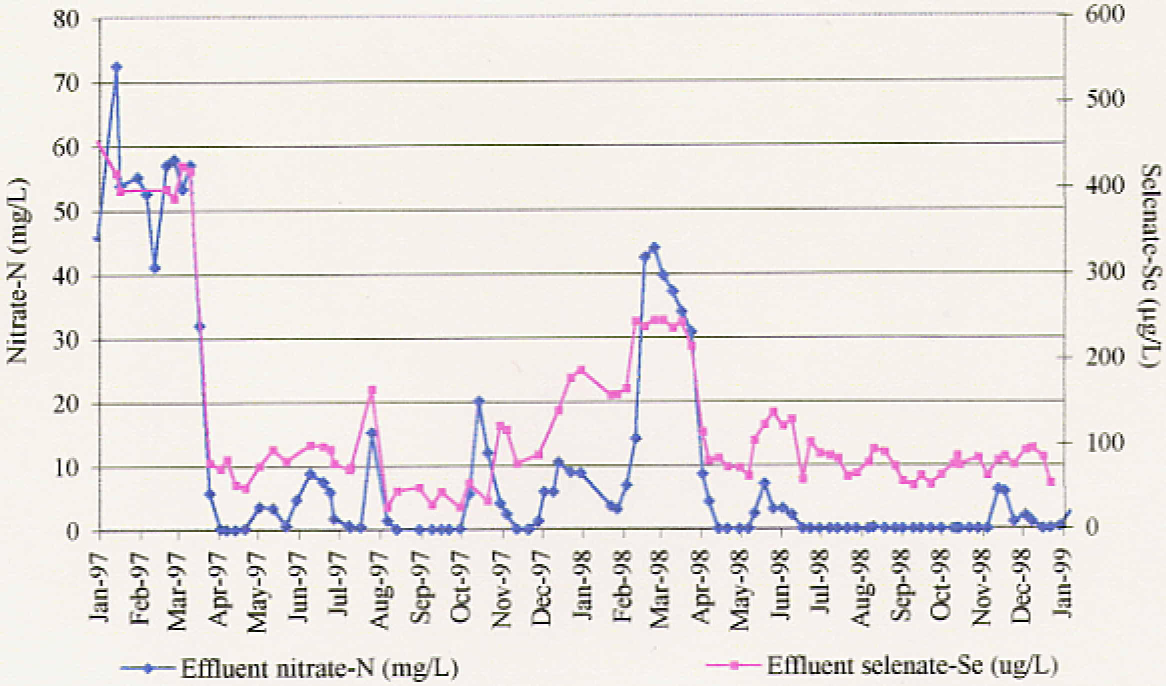

Figure 20. Comparison of residual nitrate and selenate in the North RP effluent of the ABSR Facility at the PDD.

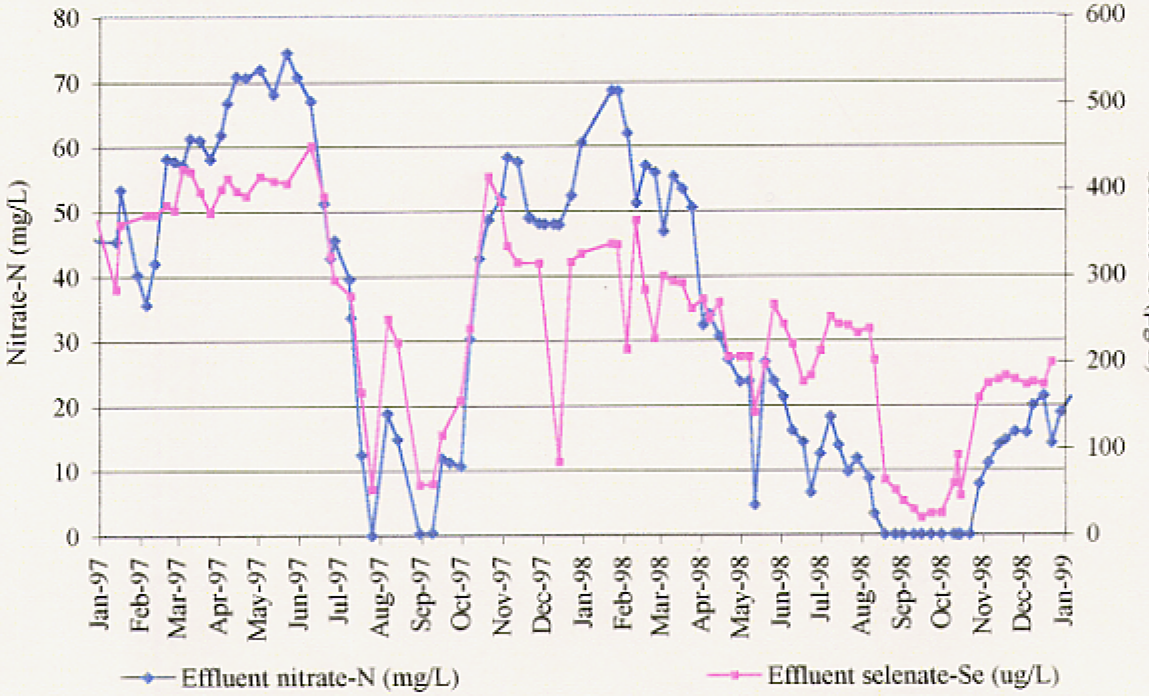

Figure 21. Comparison of residual nitrate and selenate in the South RP effluent of the ABSR Facility at the PDD.

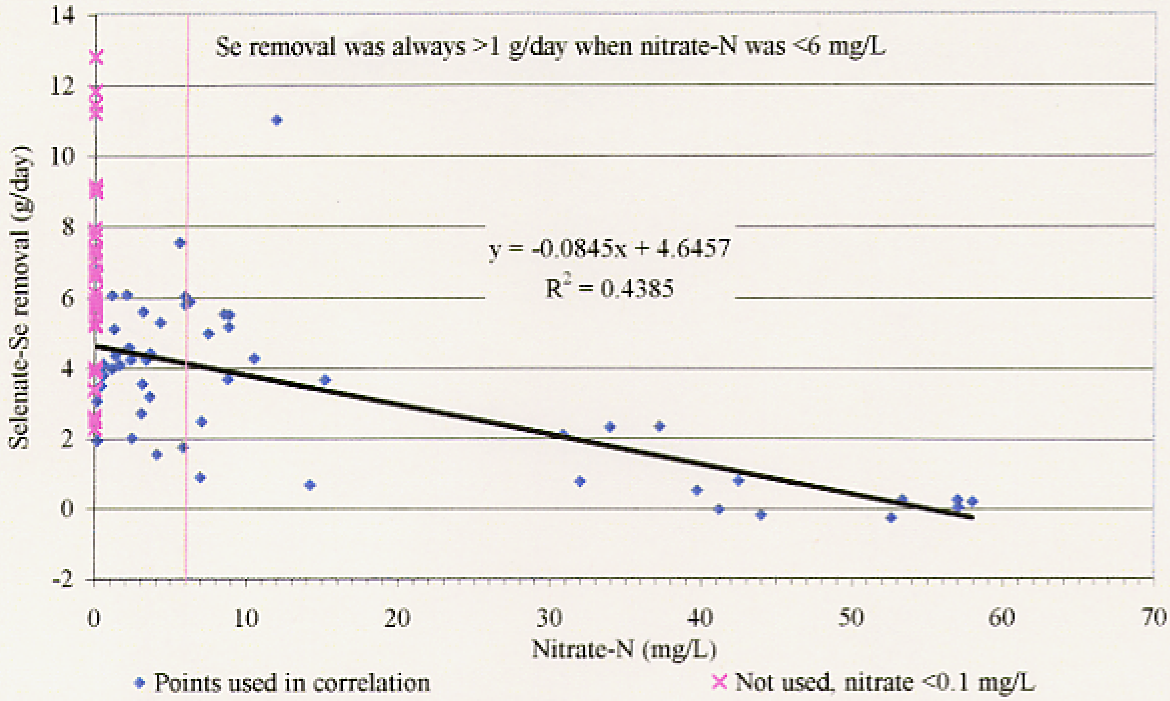

Figure 22. Correlation of effluent nitrate-N concentration to selenate-Se removal rate in the North RP effluent of the ABSR Facility at the PDD.

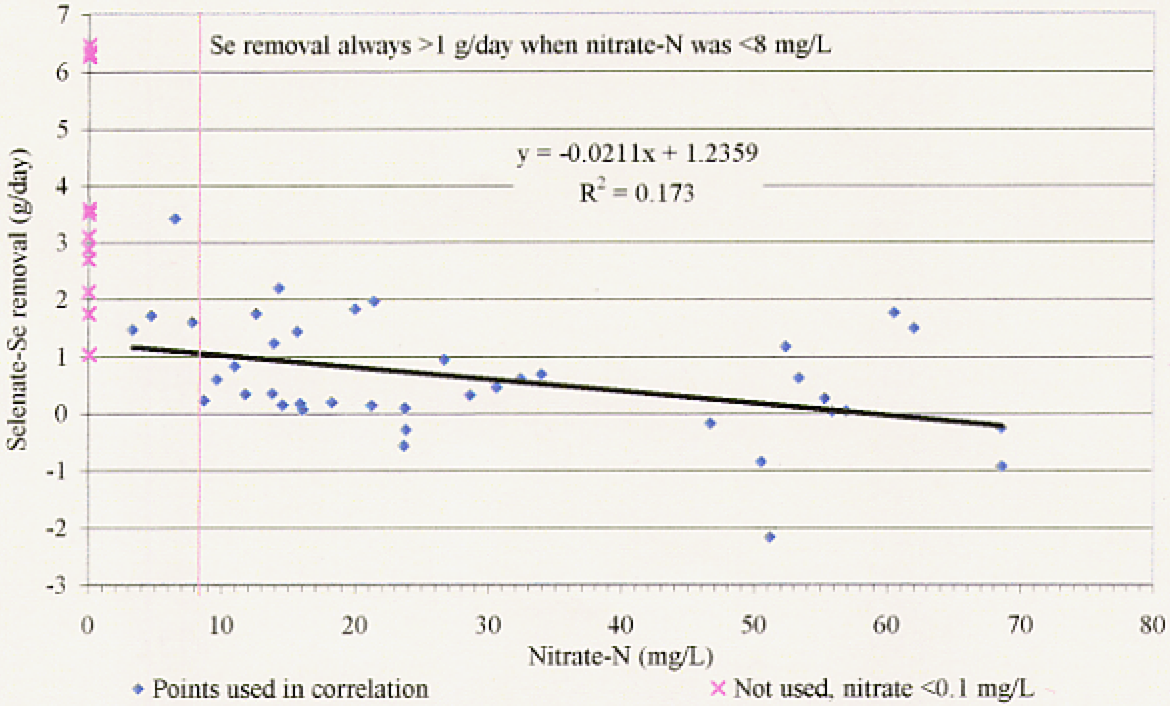

Figure 23. Correlation of effluent nitrate-N concentration to selenate-Se removal rate in the South RP effluent of the ABSR Facility at the PDD.

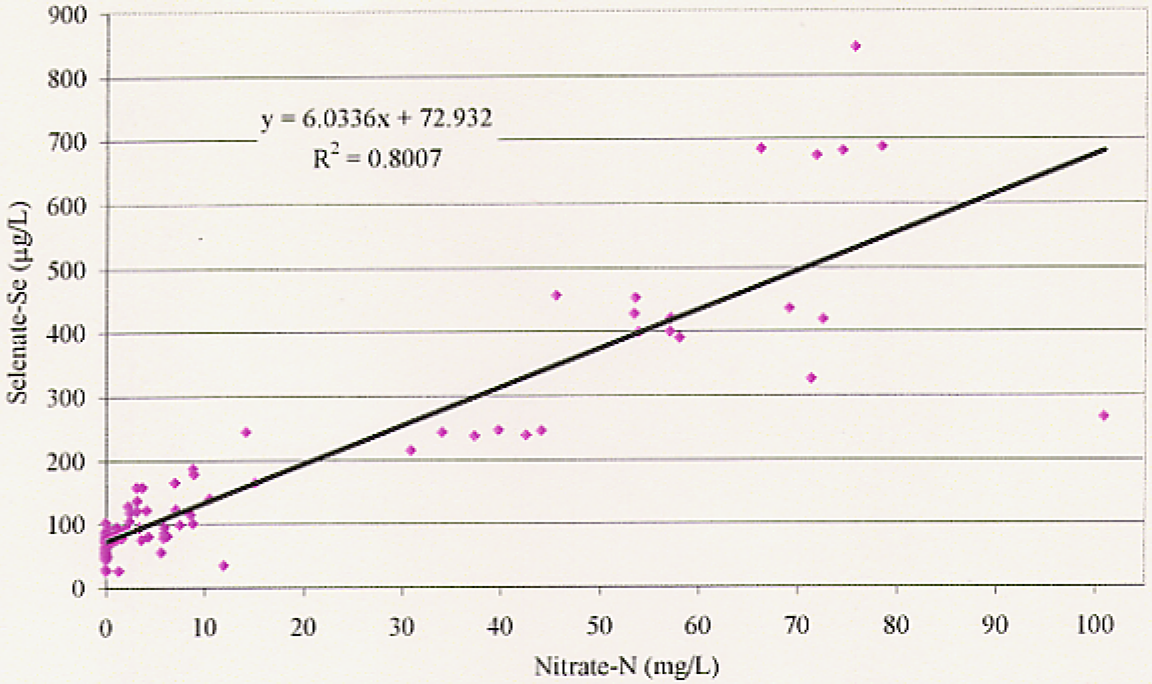

Figure 24. Correlation of nitrate-N to selenate-Se concentrations in the North RP effluent of the ABSR Facility at the PDD.

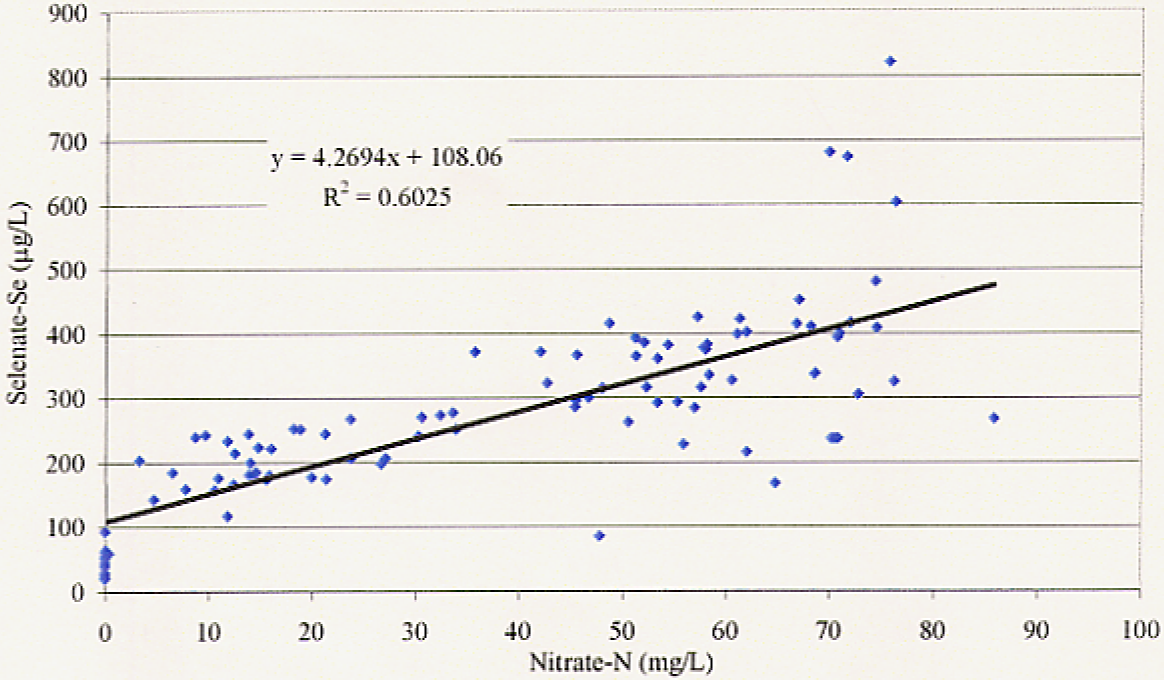

Figure 25. Correlation of nitrate-N to selenate-Se concentrations in the South RP effluent of the ABSR Facility at the PDD.

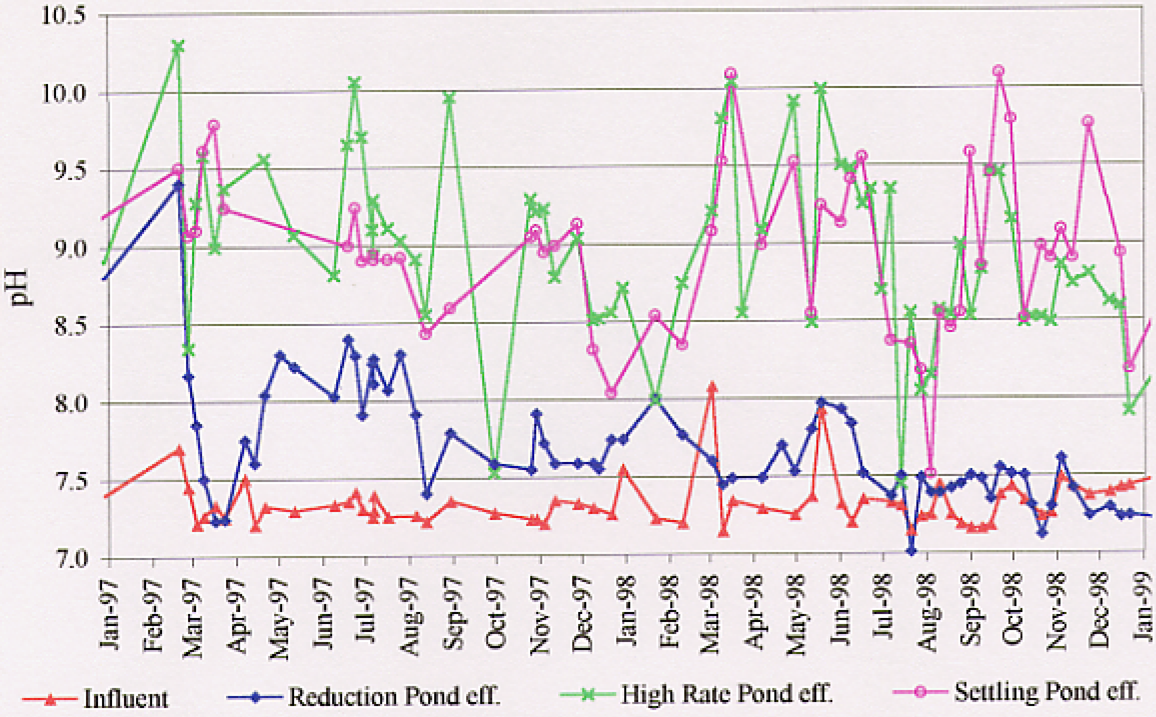

Figure 26. Levels of pH in the North ABSR System at the PDD.

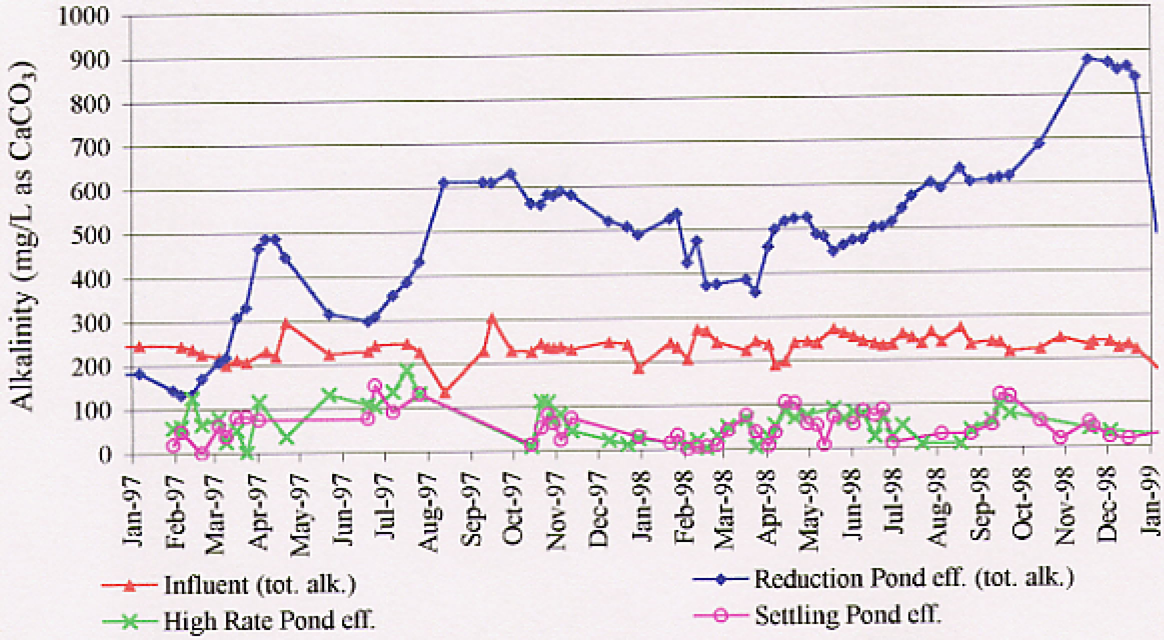

Figure 27. Phenolphthalein alkalinity concentrations in the North ABSR System at the PDD. No phenolphthalein alkalinity was present in the influent or the North RP effluent. Total alkalinity is shown for comparison.

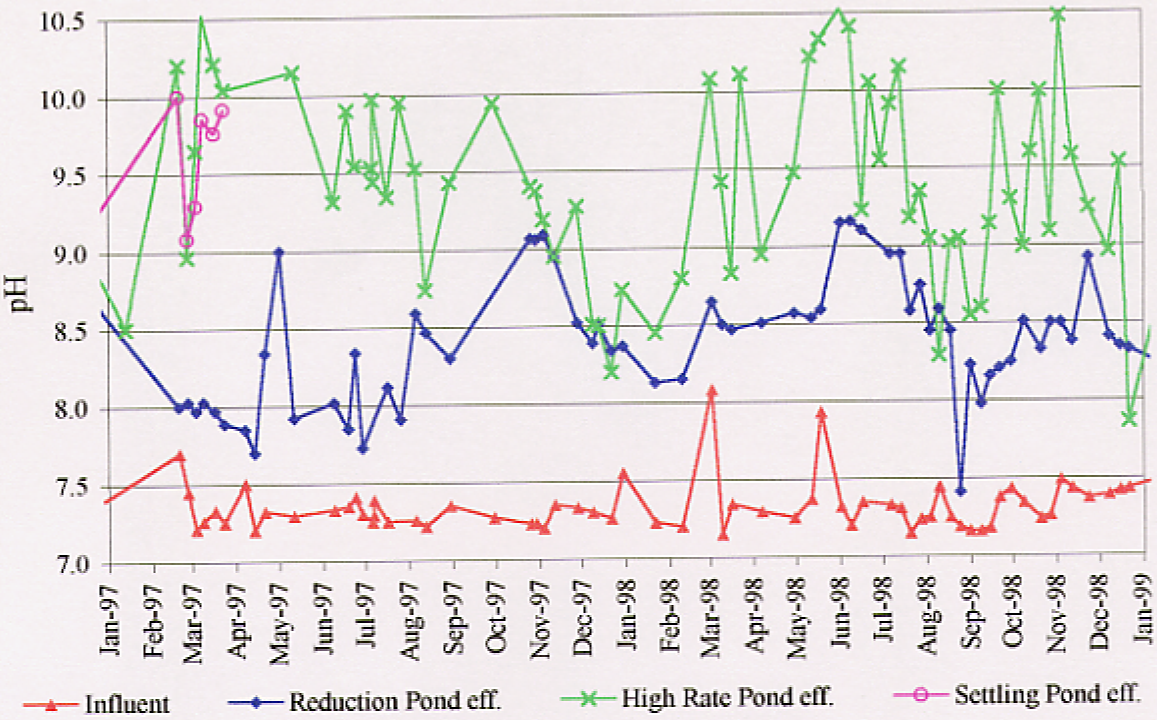

Figure 28. Levels of pH in the South ABSR System at the PDD.

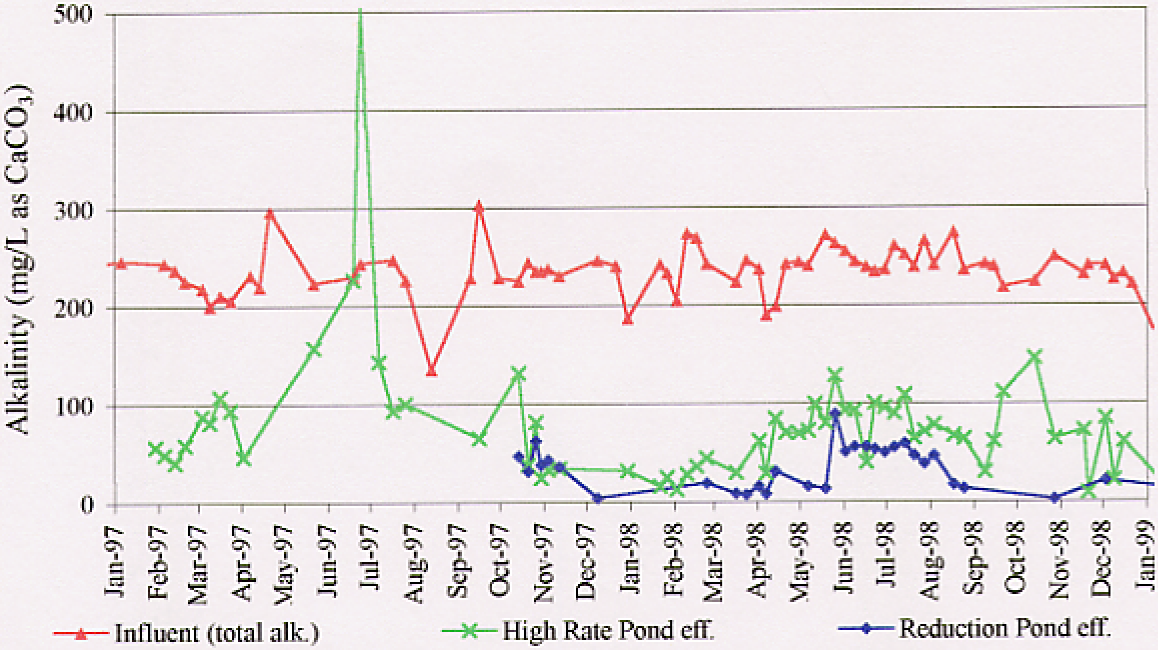

Figure 29. Phenolphthalein alkalinity concentrations in the South ABSR System at the PDD. Influent total alkalinity is shown for comparison. Phenolphthalein alkalinity was not present in the influent.

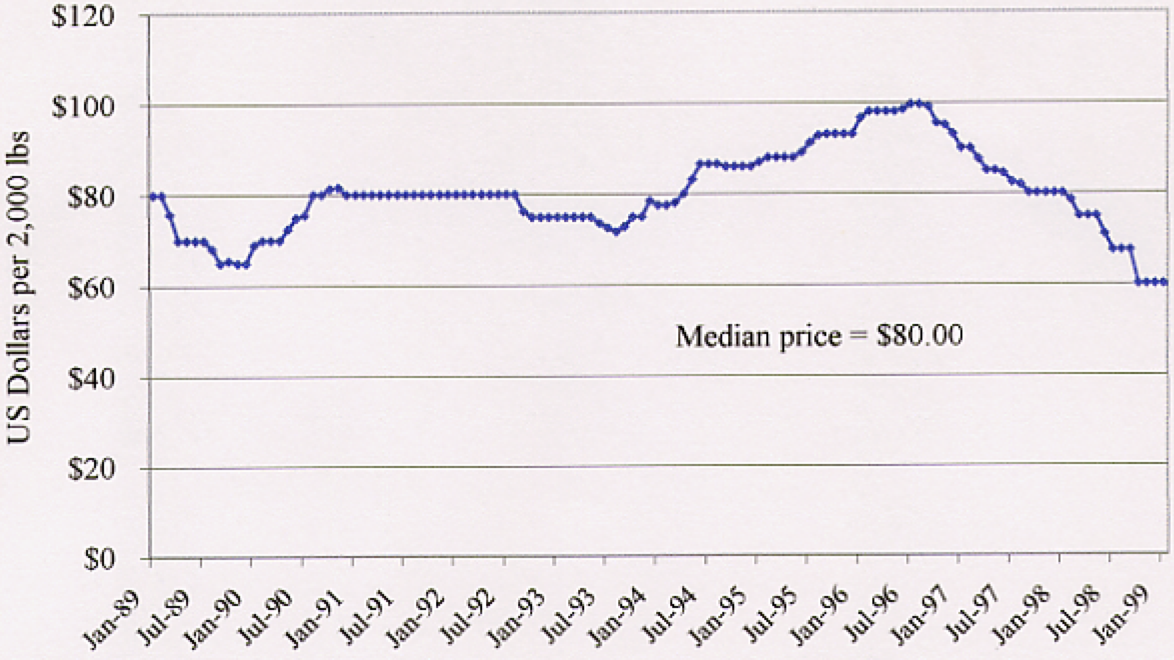

Figure 30. Monthly wholesale price history for blackstrap molasses at the Port of Stockton (USDA, 1999).

CONVERSION FACTORS

(Atmospheres are standard; calories are gram-calories; gallons are U.S. liquid;
miles are statute; pounds-mass are avoirdupois.)

multiply	by	to obtain
acre	43,560	ft^2
angstrom	1×10^{-10}	m
atm	1.01325	bar
atm	76.0	cm Hg
atm	33.90	ft water
atm	29.92	in Hg
atm	14.696	in^2
atm	101.3	kPa
atm	1.013×10^5	Pa
bar	0.9869	atm
bar	10^5	Pa
BTU	778.17	ft-lbf
BTU	1055	J
BTU	2.928×10^{-4}	kW-hr
BTU	10^{-5}	therm
BTU/hr	0.216	ft-lbf/sec
BTU/hr	3.929×10^{-4}	hp
BTU/hr	0.2931	W
BTU/lbm	2.326	kJ/kg
BTU/lbm-°R	4.1868	kJ/kg·K
cal (gm-cal)	3.968×10^{-3}	BTU
cal (gm-cal)	4.1868	J
cm	0.03281	ft
cm	0.3937	in
eV	1.602×10^{-19}	J
ft	0.3048	m
ft^2	2.2957×10^{-5}	acre
ft^3	7.481	gal
ft-lbf	1.285×10^{-3}	BTU
ft-lbf	1.35582	J
ft-lbf	3.766×10^{-7}	kW-hr
ft-lbf	1.3558	N·m
gal	0.13368	ft^3
gal	3.785	l
gal	3.7854×10^{-3}	m^3
gal/min	0.002228	ft^3/sec
g/cm^3	1000	kg/m^3
g/cm^3	62.428	lbm/ft^3
hp	2545	BTU/hr
hp	33,000	ft-lbf/min
hp	550	ft-lbf/sec
hp	0.7457	kW
hp-hr	2545	BTU
in	2.54	cm
J	9.478×10^{-4}	BTU
J	6.2415×10^{18}	eV
J	0.73756	ft-lbf
J	1.0	N·m
J/s	1.0	W
kg	2.20462	lbm
kip	1000	lbf
kip	4448	N
kJ	0.9478	BTU
kJ	737.56	ft-lbf
kJ/kg	0.42992	BTU/lbm
kJ/kg·K	0.23885	BTU/lbm-°R
km	3280.8	ft
km	0.6214	mi
km/hr	0.6214	mi/hr
kPa	9.8693×10^{-3}	atm
kPa	0.14504	lbf/in^2
kW	3413	BTU/hr
kW	0.9481	BTU/sec
kW	737.6	ft-lbf/sec
kW	1.341	hp
kW-hr	3413	BTU
kW-hr	3.6×10^6	J
l	0.03531	ft^3
l	61.02	in^3
l	0.2642	gal
l	0.001	m^3
l/sec	2.119	ft^3/min
l/sec	15.85	gal/min
lbf	4.4482	N
lbf/in^2	0.06805	atm
lbf/in^2	2.307	ft water
lbf/in^2	2.036	in Hg
lbf/in^2	6894.8	Pa
lbm	0.4536	kg
lbm/ft^3	0.016018	g/cm^3
lbm/ft^3	16.018	kg/m^3
m	3.28083	ft
m/sec	196.8	ft/min
mi	5280	ft
mi	1.6093	km
micron	1×10^{-6}	m
N	0.22481	lbf
N·m	0.7376	ft-lbf
N·m	1.0	J
Pa	1.4504×10^{-4}	lbf/in^2
therm	10^5	BTU
W	3.413	BTU/hr
W	0.7376	ft-lbf/sec
W	1.341×10^{-3}	hp
W	1.0	J/sec

APPENDIX

WATER QUALITY DATA RECORD

Total soluble selenium and selenite concentrations in ug/L as Se at the ABSR Facility in the PDD.

	Influent		North RP eff.		North HRP eff.		North ASP eff.		South HRP eff.		South RP eff.	
Date	Total	Selenite	Total	Selenite	Total	Selenite	Total	Selenite	Total	Selenite	Total	Selenite
19-Jul-96	228.5	1.0	188.4		208.9	1.3					110.0	2.9
5-Aug-96	692.1	0.6	687.0	13.0		6.3				5.4	629.4	27.2
12-Aug-96	261.6	0.9	470.4	18.1		10.1		18.8		29.5	414.3	33.4
27-Aug-96	354.5	0.9	278.2	13.4			521.3	10.2			290.8	23.8
9-Sep-96	376.1	1.0	336.0	10.5			497.2	17.0			327.1	23.2
30-Sep-96	512.1	1.0	697.1	9.5	464.0	13.8	328.9	17.8	173.8	18.3	183.3	16.8
10-Oct-96	744.2	1.3	691.1	10.3	820.1	16.8	842.2	19.7	779.8	23.7	689.0	16.0
16-Oct-96	758.2	1.0	695.8	11.5	773.8	19.5	767.1	18.7	774.5	24.8	699.3	19.0
23-Oct-96	838.6	1.1	854.9	11.3		21.3	999.7	14.0		26.8	837.8	17.0
9-Nov-96	220.7	0.6	444.6	9.2	496.7	11.8	603.5		536.4	15.0	491.6	12.0
1-Dec-96								17.0				
29-Dec-96	369.1	1.1	462.8	6.6							374.4	8.8
13-Jan-97	335.6	1.0	424.1	5.5	345.6	6.2			316.7	7.1	291.3	6.4
16-Jan-97	305.6	1.0	403.7	5.4							367.7	7.3
5-Feb-97	401.6		431.1		364.3		162.8		329.9		297.7	
11-Feb-97	401.6		431.1		405.2		372.2		418.2		317.4	
20-Feb-97	397.5	0.9	403.6	4.2	404.4	6.8	353.6	8.0	357.4	6.2	387.9	5.9
26-Feb-97	376.4	0.9	394.1	4.6	426.0	7.8	399.2	7.0	424.7	8.9	383.0	6.5
4-Mar-97	433.3	0.9	428.9	1.8	478.1	5.8	454.9	7.5	478.2	10.1	431.1	6.9
9-Mar-97	420.6	0.7	428.0	7.2	476.1	3.5	459.5	7.4	463.5	13.1	429.0	7.3
17-Mar-97	426.4		285.4		500.7		474.5		510.4		421.3	
24-Mar-97	322.8	0.5	95.1	16.5	361.6	34.9	443.0	17.0	461.6	28.7	381.3	7.6
2-Apr-97			86.6	14.5			356.8	42.8	573.0	29.9	408.9	8.1
7-Apr-97	338.8	0.7	97.8	14.8							421.8	8.6
14-Apr-97	336.0	0.8	70.8	17.8							407.0	8.3
21-Apr-97	382.9	0.7	75.1	25.8	282.0	68.0					401.9	9.0
2-May-97	411.6	1.5	89.1	14.0	151.2	60.2			670.3	53.3	424.1	8.6
12-May-97	412.7	0.5	112.7	18.4	85.1	60.5			648.9	45.1	414.9	4.9
22-May-97	414.2	0.7	122.0	41.0	91.9	53.3			700.9	49.4	419.1	11.6
9-Jun-97	397.3	0.6	113.8	14.0	146.3	34.1			729.9	45.5	469.2	18.5
19-Jun-97	376.6	0.7	134.3	36.2	137.3	67.9	102.3	48.2	802.1	113.4	422.7	30.8
24-Jun-97	396.4	0.9	118.3	23.9			83.9	33.2	736.9	286.6	347.0	24.3
28-Jun-97	403.4	0.8	99.2	21.3	114.6	53.9	91.2	29.6			315.3	19.8
6-Jul-97	386.8	0.7	101.1	30.5	78.0	33.8			518.5	66.6		
7-Jul-97	389.2	0.7	98.2	24.8	61.2	21.6	56.1	10.8	524.4	68.0	302.9	26.1
7-Jul-97					73.0	37.6	47.1	18.7				
17-Jul-97	396.7		116.9		61.1		34.1		422.4		133.1	
26-Jul-97	383.6	0.8	217.1	52.2	55.2	22.6	38.5	6.6	374.1		91.9	38.6
6-Aug-97	432.0	0.8	41.1	14.7	37.5	7.5		8.9	314.5	48.4	282.1	31.8
13-Aug-97	441.8	1.2	53.7	7.8	26.8	6.7	35.6	3.9	286.4	52.5	253.3	30.2
30-Aug-97	515.3	1.3	58.8	9.0	48.1	18.3	31.4		120.1	79.4	110.8	52.5
9-Sep-97	572.9	0.7	31.8	2.7	36.0	14.4			574.1	53.4	71.4	12.6
16-Sep-97	461.2	0.8	49.7	5.5	33.9	15.5			517.5	22.0	155.2	39.1
30-Sep-97	584.5	0.9	102.5	76.6	95.0	69.7		58.8	576.6	34.9	267.1	111.4
7-Oct-97	332.9	0.9	179.9	124.8	108.0	60.9	92.6		441.8	21.1	323.1	83.8

Total soluble selenium and selenite concentrations in ug/L at the ABSR Facility in the PDD, continued.

	Influent		North RP eff.		North HRP eff.		North ASP eff.		South HRP eff.		South RP eff.	
Date	Total	Selenite	Total	Selenite	Total	Selenite	Total	Selenite	Total	Selenite	Total	Selenite
21-Oct-97	448.6	1.0	154.3	120.4	229.0	112.6	201.8	110.7	471.0	27.2	457.2	42.7
30-Oct-97	215.8	1.2	155.7	34.0	210.6	92.6	164.5	76.2	395.0	30.6	426.4	41.2
4-Nov-97	231.7	0.6	134.4	17.1	148.4	85.1	170.0	74.0	358.6	25.8	366.1	31.8
20-Nov-97	370.2	1.0	88.9	11.3							347.6	32.3
28-Nov-97	408.0	0.9	94.1	6.6	74.8	30.8	73.4	29.0	377.0	15.8	345.2	30.7
13-Dec-97	392.7	1.0	147.7	8.1					344.4	7.1	337.0	252.0
22-Dec-97	433.9	0.9	185.2	7.2	154.8	21.8	117.8	5.2	378.6	9.0	336.2	20.6
30-Dec-97	445.5	0.8	194.7	7.9	178.7	22.4	147.3	15.4	451.9	7.0	347.6	21.8
22-Jan-98	374.3	0.9	178.9	21.7	83.6	27.0	97.3	22.1	306.0	6.1	350.9	14.0
27-Jan-98	391.7	0.8	172.6	14.7	104.5	25.0	87.4	20.4	340.3	12.6	348.8	13.2
3-Feb-98	230.5	0.7	182.0	17.2	94.2	17.9	66.1	7.3	306.0	8.5	221.5	6.7
10-Feb-98	318.2	0.9	247.5	3.9	180.4	3.8	151.8	2.5	260.1	8.7	376.4	12.4
17-Feb-98	293.8	0.8	255.5	17.5	229.3	26.2	218.4	24.8	297.8	5.3	293.8	10.2
24-Feb-98	286.6	0.9	259.9	14.7	163.1	31.7	207.5	25.0	270.3	9.4	236.6	9.4
3-Mar-98	326.4	0.7	265.7	20.2	228.6	41.8	214.8	26.0	312.1	16.3	312.1	12.5
10-Mar-98	401.9	0.7	256.3	19.9	222.0	51.6	207.5	34.6	330.5	14.6	304.0	11.3
17-Mar-98	446.8	0.6	265.4	22.4	165.6	46.4	194.7	32.2	372.3	21.7	302.9	11.5
24-Mar-98	415.1	0.7	238.8	23.9	119.8	42.0	148.9	26.5	215.2	34.0	272.3	10.3
2-Apr-98	513.3	0.8	163.8	49.9	110.0	44.6	88.5	16.5	353.9	32.4	289.7	17.1
7-Apr-98	439.1	0.7	93.9	14.0		25.8	69.4	27.7	328.4	25.6	268.3	17.9
14-Apr-98	475.8	0.8	100.4	17.0	49.0	25.7	52.6	19.0	350.9	26.6	283.6	14.4
21-Apr-98	410.0	0.8	76.9	4.2	68.8	24.2	55.3	23.3	304.5	47.5		
28-Apr-98	477.4	0.8	75.9	3.7	67.2	36.2	49.9	12.3	120.6	67.6		
7-May-98	460.4	0.7	66.1	3.9	39.9	9.1	34.6	7.1	190.5	50.2		
12-May-98	665.9	0.9	113.5	9.5	35.0	10.2	25.8	4.6	478.6	31.0	169.7	27.8
19-May-98	457.8	1.0	134.8	12.8	48.4	21.8	26.4	8.0	426.0	31.4	217.1	19.9
26-May-98	586.0	0.7	150.4	13.8	36.5	19.4			318.2	42.7	306.0	39.5
2-Jun-98	483.5	0.8	137.7	17.3	46.4	25.5	34.9	13.5	303.6	45.6		
9-Jun-98	419.8	0.9	142.4	13.9	49.8	21.5	26.6	11.4	275.4	51.5	266.0	45.4
17-Jun-98	394.1	0.8	76.5	18.8	40.4	26.8	27.3	8.0	422.3	55.2	222.0	44.6
23-Jun-98	449.1	0.7	109.2	7.2	61.8	34.9	25.9	6.7	453.0	35.0	224.4	40.2
30-Jun-98	400.9	0.7	94.6	6.4	51.4	14.4			462.3	47.5	246.4	33.1
7-Jul-98	392.2	1.0	94.6	8.3	65.3	26.0	37.1	4.8	300.4	40.1	275.8	24.2
14-Jul-98	407.0	0.7	90.5	8.0	46.6	3.3			315.7	38.1	262.3	18.5
21-Jul-98	389.6	0.7	75.5	13.9	63.0	25.0	39.3	11.6	322.3	29.7	260.3	18.4
28-Jul-98	428.4	0.6	74.5	8.9	40.1	14.2	27.5	6.0	287.6	35.1	250.4	17.4
6-Aug-98			86.1	7.9	38.5	14.0	34.3	8.8	289.7	38.8	248.9	10.7
10-Aug-98	374.3	0.9	103.6	9.9	47.0	21.7	29.5	8.1	348.8	23.8	218.4	15.9
18-Aug-98			99.4	9.2	62.2	23.2	43.9	18.1	229.5	90.8	98.9	35.3
25-Aug-98	308.0	0.9	82.6	9.1	72.4	35.3	36.8	5.6	254.0	68.4	117.5	117.6
1-Sep-98	336.6	0.6	88.2	32.0	70.5	28.2	45.3	19.3	300.9	24.6	106.5	67.3
9-Sep-98	339.5	0.8	60.0	9.2	61.7	30.2	49.6	21.0	292.5	40.4	194.2	165.0
15-Sep-98	381.2	0.7	71.6	9.4	65.3	41.0	54.3	27.6	238.8	65.7	47.0	27.2
22-Sep-98	470.0	0.8	64.1	11.4	62.9	41.4	53.4	32.2	319.9	57.3	51.6	26.5
30-Sep-98	479.2	0.8	80.6	16.8	65.3	34.3	61.7	36.4	434.1	49.4	179.2	154.0

Total soluble selenium and selenite concentrations in ug/L at the ABSR Facility in the PDD, continued.

	Influent		North RP eff.		North HRP eff.		North ASP eff.		South HRP eff.		South RP eff.	
Date	Total	Selenite	Total	Selenite	Total	Selenite	Total	Selenite	Total	Selenite	Total	Selenite
9-Oct-98	515.7	0.8	92.4	16.5	63.5	28.0	59.7	28.2	455.8	46.9	84.5	25.2
12-Oct-98	369.5	1.3	102.6	16.5	99.3	58.0	100.3	62.9	445.5	35.0	148.4	55.8
14-Oct-98	519.6	0.7	96.5	21.4	76.9	44.2	62.3	31.5	504.9	44.1	85.8	40.8
28-Oct-98	326.4	0.8	95.4	11.6	96.7	64.2	99.7	66.5	368.1	21.4	179.9	22.0
4-Nov-98	287.2	0.8	91.5	28.7	91.6	59.4	99.7	70.2	287.9	16.1	202.0	27.0
12-Nov-98	297.7	0.8	108.2	27.2	81.1	46.6	77.8	49.4	251.4	13.2	210.2	30.6
17-Nov-98	308.1	0.9	97.5	12.0	98.8	50.8	93.8	55.0	285.6	13.7	215.2	31.1
24-Nov-98	199.8	0.5	91.2	15.2	94.6	42.3	97.1	49.8	196.5	9.1	207.1	27.7
3-Dec-98	282.0	0.6	110.2	17.4	77.2	32.8	97.5	41.8	213.0	30.2	204.0	30.5
8-Dec-98	284.6	0.5	103.9	8.4	112.3	22.6			269.3	12.8	204.0	27.5
16-Dec-98	313.3	0.6	92.8	8.0	78.0	21.6	79.2	27.8	283.6	10.4	197.5	24.4
22-Dec-98	334.2	0.6	62.3	8.4	70.4	25.8	79.6	26.2	315.2	8.2	224.4	25.4
29-Dec-98	346.0	0.7	63.0									
6-Jan-99	344.7	0.7	104.4	7.1	81.6	26.0	78.0	24.2	348.8	9.3	256.2	22.8

Nitrate + nitrite concentrations as mg/L-N at the ABSR Facility in the PDD.

Date	Influent	North RP eff.	North HRP eff.	North ASP eff.	South HRP eff.	South RP eff.
19-Jul-96	63.7	70.8	93.9		87.2	71.8
23-Jul-96		53.9	93.7		112.4	49.4
5-Aug-96	86.8	71.8	200.0		196.3	76.3
12-Aug-96	58.6	53.5	188.3		103.9	54.3
19-Aug-96	79.8	60.9	100.3		138.3	76.2
27-Aug-96	123.2	100.8	183.8		200.0	85.8
9-Sep-96	92.7	71.3	125.0		113.1	72.8
13-Sep-96	92.8	70.7	128.9		109.9	70.2
23-Sep-96	99.9	86.6	99.3	120.1	105.2	70.8
30-Sep-96	84.6	78.3	91.1	89.5	83.8	64.7
10-Oct-96	81.9	74.4	79.3	86.2	76.9	71.6
16-Oct-96	86.0	66.1	81.5	82.1	82.7	69.8
23-Oct-96	80.8	75.7	90.4	82.6	84.0	75.7
9-Nov-96	79.0	69.1	76.6	73.3	73.8	74.4
23-Dec-96	67.6	48.0				48.0
29-Dec-96	78.3	45.5				45.5
13-Jan-97	83.1	72.5	56.2		52.1	45.4
16-Jan-97	64.6	53.8	43.1	45.3	45.3	53.3
29-Jan-97	69.9	55.2	42.0	36.5	37.6	40.2
5-Feb-97	68.5	52.6	39.8	35.4	33.4	35.7
11-Feb-97	73.4	41.2	35.8		22.5	42.0
20-Feb-97	68.4	57.0	51.5	25.3	48.4	58.1
26-Feb-97	69.9	57.9	49.8	45.5	50.9	57.7
4-Mar-97	65.7	53.3	44.2	46.1	49.6	57.2
9-Mar-97	66.5	57.0	44.1	42.2	43.2	61.3
17-Mar-97	73.0	32.0	28.8	36.6	35.6	61.0
24-Mar-97	69.3	5.8	11.4	25.4	30.2	58.0
2-Apr-97		0.2	1.9	7.5	26.2	61.9
7-Apr-97	73.4	<0.2				66.8
14-Apr-97	75.1	<0.2				70.9
21-Apr-97	80.0	0.2	6.3			70.7
2-May-97	78.9	3.6	<0.2		66.0	72.0
12-May-97	76.1	3.4	<0.2		67.3	68.1
22-May-97	91.0	0.6	<0.2		63.8	74.5
9-Jun-97	82.3	8.8	1.7		54.2	67.0
19-Jun-97	83.0	7.5	<0.2	<0.2	15.4	51.1
24-Jun-97	86.9	5.9	<0.2	<0.2	0.1	42.7
28-Jun-97	80.7	1.7	<0.2	<0.2		45.4
6-Jul-97	81.3	0.6	<0.2		52.0	

Nitrate + nitrite concentrations as mg/L-N at the ABSR Facility in the PDD, continued.

Date	Influent	North RP eff.	North HRP eff.	North ASP eff.	South HRP eff.	South RP eff.
7-Jul-97	76.9	0.4	<0.2	<0.2	50.0	33.6
7-Jul-97	82.5		<0.2	<0.2	53.9	
17-Jul-97	79.1	0.4	<0.2	<0.2	70.6	12.4
26-Jul-97	82.4	15.2	<0.2	<0.2	51.9	0.0
6-Aug-97	80.0	1.4	<0.2	<0.2	24.2	18.8
13-Aug-97	80.1	0.0	<0.2	<0.2	19.9	14.8
30-Aug-97	91.1	0.0	<0.2	<0.2	0.2	0.3
9-Sep-97	81.7	0.0	<0.2		47.5	0.4
16-Sep-97	89.9	0.0	<0.2		82.6	11.8
30-Sep-97	95.0	0.1	<0.2		64.1	10.6
7-Oct-97	78.3	5.6	<0.2	<0.2	71.4	30.2
14-Oct-97	88.0	20.1	5.6	1.8	69.1	42.6
21-Oct-97	75.2	12.0	7.6	4.7	55.2	48.7
30-Oct-97	69.7	4.1	4.4	2.6	56.0	52.0
4-Nov-97	75.8	2.4	1.7	0.5	56.0	58.3
12-Nov-97	72.7	<0.2	<0.2	0.2	55.3	57.6
20-Nov-97	77.2	<0.2				48.9
28-Nov-97	70.3	1.3	<0.2	<0.2	57.1	48.0
13-Dec-97	74.6	10.5			68.1	47.8
22-Dec-97	79.7	8.9	3.2	1.8	74.1	52.3
30-Dec-97	81.4	8.8	6.9	4.2	78.7	60.5
22-Jan-98	88.8	3.6	<0.2	0.9	67.2	68.6
27-Jan-98	83.4	3.1	2.6	0.8	63.4	68.5
3-Feb-98	85.7	7.0	0.9	1.5	46.9	62.0
10-Feb-98	75.5	14.2	7.5	9.0	52.9	51.2
17-Feb-98	81.9	42.5	28.6	22.0	60.5	56.9
24-Feb-98	76.6	44.0	20.9	22.5	51.2	55.8
3-Mar-98	75.1	39.7	15.3	16.4	25.1	46.7
10-Mar-98	83.5	37.2	9.3	11.5	24.1	55.3
17-Mar-98	80.2	34.0	3.3	5.4	23.5	53.3
24-Mar-98	82.1	30.8	1.4	1.6	1.9	50.5
2-Apr-98	79.7	8.6	1.2	0.1	30.4	32.3
7-Apr-98	79.3	4.3		0.6	35.1	33.9
14-Apr-98	82.3	<0.2	<0.2	<0.2	22.1	30.6
21-Apr-98	81.1	<0.2	<0.2	<0.2	0.6	
30-Apr-98	76.1	<0.2	<0.2	<0.2	<0.2	23.6
7-May-98	77.3	<0.2	<0.2	<0.2	3.2	23.7
12-May-98	79.7	2.4	<0.2	<0.2	47.7	4.7
19-May-98		7.1	<0.2	<0.2	40.4	26.6

Nitrate + nitrite concentrations as mg/L-N at the ABSR Facility in the PDD, continued.

Date	Influent	North RP eff.	North HRP eff.	North ASP eff.	South HRP eff.	South RP eff.
26-May-98	83.3	3.1	<0.2	<0.2	23.6	23.7
2-Jun-98	86.2	3.2	<0.2	<0.2	21.1	21.2
9-Jun-98	78.4	2.2	<0.2	0.2	12.4	16.0
17-Jun-98	83.6	<0.2	<0.2	<0.2	45.5	14.3
23-Jun-98	79.9	<0.2	<0.2	<0.2	37.4	6.4
30-Jun-98	68.3	<0.2	<0.2	<0.2	46.5	12.5
7-Jul-98	75.9	<0.2	<0.2	<0.2	19.5	18.2
14-Jul-98	81.2	<0.2	<0.2	<0.2	20.3	13.8
21-Jul-98	73.9	<0.2	<0.2	<0.2	31.0	9.6
28-Jul-98	72.9	<0.2	<0.2	<0.2	25.1	11.8
4-Aug-98	73.1	<0.2	<0.2	<0.2	20.9	8.7
10-Aug-98	73.4	0.2	<0.2	<0.2	54.4	3.3
18-Aug-98	74.5	<0.2	<0.2	<0.2	13.4	<0.2
25-Aug-98	72.6	<0.2	0.1	<0.2	21.2	<0.2
1-Sep-98	71.1	<0.2	0.0	<0.2	34.7	<0.2
9-Sep-98	67.7	<0.2	0.0	<0.2	33.0	<0.2
15-Sep-98	72.3	<0.2	0.0	<0.2	17.9	<0.2
22-Sep-98	74.8	<0.2	0.0	<0.2	30.1	<0.2
30-Sep-98	77.8	<0.2	0.0	<0.2	45.8	<0.2
9-Oct-98	71.4	<0.2	0.0	<0.2	47.1	<0.2
14-Oct-98	79.9	<0.2	0.7	<0.2	44.0	<0.2
21-Oct-98	72.7	<0.2	0.3	0.2	47.7	<0.2
28-Oct-98	61.9	<0.2	<0.2	0.2	38.3	7.8
4-Nov-98	59.8	<0.2	0.4	0.2	44.6	11.0
12-Nov-98	62.9	6.2	1.8	0.8	40.1	13.9
17-Nov-98	63.8	5.9	4.5	2.5	42.5	14.6
24-Nov-98	65.5	1.1	3.8	3.9	43.9	15.9
3-Dec-98	67.5	2.1	1.0	1.6	26.8	15.6
8-Dec-98	63.4	1.1	0.9		45.2	19.9
16-Dec-98	66.3	<0.2	0.5	0.6	46.7	21.3
22-Dec-98	61.6	0.1	0.2	0.3	40.3	14.0
29-Dec-98	65.0	0.4	0.2	<0.2	56.5	18.8
6-Jan-99	67.9	2.6	0.7	0.4	60.5	21.0

Dissolved oxygen concentrations in mg/L at the ABSR Facility in the PDD.

Date	Influent	North RP eff.	North HRP eff.	North ASP eff.	South HRP eff.	South RP eff.
16-Oct-96	8.4	11.5	14.8	11.6	15.5	14.0
23-Oct-96	10.2		11.2	12.0	11.4	
09-Nov-96	7.8	19.2	18.0	17.0	18.7	20.8
23-Dec-96	8.9		12.0	13.1	11.6	
29-Dec-96	7.8		10.0	10.2	9.4	
29-Dec-96	8.6					
08-Jan-97	8.2					
13-Jan-97	9.1		13.3		14.4	
16-Jan-97						
11-Feb-97	8.4	11.5	12.7		12.7	3.8
20-Feb-97	9.4		16.9	13.9	17.3	
26-Feb-97	9.1		10.7	11.5	12.5	
04-Mar-97	8.5		15.0	11.8	12.7	
09-Mar-97	10.0		24.4	16.1	24.4	
17-Mar-97	8.9		39.5	26.0	35.0	
24-Mar-97	6.8		17.8	17.8	17.8	
02-Apr-97			17.6		17.6	
07-Apr-97	7.1					
14-Apr-97	10.7	5.6				
21-Apr-97	9.8					
12-May-97	9.4	9.3	22.8		21.7	4.9
09-Jun-97	8.4	10.6	23.7		17.0	2.0
19-Jun-97	8.6	12.9	24.2	31.5	16.0	1.4
24-Jun-97	8.4	10.5	25.2	25.6	17.8	11.6
29-Jun-97	8.2	3.4	13.4	5.1		1.8
07-Jul-97	10.0	8.8	27.3	10.5	30.2	
17-Jul-97	8.4		24.0	17.6	20.5	
26-Jul-97		1.3	16.8	19.8	27.1	3.4
06-Aug-97	8.5	1.2	21.7		34.4	
13-Aug-97	8.1	0.5	26.0	1.2	22.4	1.1
30-Aug-97	8.9	0.1	31.9	10.1	37.1	0.1
09-Sep-97	8.7	0.7	15.5		23.8	0.1
30-Sep-97	9.7	1.2	24.6		31.0	
21-Oct-97	9.2	1.6	27.5	16.6	23.9	15.5
26-Oct-97	8.7	2.7	33.7	33.8	29.8	19.3
30-Oct-97	9.0	3.3	31.4	25.3	27.2	21.5
04-Nov-97	8.0	2.1	25.4	11.3	24.4	18.6
12-Nov-97	8.4	1.9	32.4	32.3	19.3	10.3
28-Nov-97	8.9	1.8	28.3	42.5	23.6	7.2
09-Dec-97	9.1	5.8	29.3	13.2	16.4	5.9
22-Dec-97	9.3	6.2	25.5	6.8	14.8	6.7
30-Dec-97	9.5	1.4	31.2		20.5	7.0
10-Feb-98	6.1	8.3	25.4	13.0	18.0	7.8
03-Mar-98	14.3	4.6	20.2	19.8	19.9	11.4
10-Mar-98	7.3	1.8	26.3	18.8	27.3	4.1
17-Mar-98	8.4	2.6	32.8	24.9	26.5	3.6

Dissolved oxygen concentrations in mg/L at the ABSR Facility in the PDD, continued.

Date	Influent	North RP eff.	North HRP eff.	North ASP eff.	South HRP eff.	South RP eff.
24-Mar-98	8.3	7.9	10.8	4.3	15.5	0.9
02-Apr-98	9.1	3.5	21.6	11.1	26.0	1.9
14-Apr-98	8.9	1.2	24.1	38.5	25.0	
30-Apr-98	8.5	0.2	19.6	7.7	8.9	2.7
07-May-98	8.8	2.5	2.4	19.9	39.6	7.3
12-May-98	7.9	1.1	11.9	4.5	17.1	0.6
19-May-98		5.3	25.8	21.0	14.8	2.8
02-Jun-98	6.5	2.0	22.2	9.1	12.7	3.4
09-Jun-98	8.5	2.7	25.8	25.3	23.6	1.5
17-Jun-98	9.1	0.1	19.3	24.8	31.1	1.3
23-Jun-98	9.6	0.3				1.3
07-Jul-98	9.0	0.2	21.3	0.1	30.1	2.1
28-Jul-98	8.2	0.2	6.9	0.1	18.0	1.4
04-Aug-98	8.9	0.2	9.2	25.4	22.6	1.4
10-Aug-98	9.4	0.2	20.7	22.5	8.4	1.5
18-Aug-98	8.9	0.3	15.8	10.2	20.4	0.2
25-Aug-98	10.1	0.3	38.1	15.5	33.3	0.5
01-Sep-98	8.3	1.0	20.6	31.3	21.0	0.1
09-Sep-98	9.0	0.3	32.6	14.6	20.9	0.2
15-Sep-98	9.3	0.3	28.3	31.0	31.4	0.2
22-Sep-98	9.4	0.5	47.3	52.0	42.9	0.7
30-Sep-98	9.5	0.8	44.7	53.5	27.3	0.2
09-Oct-98	7.1	2.6	24.6	14.6	21.8	2.0
14-Oct-98	10.6	0.4	41.3	35.0	33.2	0.3
21-Oct-98	9.1	0.4	34.1	46.4	34.2	2.2
28-Oct-98	9.4	0.2	30.0	42.7	22.8	1.0
04-Nov-98	10.0	0.6	43.9	52.3	34.7	0.8
12-Nov-98	10.1	1.9	39.5	46.6	20.1	1.6
30-Nov-98	9.5	2.6	22.5	18.5	18.2	2.3
08-Dec-98	10.4	2.3	2.0		19.4	2.1
16-Dec-98	10.3	1.4	28.1	35.1	25.3	2.3
29-Dec-98	10.9	1.1	9.9	4.0	11.1	2.6

Volatile suspended solids concentrations in mg/L at the ABSR Facility in the PDD.

		North	North	North	South	South
Date	Influent	RP eff.	HRP eff.	ASP eff.	HRP eff.	RP eff.
5-Aug-96		94	36	42		78
12-Aug-96	46	60	110	42	252	54
19-Aug-96	28	49	71	42	268	49
27-Aug-96	28	49	71	42	268	49
9-Sep-96	28	49	71	42	268	49
13-Sep-96	28	49	71	42	268	49
23-Sep-96	9	38	31	42	285	43
30-Sep-96	58	83	87	88	100	80
10-Oct-96	34	57	70	61	74	61
16-Oct-96	34	57	70	61	74	61
23-Oct-96	9	32	52	34	48	43
9-Nov-96	<2	17	44	37	30	61
23-Dec-96	11	37	37	27	28	53
29-Dec-96	22	57	37	27	28	45
13-Jan-97	13	37	37	27	28	26
16-Jan-97	13	37	37	27	28	26
29-Jan-97	3	16	30	17	25	6
5-Feb-97	4	20	38	32	65	15
11-Feb-97	<2	19	38	44	57	7
20-Feb-97	4	24	39	47	48	4
26-Feb-97	7	30	92	52	68	16
4-Mar-97	3	35	155	91	60	3
9-Mar-97	<2	35	225	68	60	3
17-Mar-97	<2	47	275	97	63	4
24-Mar-97	2	38	350	115	60	12
2-Apr-97	2	62	493	195		13
7-Apr-97	<2	20	277	128		5
14-Apr-97	<2	17	277	128		4
21-Apr-97	<2	12	61	128	56	2
2-May-97	<2	20	60	128	56	<2
12-May-97	3	31	119	128	14	5
22-May-97	14	28	88	128	38	15
9-Jun-97	25	24	58	128	61	25
19-Jun-97	<2	21	83	60	56	18
24-Jun-97	8	32	155	43	50	8
29-Jun-97	4	4	185	45	79	23
6-Jul-97	17	22	165	29	109	82
7-Jul-97	22	<2	95	45	79	141
7-Jul-97	26	14	186	45	94	75
17-Jul-97	30	27	79	13	76	9
26-Jul-97	5	13	126	43	82	21
13-Aug-97	<2	33	216	166	45	18
9-Sep-97	12	51	143	134	29	25
16-Sep-97	17	49	170	134	40	25
30-Sep-97	4	64	123	103	96	25
7-Oct-97	<2	55	258	187	66	38

Volatile suspended solids concentrations in mg/L at the ABSR Facility in the PDD, continued.

Date	Influent	North RP eff.	North HRP eff.	North ASP eff.	South HRP eff.	South RP eff.
14-Oct-97	4	25	178		47	28
21-Oct-97	4	8	185	105	17	17
26-Oct-97	20	25	225	155	46	26
30-Oct-97	47	17	185	113	32	53
4-Nov-97	13	32	216	80	21	15
12-Nov-97	2	38	188	113	19	13
20-Nov-97	5	43	133	102	18	7
28-Nov-97	4	8	145	126	21	4
9-Dec-97	<2	40	90	72	15	5
22-Dec-97	11	63	161		44	8
30-Dec-97	15	57	170	91	23	23
22-Jan-98	4	49	148	46	40	8
27-Jan-98	6	38	175	90	29	6
3-Feb-98	15	44	61	80	36	15
10-Feb-98	8	40	81	39	25	19
17-Feb-98	6	26	55	60	29	15
24-Feb-98	4	17	76	40	21	6
3-Mar-98	4	15	49	28	52	8
10-Mar-98	6	21	108	62	120	4
17-Mar-98	8	11	136	99	52	4
24-Mar-98	6	17	140	90	76	7
2-Apr-98	6	22	129	80	79	22
7-Apr-98	17	38	162	105	90	25
14-Apr-98	2	13	270	184	101	21
21-Apr-98	2	11	189	100	151	30
7-May-98	8	36	79	121	159	40
12-May-98	2	27	50	80	149	21
19-May-98	<2	13	157	59	123	2
26-May-98	5	7	184	55	131	2
2-Jun-98	11	25	152	51	162	15
9-Jun-98	8	19	118	28	151	11
17-Jun-98	2	27	274	86	163	<2
23-Jun-98	9	34	270	81	173	5
30-Jun-98	<2	55	338	157	189	<2
7-Jul-98	2	49	351	140	150	21
14-Jul-98	4	2	498	122	103	2
21-Jul-98	2	24	227	104	43	16
28-Jul-98	<2	2	77	61	66	<2
4-Aug-98	48	62	144	85	121	44
10-Aug-98	<2	49	143	53	<2	<2
18-Aug-98	36	51	189	130	36	25
25-Aug-98	6	44	247	158	59	21
1-Sep-98	13	36	211	171	76	21
9-Sep-98	7	27	197	169	31	25

Volatile suspended solids concentrations in mg/L at the ABSR Facility in the PDD, continued.

Date	Influent	North RP eff.	North HRP eff.	North ASP eff.	South HRP eff.	South RP eff.
15-Sep-98	2	32	269	230	92	27
22-Sep-98	27	42	215	253	92	31
30-Sep-98	10	38	211	270	25	16
9-Oct-98	10	50	212	254	65	19
14-Oct-98	9	29	199	201	67	8
21-Oct-98	4	55	170	205	100	25
28-Oct-98	16	29	178	202	152	22
12-Nov-98	26	25	159	152	134	29
17-Nov-98	21	38	163	142	139	34
24-Nov-98	26	51	131	115	106	30
3-Dec-98	17	33	130	101	140	30
8-Dec-98	8	42	100	77	94	21
16-Dec-98	17	49	97	54	116	21
22-Dec-98	42	63	109	68	71	38
6-Jan-99	21	59	80	55	30	26

Levels of pH at the ABSR Facility in the PDD.

Date	Influent	North RP eff.	North HRP eff.	North ASP eff.	South HRP eff.	South RP eff.
9-Dec-96		8.83	9.06	9.09	9.03	8.87
29-Dec-96	7.40	8.80	8.90		8.80	8.60
13-Jan-97					8.50	
20-Feb-97	7.70	9.40	10.30	9.50	10.20	8.00
26-Feb-97	7.45	8.17	8.34	9.07	8.96	8.03
4-Mar-97	7.21	7.85	9.28	9.10	9.65	7.97
9-Mar-97	7.26	7.50	9.58	9.61	10.52	8.03
17-Mar-97	7.33	7.23	8.99	9.78	10.21	7.97
24-Mar-97	7.25	7.24	9.37	9.24	10.04	7.89
7-Apr-97	7.50	7.75				7.85
14-Apr-97	7.20	7.60				7.70
21-Apr-97	7.32	8.04	9.56			8.34
2-May-97		8.30				9.00
12-May-97	7.29	8.22	9.07		10.15	7.92
9-Jun-97	7.33	8.03	8.81		9.31	8.02
19-Jun-97	7.35	8.40	9.65	9.00	9.90	7.85
24-Jun-97	7.41	8.29	10.05	9.24	9.54	8.34
29-Jun-97	7.30	7.91	9.70	8.90		7.73
6-Jul-97	7.25	8.24	9.10		9.53	
7-Jul-97	7.29	8.11	8.94	8.94	9.44	
7-Jul-97	7.39	8.27	9.29	8.91	9.97	
17-Jul-97	7.25	8.07	9.11	8.91	9.34	8.12
26-Jul-97		8.30	9.03	8.92	9.95	7.91
6-Aug-97	7.26	7.91	8.91		9.52	8.59
13-Aug-97	7.22	7.40	8.55	8.43	8.74	8.47
30-Aug-97	7.35	7.79	9.95	8.59	9.43	8.30
30-Sep-97	7.27	7.59	7.53		9.94	
26-Oct-97	7.23	7.55	9.29	9.05	9.40	9.07
30-Oct-97	7.23	7.91	9.21	9.09	9.37	9.06
4-Nov-97	7.20	7.72	9.23	8.95	9.19	9.09
12-Nov-97	7.35	7.59	8.79	8.99	8.95	8.95
28-Nov-97	7.33	7.59	9.04	9.13	9.27	8.52
9-Dec-97	7.30	7.59	8.51	8.32	8.51	8.39
13-Dec-97		7.55	8.52		8.50	8.51
22-Dec-97	7.26	7.74	8.56	8.04	8.20	8.34
30-Dec-97	7.55	7.74	8.72		8.73	8.37
22-Jan-98	7.23	8.00	7.99	8.54	8.45	8.13
10-Feb-98	7.20	7.77	8.75	8.35	8.80	8.15
3-Mar-98	8.08	7.60	9.21	9.08	10.08	8.65
10-Mar-98	7.15	7.45	9.80	9.53	9.42	8.50
17-Mar-98	7.34	7.49	10.04	10.09	8.83	8.47
24-Mar-98			8.55		10.11	
7-Apr-98	7.29	7.49	9.09	8.99	8.95	8.51
21-Apr-98		7.70				
30-Apr-98	7.25	7.53	9.91	9.52	9.47	8.57
12-May-98	7.37	7.80	8.49	8.55	10.22	8.54

Levels of pH at the ABSR Facility in the PDD, continued.

Date	Influent	North RP eff.	North HRP eff.	North ASP eff.	South HRP eff.	South RP eff.
19-May-98	7.93	7.97	9.99	9.24	10.33	8.59
2-Jun-98	7.32	7.93	9.50	9.13	10.52	9.15
9-Jun-98	7.20	7.84	9.48	9.41	10.41	9.16
17-Jun-98	7.35	7.52	9.25	9.55	9.23	9.10
23-Jun-98			9.35		10.05	
30-Jun-98			8.70		9.55	
7-Jul-98	7.33	7.37	9.35	8.37	9.91	8.95
14-Jul-98	7.31	7.50	7.45		10.15	8.95
21-Jul-98	7.15	7.01	8.55	8.35	9.18	8.58
28-Jul-98	7.24	7.49	8.05	8.18	9.35	8.75
4-Aug-98	7.25	7.39	8.15	7.51	9.05	8.45
10-Aug-98	7.45	7.39	8.57	8.55	8.29	8.59
18-Aug-98	7.25	7.42	8.54	8.45	9.02	8.45
25-Aug-98	7.19	7.45	8.99	8.55	9.05	7.41
1-Sep-98	7.16	7.50	8.53	9.58	8.55	8.23
9-Sep-98	7.16	7.48	8.83	8.85	8.60	7.98
15-Sep-98	7.18	7.35	9.45	9.45	9.14	8.16
22-Sep-98	7.38	7.55	9.45	10.09	10.00	8.21
30-Sep-98	7.43	7.51	9.15	9.79	9.30	8.25
9-Oct-98	7.34	7.50	8.49	8.51	8.99	8.51
14-Oct-98		7.31	8.52		9.60	
21-Oct-98	7.24	7.12	8.52	8.98	9.99	8.33
28-Oct-98	7.26	7.30	8.49	8.90	9.09	8.50
4-Nov-98	7.49	7.61	8.86	9.08	10.47	8.50
12-Nov-98	7.43	7.42	8.74	8.90	9.58	8.38
24-Nov-98	7.37	7.24	8.80	9.76	9.24	8.92
8-Dec-98	7.39	7.29	8.62		8.96	8.41
16-Dec-98	7.42	7.23	8.59	8.93	9.53	8.35
22-Dec-98	7.43	7.24	7.91	8.18	7.86	8.33

Total and phenolphthalein alkalinity concentrations in mg/L as $CaCO_3$ at the ABSR Facility in the PDD.

		North	North		North		South		South	
	Influent	RP eff.	HRP eff.		ASP eff.		HRP eff.		RP eff.	
pH Endpoint	4.5	4.5	8.3	4.5	8.3	4.5	8.3	4.5	8.3	4.5
Date										
12-Aug-96	222	164		492				784		125
6-Jan-97	246	184		98		118		160		
30-Jan-97		144	56	63	19	94	56	50		
5-Feb-97	244	132	60	74	48	64	49	57		
13-Feb-97	238	134	125	50			41	78		213
20-Feb-97	226	171	64	65	<2	53	58	91		
4-Mar-97	219	206	78	81	62	68	87	63		
9-Mar-97	200	219	25	138	37	86	81	69		225
17-Mar-97	212	308	51	128	79	49	108	52		218
24-Mar-97	206	331	<2	156	81	94	94	69		
2-Apr-97		465	116	87	74	117	46	175		
7-Apr-97	231	487								
14-Apr-97	220	486								
21-Apr-97	296	444	37	110						
22-May-97	223	315	131	318			157	96		
19-Jun-97	230	298	107	140	76	150	226	121		
24-Jun-97	243	308	104	156	151	122	503	289		
7-Jul-97		356	136	225	90	250	143	61		
17-Jul-97	247	385	186	206		108	93	93		
26-Jul-97	226	431	131	270	131	290	100	71		
13-Aug-97	135	613		394		469		250		
10-Sep-97	228	613		494				203		366
16-Sep-97	303	610		512			65	123		
30-Sep-97	228	631		375		459		192		331
14-Oct-97	225	563	9	306	13	734	131	91	47	244
21-Oct-97	244	559	111	191	51	291	38	183	31	176
26-Oct-97	235	584	110	246	81	281	81	100	63	138
30-Oct-97	235	580	70	297	61	304	24	96	38	119
4-Nov-97	238	590	82	286	23	363	32	130	43	102
12-Nov-97	230	581	43	433	72	351	33	146	36	143
9-Dec-97	246	521	22	191		401		349	4	213
22-Dec-97	240	508	12	455		533		249		225
30-Dec-97	186	488	25	394	29	437	31	224		264
22-Jan-98	242	525		401	14	372	16	216		255
27-Jan-98	233	536		457	33	371	25	245		247
3-Feb-98	205	424	11	338	<2	348	13	181		243
10-Feb-98	273	473	20	298	6	325	28	231		239
17-Feb-98	269	372	2	351	6	337	36	274		248
24-Feb-98	242	374	31	196	8	304	44	176	19	244
4-Mar-98			51	163	42	149				
17-Mar-98	224	386	66	186	76	148	29	211	9	235
24-Mar-98	246	356	5	208	38	139			7	250
2-Apr-98	237	460	28	225	6	189	62	216	16	259

Total and phenolphthalein alkalinity concentrations in mg/L as $CaCO_3$ at the ABSR Facility in the PDD, continued.

		North	North		North		South		South	
	Influent	RP eff.	HRP eff.		ASP eff.		HRP eff.		RP eff.	
pH Endpoint	4.5	4.5	8.3	4.5	8.3	4.5	8.3	4.5	8.3	4.5
Date										
7-Apr-98	190	498	54	309	36	262	29	235	8	241
14-Apr-98	199	518	84	178	106	240	84	130	31	232
21-Apr-98	242	523	70	188	103	191	70	123		
30-Apr-98	244	526	75	248	56	238	69	180		
7-May-98	240	487		293	53	250	72	174	16	287
12-May-98		482		410	7	325	99	171		404
19-May-98	271	448	91	212	71	254	80	142	13	252
26-May-98	263	463	66	279			128	176	89	226
2-Jun-98	255	474	83	274	53	294	93	169	51	222
9-Jun-98	244	475	78	286	84	282	93	193	56	203
17-Jun-98	239	502	26	234	74	213	39	261	56	202
23-Jun-98	234	503	73	249	87	226	100	221	53	231
30-Jun-98	236	514	26	304	11	333	96	233	50	265
7-Jul-98	260	544	51	311		379	90	238	55	261
14-Jul-98	252	573		406			109	178	59	252
21-Jul-98	239		9	539		492	64	209	47	273
28-Jul-98	265	603		489		506	71	194	39	273
4-Aug-98	241	591		516	31	503	78	234	47	263
18-Aug-98	274	636	8	331		399	67	238	17	329
25-Aug-98	236	604	39	278	30	361	64	223	13	354
9-Sep-98	242	609	61	278	51	343	30	296		493
15-Sep-98	239	613	96	260	120	319	61	291		440
22-Sep-98	218	617	78	234	116	228	111	203		449
14-Oct-98	224	688		477	58	433	146	236		438
28-Oct-98	249			490	18	462	64	321	2	405
18-Nov-98	231	879	40	411	56	383	72	188		354
21-Nov-98	240			317	43	343	9	171		350
3-Dec-98	240	873	33	228	22	251	84	153	21	329
9-Dec-98	226	856		418			21	238		328
16-Dec-98	232	863		426	16	351	61	169		334
22-Dec-98	221	838		506		468		189		320
6-Jan-99	174	482		551		419		537		312