State of California
The Resources Agency
DEPARTMENT OF WATER RESOURCES
Division of Planning and Local Assistance
San Joaquin District

SELENIUM REMOVAL
at
ADAMS AVENUE AGRICULTURAL DRAINAGE RESEARCH CENTER

Agricultural Drainage Program
Drainage Treatment

District Report

May 2004

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Governor
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Michael Chrisman
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FOREWORD

This district report is to provide documentation and evaluation of the biological processes that were tested to reduce/remove selenium from agricultural drainage water at the Adams Avenue Agricultural Drainage Research Center in western Fresno County, California. This report provides a summary of the work that was performed and combines data, results, and other information from operation logs, monthly reports, status reports, *Appendices Report* and two final operation reports - *Final Report on Reactor Operations for the Period September, 14, 1993 to December 31, 1994 and Final Report on Reactor Operations for the Period January 1, 1995 to November 21, 1995.*

The Adams program was developed in September 1990 to test and develop processes to remove selenium from agricultural drainage water. The program was a cooperative effort among four groups: the California Department of Water Resources (DWR), the Engineering Research Institute of California State University, Fresno (CSUF), Westlands Water District, and the U.S. Bureau of Reclamation (USBR).

The work at Adams was a continuation and further development of selenium removal processes that were tested at Murrieta Farms in western Fresno county by EPOC AG in 1985 and 1986. In the final report to DWR (Contract B-55712), recommendations included operation of a prototype plant to maximize selenium removal rates of a two-stage biological plant, development of a single-stage biological reactor (the upflow anaerobic sludge blanket reactor process) to replace the two-stage process, and the use of a crossflow filter as a polishing step to remove residual selenium. The Adams testing plan was based upon the recommendations but tested slow sand filtration in lieu of crossflow filtration. A packed bed reactor process was included in the Adams investigation to determine its use as a simple, alternative process for on-farm management of selenium. Other investigations included the use of molasses as an alternative carbon source for denitrification and the use of ferric chloride to coagulate and adsorb selenium from the effluent of first and second-stage processes.

Funding for this program was provided by DWR and USBR through DWR Contracts B-57806 and B-80502 to the Engineering Research Institute via the CSUF Foundation.

Paula J. Landis, Chief
San Joaquin District

TABLE OF CONTENTS

Page

FOREWORD iii

ORGANIZATION x

BACKGROUND INFORMATION 1

Introduction 1
Processes and Treatment Trains Tested 1
Anaerobic Treatment Processes 3
Selenium: A Brief Description of the Element and Commercial Uses 3
Selenium Analyses 4
Nitrate Analyses 5
Agricultural Drainage Water 5
Location, Site Development, and Infrastructure 6
Laboratory-scale Investigations 6

UPFLOW ANAEROBIC SLUDGE BLANKET REACTOR TEST 11

Upflow Anaerobic Sludge Blanket Reactor Test Unit 11
UASBR Operations 11
Period 1 Operations - September 14, 1992 through April 29, 1993 13
Period 1 Results 13
Period 2 Operations - July 19, 1993 through August 19, 1993 14
Period 2 Results 17
Period 3 Operations - September 1, 1993 through November 21, 1995 17
Period 3 Results 20

FLUIDIZED BED REACTOR TEST 25

Fluidized Bed Reactor Test Units 25
Fluidized Bed Reactor 1 Operations - October 12, 1993 through November 21, 1995 25
Fluidized Bed Reactor 1 Results 27
Fluidized Bed Reactor 2 Operations - October 13, 1993 through November 21, 1995 30
Fluidized Bed Reactor 2 Results 31

SLOW SAND FILTER TEST 37

Slow Sand Filter Test Units 37
Sand Filters 1 and 2 Operations - October 14, 1993 through November 2, 1994 37
Slow Sand Filter 1 Results 37
Slow Sand Filter 2 Results 39

Page

PACKED BED REACTOR TEST 45

Packed Bed Reactor Test Unit 45
Packed Bed Reactor Operations - December 16, 1993 through November 21, 1995 45
Packed Bed Reactor Results 45

PILOT UPFLOW ANAEROBIC SLUDGE BLANKET REACTOR (UA2) TEST 52

UA2 Test Unit 52
UA2 Operations - March 16, 1994 through November 16, 1995 52
UA2 Results 55

EVALUATION 59

First-stage Processes 59
Second-stage Processes 63
Third-stage Process 64
Process Trains 1 and 2 65

SUMMARY 67

REPORT BIBLIOGRAPHY 70

PROJECT BIBLIOGRAPHY 71

APPENDIX 73

Dates for Significant Events 74
Definition of Abbreviations 75

Figures

1. Process Trains and Process Tested at the Adams Avenue Facility 2
2. Location of the Adams Avenue Agricultural Drainage Research Center 7
3. Adams Facility Infrastructure Plan 8
4. Upflow Anaerobic Sludge Blanket Reactor Schematic 12
5. UASBR Period 1 - Influent Total Selenium, Soluble Selenium and Selenite 15
6. UASBR Period 1 - Effluent Total Selenium, Soluble Selenium and Selenite 15
7. UASBR Period 1 - Percentage of Soluble Selenium Reduced 15
8. UASBR Period 1 - Influent and Effluent Nitrate 15
9. UASBR Period 1 - Influent and Port 5 Dissolved Oxygen and Port 5 Temperature 16
10. UASBR Period 1 - Influent and Effluent Total and Volatile Suspended Solids 16
11. UASBR Period 1 - Influent and Effluent Total Organic Carbon 16

Figures (continued)

Page

12. UASBR Period 1 - Methanol Dosage 16
13. UASBR Period 3 - Influent Total Selenium, Soluble Selenium and Selenite 21
14. UASBR Period 3 - Effluent Total Selenium, Soluble Selenium and Selenite 21
15. UASBR Period 3 - Percentage of Soluble Selenium Reduced 21
16. UASBR Period 3 - Influent and Effluent Nitrate 21
17. UASBR Period 3 - Influent and Port 5 Dissolved Oxygen and Port 5 Temperature 23
18. UASBR Period 3 - Port 5 and Ambient Temperature 23
19. UASBR Period 3 - Influent and Effluent Total Organic Carbon 23
20. UASBR Period 3 - Methanol Dosage 23
21. UASBR Period 3 - Influent and Effluent Alkalinity 24
22. UASBR Period 3 - Sludge Volume 24
23. UASBR Period 3 - Influent and Effluent Total Dissolved Solids 24
24. UASBR Period 3 - Influent and Effluent Volatile Suspended Solids 24
25. Fluidized Bed Reactor Schematic 26
26. FBR1 - Influent Total Selenium, Soluble Selenium and Selenite 28
27. FBR1 - Effluent Total Selenium, Soluble Selenium and Selenite 28
28. FBR1 - Influent and Effluent Nitrate 28
29. FBR1 - Influent and Effluent Dissolved Oxygen 28
30. FBR1 - Reactor and Ambient Temperature 29
31. FBR1 - Influent and Effluent Alkalinity 29
32. FBR1 - Influent and Effluent Total Organic Carbon 29
33. FBR1 - Influent and Effluent Total Suspended Solids 29
34. FBR2 - Effluent Total Selenium, Soluble Selenium and Selenite 32
35. FBR2 - Percentage of Soluble Selenium Reduced and Dates for Media and Phosphate Dosage Changes 32
36. FBR2 - Influent and Effluent Nitrate 32
37. FBR2 - Reactor and Ambient Temperatures and Date for Recycle Pump Change 32
38. FBR2 - Influent and Effluent Dissolved Oxygen 34
39. FBR2 - Methanol Dosage 34
40. FBR2 - Influent and Effluent Total Organic Carbon 34
41. FBR2 - Influent and Effluent Volatile Suspended Solids 34
42. FBR2 - Influent and Effluent Total Suspended Solids 35
43. FBR2 - Influent and Effluent Alkalinity 35
44. FBR2 - Influent and Effluent Electrical Conductivity 35
45. FBR2 - Influent and Effluent Total Dissolved Solids 35
46. Slow Sand Filter Schematic 38
47. SSF1 - Influent and Effluent Total Selenium 40
48. SSF1 - Influent and Effluent Soluble Selenium 40
49. SSF1 - Influent and Effluent Particulate Selenium 40
50. SSF1 - Percentage of Total Selenium Removed 40
51. SSF1 - Influent and Effluent Nitrate 41

Figures (continued)

Page

52. SSF1 - Influent and Effluent Total Organic Carbon....41
53. SSF1 - Influent and Effluent Total Suspended Solids....41
54. SSF1 - Influent and Effluent Volatile Suspended Solids....41
55. SSF2 - Influent and Effluent Total Selenium....43
56. SSF2 - Influent and Effluent Soluble Selenium....43
57. SSF2 - Influent and Effluent Particulate Selenium....43
58. SSF2 - Percentage of Total Selenium Removed....43
59. SSF2 - Influent and Effluent Nitrate....44
60. SSF2 - Influent and Effluent Total Organic Carbon....44
61. SSF2 - Influent and Effluent Total Suspended Solids....44
62. SSF2 - Influent and Effluent Volatile Suspended Solids....44
63. Packed Bed Reactor Schematic....46
64. PBR - Effluent Total Selenium, Soluble Selenium and Selenite....48
65. PBR - Percentage of Total and Soluble Selenium Reduced and Dates for Methanol Dosage Change....48
66. PBR - Influent and Effluent Nitrate....48
67. PBR - Reactor and Ambient Temperatures....48
68. PBR - Influent and Effluent Dissolved Oxygen....49
69. PBR - Methanol Dosage and Date for Change of Target Dosage Rate....49
70. PBR - Influent and Effluent Total Organic Carbon....49
71. PBR - Influent and Effluent Total Suspended Solids....49
72. PBR - Influent and Effluent Volatile Suspended Solids....50
73. PBR - Influent and Effluent Total Dissolved Solids....50
74. PBR - Influent and Effluent Alkalinity....50
75. PBR - Influent and Effluent Electrical Conductivity....50
76. Pilot-Scale Upflow Anaerobic Sludge Blanket Reactor Schematic....53
77. UA2 - Effluent Total Selenium, Soluble Selenium and Selenite....57
78. UA2 - Percentage of Soluble Selenium Reduced and Dates for Influent Flow Change and Restart after Flooding....57
79. UA2 - Influent and Effluent Nitrate....57
80. UA2 - Influent and Effluent Dissolved Oxygen....57
81. UA2 - Influent and Effluent Total Organic Carbon....58
82. UA2 - Influent and Effluent Total Dissolved Solids....58
83. UA2 - Influent and Effluent Alkalinity....58
84. UA2 - Influent and Effluent Electrical Conductivity....58

Tables

1. Relationship of Measured Selenium Values to Possible Selenium Species....5
2. Agricultural Drainage Water Constituents....6
3. UASBR Period 3 Methanol Dosages....19

Tables (continued)

Page

4. First-stage Processes - Reduction of Soluble Selenium and Retention Time 60
5. First-stage Processes - Change in Alkalinity and pH 60
6. First-stage Processes - Operation Parameters, Effluent Concentrations and Reduction of Nitrate and Soluble Selenium 61
7. First-stage Processes - Effluent Selenium Concentrations and Selenium Reductions 62
8. Second-stage Processes - Operation Parameters and Nitrate and Soluble Selenium Reduced 63
9. Second-stage Processes - Effluent Selenium Concentrations and Percentages of Selenium Reductions 64
10. Third-stage Process - Effluent Selenium Concentrations and Percentages of Selenium Reductions 65
11. Process Trains 1 and 2 - Effluent Selenium Concentrations and Percentages of Selenium Reductions 65

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Recognition is also given to Dr. Lawrence P. Owens
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BACKGROUND INFORMATION

Introduction

The Department of Water Resources has participated in or sponsored investigations involving agricultural drainage water since early 1960. Selenium in agricultural drainage water became a concern in the 1980s with problems at Kesterson National Wildlife Refuge in Merced County. Birth deformities and deaths of aquatic birds at the refuge were attributed to the accumulation of selenium in the refuge's water and soils. The refuge was operated as a staged evaporation basin complex for drainage water while documentation was being prepared to complete the San Luis Drain. Discharge of drainage into the refuge terminated in 1985. The San Luis Drain was closed a year later.

The San Joaquin Valley Drainage Program was established in 1984 to address drainage and drainage-related problems and impacts of drainage activities on the environment. In 1990, the SJVDP, a joint federal and State effort, recommended further development of the "Binnie Process" to reduce or remove selenium from drainage water. This process employs an anaerobic treatment or a combination of anaerobic treatments in series followed by filtration. Development of this process led to the establishment of the Adams Avenue Agricultural Drainage Research Center near Tranquillity, California.

In September 1990, the Adams Avenue project commenced as a cooperative effort among DWR, United States Bureau of Reclamation, Westlands Water District, and the Engineering Research Institute at the California State University, Fresno to provide a facility to develop and field demonstrate processes to treat agricultural drainage water. Testing began in September 1992 and ended November 1995.

Processes and Treatment Trains Tested

At one time, seven processes were operated at the Adams facility. These processes included an upflow anaerobic sludge blanket reactor (UASBR), two fluidized bed reactors (FBR 1 and 2), two slow sand filters (SSF 1 and 2), a packed bed reactor (PBR), and a pilot upflow anaerobic sludge blanket reactor (UA2). The processes were arranged in two treatment trains consisting of an UASBR/FBR1/SSF1 (Train 1) and UASBR/SSF2 (Train 2). The FBR2, PBR, and UA2 processes were operated as stand-alone processes. A schematic of the process trains and processes tested at the Adams facility is shown in Figure 1. Also, laboratory-scale investigations were performed at the CSUF campus to develop start-up parameters when the infrastructure for the facility was being developed and constructed. These investigations tested a sequencing batch reactor, a UASBR, a packed bed reactor, and slow sand filtration processes.

Laboratory-scale investigations at the CSUF campus to develop start-up parameters commenced in August 1991 and were completed October 1992. UASBR began operating in September 1992 and continued until closure of the Adams facility in November 1995. Testing was interrupted for two periods, from April 1993 to July 1993 and from August 1993 to September 1993, for system modifications and repairs. The fluidized bed reactors were brought online in October 1993 and remained in operation until November 1995. The slow sand filters were operated from

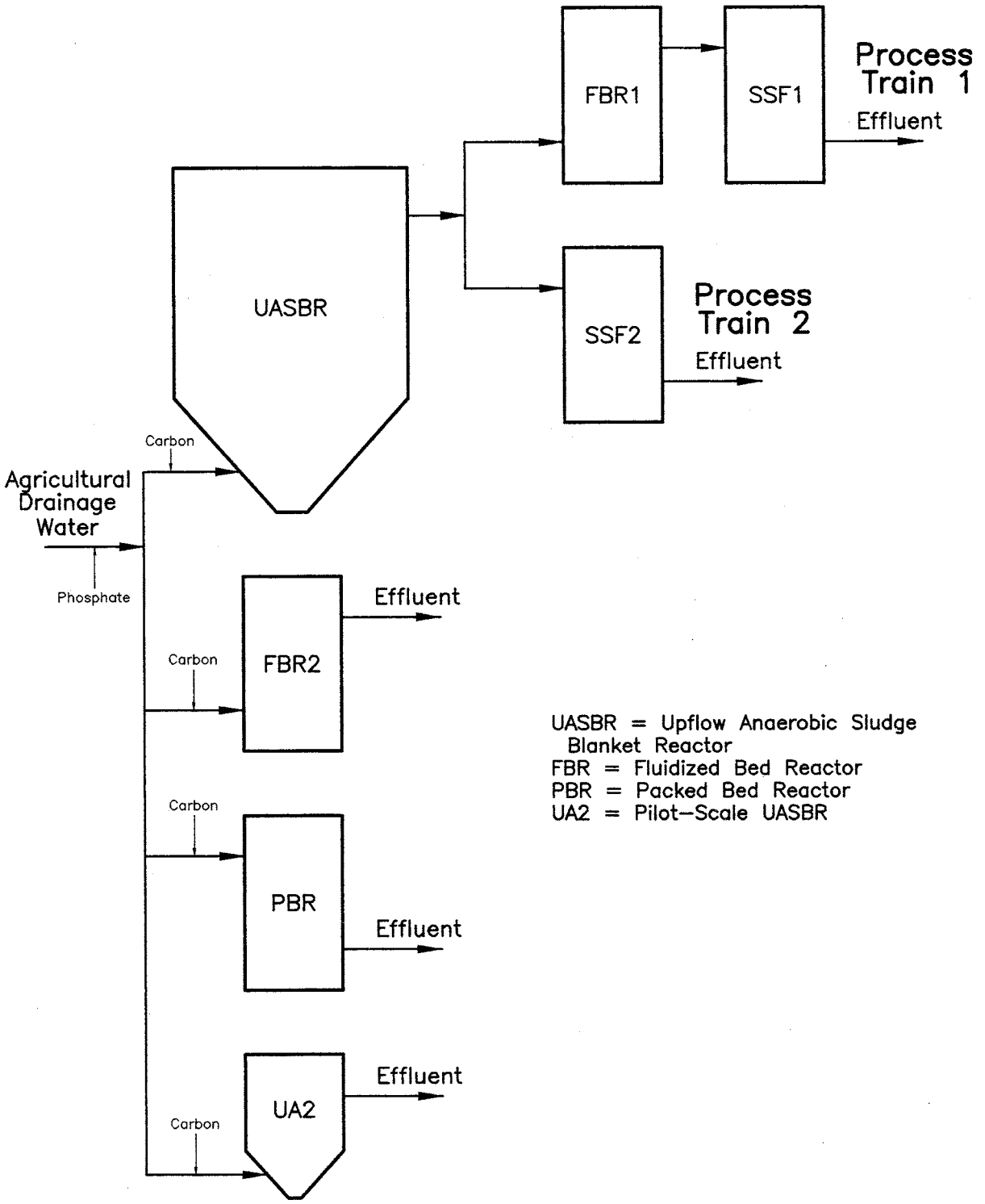


Figure 1. Process Trains and Process Tested at the Adams Avenue Facility

October 1993 to November 1994. Testing with the UA2, the pilot UASBR, began June in 1994 and ended in November 1995.

Anaerobic Treatment Processes

The sludge blanket reactor and fluidized bed reactor processes were the anaerobic processes tested by EPOC AG and Binnie California, Inc. at Murrieta Farms and by CSUF at the Adams facility. Anaerobic processes are used in a wide variety of applications. Anaerobic digestion is commonly used to stabilize municipal sewage sludge. Other applications include removal of organic constituents in high-strength industrial wastewaters in pulp and paper, food processing, and beverage industries. Use of these processes is also being developed to treat low-strength wastewaters. The work at Murrieta Farms and the Adams Avenue facility were initial developments of anaerobic processes to reduce and remove selenium from agricultural drainage water.

Anaerobic treatment involves decomposing organic and inorganic material in the absence of oxygen. In a closed system, anaerobic bacteria break down complex organic compounds into more basic ones. Advantages of anaerobic treatment processes include a low production of waste biological solids, low nutrient requirements, no energy requirements for aeration, high loading rates that can be applied under favorable conditions, and anaerobic sludge that can be stored unfed for many months. Disadvantages of the processes include long periods of time required for start-up, high-sensitivity to specific compounds, and little operating experience exists on the application of the process to the direct treatment of wastewater (Lettinga and others 1980).

Selenium: A Brief Description of the Element and Commercial Uses

Selenium is the thirty-fourth element in the Periodic Table of Elements. This nonmetallic element is in the sulfur family and resembles sulfur in its various forms and compounds. Elemental selenium is considered a trace element and is thought to be non-toxic. Other valence forms of selenium are selenate (+6), selenite (+4), and selenide (-2). Selenate is the most soluble form of selenium. Selenium in agricultural drainage water is 85 percent to 95 percent in the selenate form.

Selenium is an element required by humans and livestock in trace amounts to maintain a healthy diet. It is an essential antioxidant for humans. The soil of various areas on the east side of the San Joaquin Valley is selenium deficient and selenium must be added as a supplement to cattle feed to prevent white muscle disease. Excessive selenium in livestock can cause improper bone development, alkali disease, and cerebral disorders. The effects on wildlife of an excessive amount of selenium were demonstrated at Kesterson Wildlife Refuge as previously noted.

Commercially, selenium is widely used in the glass, photographic, reprographics, and electrical industries. It is used to decolorize glass and to make ruby-colored glasses and enamels in the glass industry; produce photocells, photograph exposure meters, and solar panels in the photographic industry; reproduce and copy documents, letters, and other materials in the reprographics industry; and used in the electrical industry in rectifiers and to convert alternating current electricity to direct current electricity.

Selenium Analyses

Selenium analyses for the Adams Project were performed according to Standard Methods procedure 3500-Se C, a continuous hydride generation/atomic absorption spectrometric method. The Hydride generation method involves the addition of a strong reducing agent (sodium borohydride) to the sample to generate a gaseous hydrogen selenide. The gas is swept into a heated quartz cell aligned in the optical path of an atomic absorption spectrophotometer equipped with a selenium lamp operating at 196 nm. The signal produced by the gaseous hydrogen selenide is proportional to the amount of selenite present in the sample. A Varian SpectraAA-10 flame absorption spectrophotometer equipped with a VGA-76 vapor generation assembly and a PCS-56 automatic sampler was used for the analyses. The detection limit for the apparatus is 1 ug/L.

Three analyses were performed on most of the samples. Total selenium was measured by first oxidizing all species to the selenate form (Se^{+6}) with potassium permanganate. The selenate was then reduced to selenite with hot hydrochloric acid. Soluble selenium was similarly treated to total selenium, except the sample was filtered through a 0.22 um nylon membrane filter to remove particulate selenium prior to the oxidation step. Selenite (Se^{+4}) was determined from the sample directly without digestion, since this is the valence state from which the selenium hydride is formed.

A duplicate sample, a spiked sample, and a spiked blank were analyzed with each type of selenium determination for each sample set. The control limits were +-15% RPD for duplicates and +-20% for recovery of the spiked samples. Sample sets which did not pass the QC limits were repeated until they passed, to a maximum of three times. After the third run, if the QC values were not satisfied, judgment on which was the best value based on the historical concentration of each form of selenium in each sample was used to select the best representative analysis set.

For the discussion of selenium results in this report, total selenium refers to the concentration of all selenium species in the sample before filtration, soluble selenium is a measure of total selenium after passing through a 0.22 um laboratory filter, selenite is the concentration of selenium in the +4 valence state without the sample pretreatment steps, and particulate selenium is the difference between the total and soluble values. The relationship between the measured selenium values and the possible selenium species that might be incorporated in that measured value is shown below in Table 1.

Table 1
Relationship of Measured Selenium Values to
Possible Selenium Species

Measured Selenium Value	Selenium species that may contribute to the measured value
Total Selenium (Total Se determined for an unfiltered sample)	**Particulate Species:** Elemental Se, Se incorporated into bacterial cells or other particulates **Soluble Species:** Selenate, selenite, dissolved organic selenium (such as selenoamino acids) Notes: 1. Represents all Se species present in the sample. 2. Total Se = Particulate + Soluble
Soluble Selenium (Total Se determined for a sample after passing through a 0.22 μm membrane filter)	Selenate, selenite, dissolved organic selenium, any particulate selenium capable of passing through a 0.22 μm filter
Selenite	Selenite only

Notes: Selenate selenium is in the +6 oxidation state and the oxyanion is SeO_4^{-2}. Selenite selenium is in the +4 oxidation state and the oxyanion is SeO_3^{-2}. Elemental selenium is in the 0 oxidation state. The table above was obtained from *AAADRC Operation Report* September 1992 - December 1994.

Nitrate Analyses

Throughout the entire testing period, field nitrate analyses were performed using a colormetric method from Hach Company. The field analyses compared well with weekly laboratory analyses initially performed by the nitrate electrode method - Standard Methods procedure 4500-NO3 C. Unfortunately, a bias was found in August 1995 when nitrate was determined by ion chromatography. The field analyses provided a low bias on the untreated water and a high bias on the treated water. The UASBR's influent and effluent averaged 65 and 2.1 mg/L as N, respectively, as determined by the laboratory ion chromatographic (IC) method, while field determinations averaged 35 mg/L as N and 6.0 mg/L as N for the same period from August 1, 1995 to November 21, 1995. Such bias was also shown by comparing FBR2's and the PBR's the average effluent nitrate analyses for the two methods. Even though this bias exists, field measurements are used for evaluation in the report.

Agricultural Drainage Water

The agricultural drainage water treated at the Adams facility was subsurface drainage obtained from Westlands Water District's collector drain 136.0. The drainage water was taken from a collector sump alongside Lincoln Avenue and pumped 6,200 feet through 6-inch, Class 125 PVC pipe into a 6,000-gallon storage tank at the Adams facility. Potassium phosphate was added to the drainage water to ensure a sufficient amount of nutrient for biological growth. The constituent concentration makeup of the Adams drainage water was similar to that of

San Luis Drain water. Table 2 compares constituent concentrations from a sampling station on the San Luis Drain to drainage water tested at the Adams facility.

Table 2
Agricultural Drainage Water Constituents

	San Luis Drain*	Adams**	
Nitrate	47	30	mg/L as N
Nitrite	0.04	na	mg/L as N
Alkalinity	191	191	mg/L as CaCO3
pH	8.2	7.5	
Selenium	261	520	ug/L
Total Suspended Solids	na	19	mg/L
Volatile Suspended Solids	na	10	mg/L
Total Dissolved Solid	9,471	8,311	mg/L
Total Organic Carbon	9.3	12.4	mg/l

*Average of Monthly Values of San Luis Drain at Bass Road from 3-82 to 12-85
**Adams Avenue Average Values
na - not available

Location, Site Development, and Infrastructure

The Adams facility was adjacent to the San Luis Drain at 29177 West Adams Avenue near Tranquillity, in western Fresno County, as shown in Figure 2. The property is in an area of shallow flooding and owned by Westlands Water District.

In 1988, WWD chose the Adams site for two of its projects (a deep well injection project and a 1-mgd prototype selenium removal plant) to resolve agricultural drainage problems. These projects were never fully developed due to results for the exploratory test well and lack of funding for the treatment plant.

The infrastructure of the Adams facility was developed in a coordinated effort by WWD, Engineering Research Institute, and DWR. Site development included construction of an elevated, engineered earth pad on which the facility was built; placement of a paved roadway; installation of electrical power and control panels, switchgear, and wiring; relocation of personnel trailers, workshop sheds, equipment, tanks, and other items and materials from DWR's Los Banos desalting facility; construction of the drainage water supply and effluent lines; installation of a service water system; and other work to make the facility functional. Completion of the drainage water supply line in June 1992 signified that the core of the infrastructure work was complete. The infrastructure layout for the Adams facility is shown in Figure 3.

Laboratory-Scale Investigations

When the infrastructure of the Adams facility was being developed and constructed, and the equipment was being installed, CSUF performed on-campus, laboratory-scale investigations to develop start-up operation parameters for the processes proposed for testing at the Adams

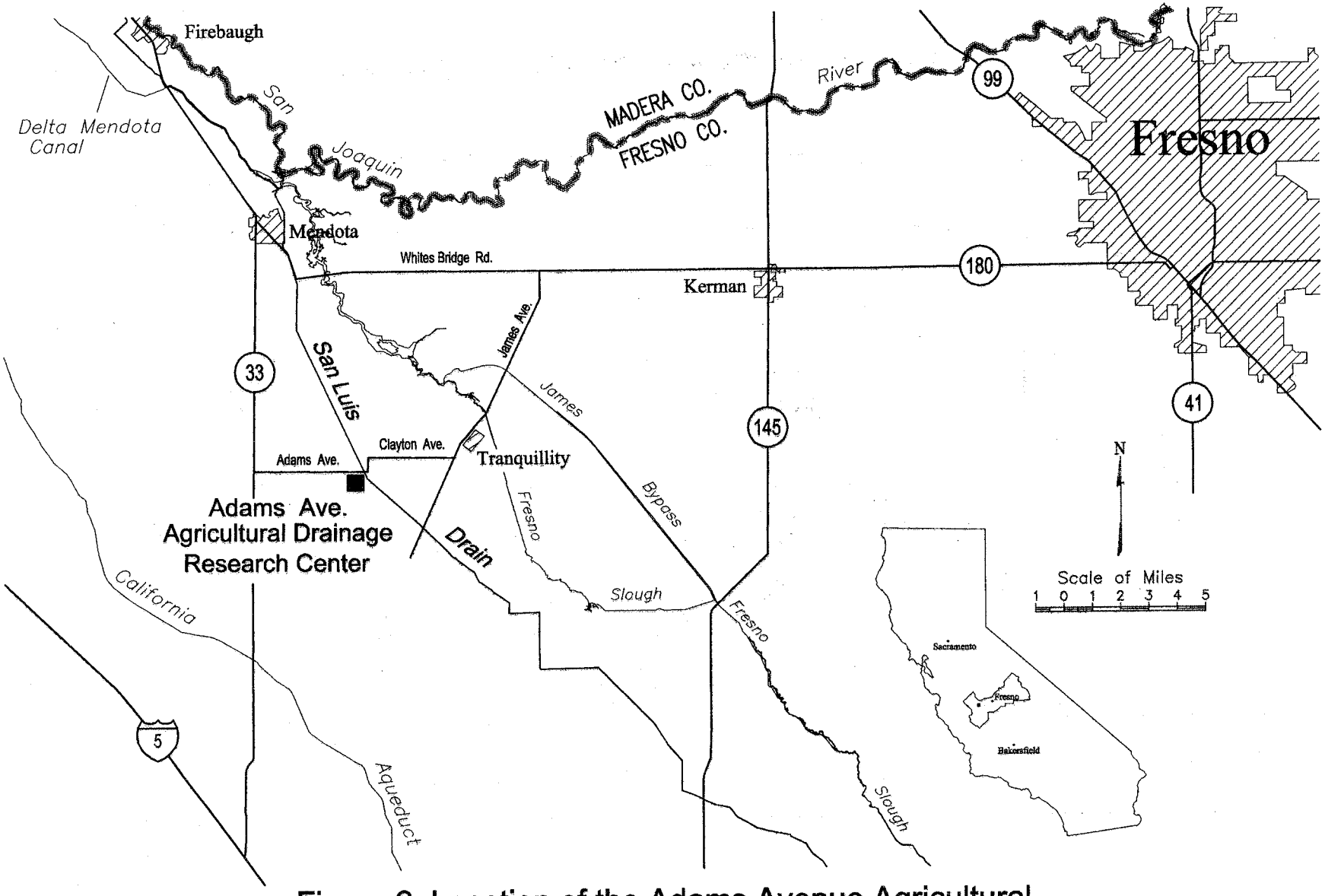


Figure 2. Location of the Adams Avenue Agricultural Drainage Research Center

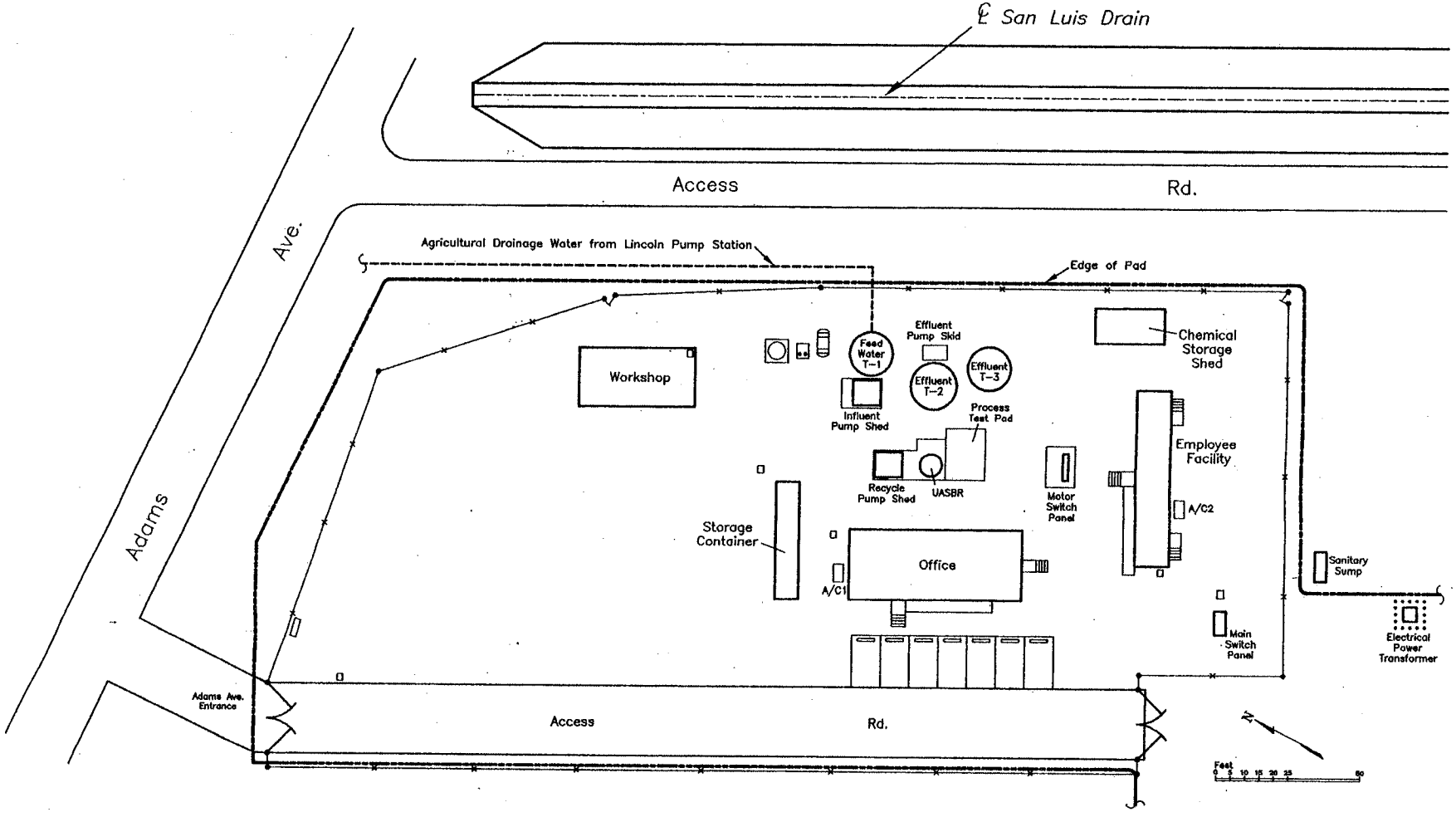


Figure 3. Adams Facility Infrastructure Plan

facility. These processes were a sequencing batch reactor, a packed bed reactor, a slow sand filter, and an upflow anaerobic sludge blanket reactor. The reactors were operated to determine the source of carbon (methanol and acetate), the residence time, and the effect of pH on selenium reduction and system operations. Actual agricultural drainage water from WWD's drain 136.0 was trucked onto the CSUF campus for use in these investigations.

The results of the laboratory-scale investigations provided basic information required for start-up. Two 30-gallon sequencing batch reactors were operated in parallel; one was fed with methanol as the carbon source, while the other was fed with acetate. Even though reduction of soluble selenium reached 86 percent and 90 percent for the methanol and acetate reactors respectively, testing showed that the SBR process was not well suited for further development on a larger scale. Selenium reduction that occurred was a result of attached-growth bacteria. The scale-up from the 30-gallon SBRs to the planned 1,000-gallon SBR predicted a lower treatment efficiency. Testing of the SBR process was terminated and replaced with testing of a continuous-flow packed bed reactor process.

Two 10-liter packed bed reactors were operated in parallel. The PBRs were operated for approximately 230 days and methanol was the carbon source. From test day 121, the PBRs reduced 77 percent and 81 percent of soluble selenium with an empty bed contact time of about 24 hours. Selenium profiles performed on the PBRs showed that selenium reduction occurred early in the reactor and that the remaining reactor volume did not provide any additional reduction.

Slow sand filtration was tested in two experiments to investigate the process as a polishing step to remove particulate selenium. In the first experiment, a slow sand filter was used to treat the effluent from the methanol-fed SBR. The second experiment consisted of testing two filters in parallel treating the effluent of the PBRs at different hydraulic loadings. For the first experiment, 67 percent of particulate selenium was removed. This percentage was calculated from the average influent and effluent selenium values for the duration of the experiment. The second experiment removed particulate selenium in both filters by 72 percent and 78 percent for hydraulic loadings of 0.04 gpm/ft^2 (0.1 m^3/(m^2*hr)) and 0.02 gpm/ft^2 (0.05 m^3/(m^2*hr)), respectively. Besides removing particulate selenium, both SSFs reduced selenium by 89 percent.

For the upflow anaerobic sludge blanket process, treatment occurs from biological reduction reactions as influent drainage water passes upwards through a sludge blanket. Retention of the sludge in the reactor is critical to the process. In addition, the chemistry of drainage water changes as it passes through the reactor, where it may cause precipitation of salt in the reactor, inhibit treatment, and lead to maintenance problems.

Lastly, two laboratory-scale upflow anaerobic sludge blanket reactors were operated to address sludge granule (biomass) retention and salt precipitation concerns and determine the efficacy of bakery sludge in reducing and removing selenium from drainage water. The lab-scale UASBRs consisted of 1-liter Imhoff cones. The sludge used in the tests was obtained from a dormant anaerobic treatment process that treated bakery waste. Methanol and potassium phosphate (to prevent nutrient deficiency) were added to the feed water for both reactors. To address the salt precipitation concern, hydrochloric acid was added to the feed of one reactor to adjust the pH from around 8 to 6.9. Both reactors were operated with a recycle flow for over 100 days at a

retention time of approximately 18 hours. Water analyses indicated both reactors completely denitrified the drainage water. Around day 40 of the test, the sludge granules of the pH-adjusted reactor broke down into floc. The floc aggregated into clumps and floated to the surface. As a result of the formation of the floc, and to maintain the biomass in the reactor, the recycle flow for the reactor was terminated for the remainder of the test. Selenium reduction, based on soluble selenium of the effluent for the entire testing period, averaged 86.8 percent for the pH-adjusted reactor, while the non-pH-adjusted reactor averaged 83.4 percent. No signs of salt precipitation were observed in either reactor.

UPFLOW ANAEROBIC SLUDGE BLANKET REACTOR TEST

Upflow Anaerobic Sludge Blanket Reactor Test Unit

The upflow anaerobic sludge blanket process consists of treating wastewater in a closed vessel containing anaerobic sludge. Treatment occurs as the influent passes upwards through the sludge blanket (bed) into a settling zone that contains a baffle and a gas/solids separator cone. The baffle directs the wastewater up into the cone. Gas and solids are separated from the wastewater as it passes down and around the separator. The treated wastewater is then withdrawn from the upper portion of the vessel. The gas generated from the decomposing matter is collected at the top of the cone and extracted. Depending on the type of wastewater being treated, UASBR may be equipped to mix the sludge bed and to recirculate the wastewater through the reactor.

The UASBR at the Adams facility consisted of a 3,000-gallon, polyethylene, closed-top, cone tank. The UASBR was initially fitted with a baffle, hypalon gas/solids separator cone and sampling ports. Throughout testing, modifications were made to the UASBR. These included the addition of sludge mixing and recirculation systems along with other modifications to influent and effluent piping, carbon injection system, and other ancillary appurtenances. The separator cone was replaced twice. Initially the hypalon cone was replaced with a Lexan cylinder. Eventually, the cylinder was replaced with a cone made from high-density polyethylene plastic. Figure 4 shows the final layout of the UASBR system.

UASBR Operations

Operation of the UASBR is divided into three periods. During Period 1, September 1992 through April 1993, the UASBR was operated using a granular sludge obtained from an anaerobic process that treated bakery waste. Operation was stopped due to failure of the hypalon gas/solids separator cone. Period 2, July 1993 through August 1993, involved operation, again using the remaining granular bakery sludge, after the hypalon separator cone was repaired and other modifications were made. Testing was stopped due to the breakup and loss (carryover) of the granular sludge from the reactor. During Period 3, September 1993 through November 1995, testing was conducted using a wastewater treatment plant sludge obtained from a mixed anaerobic digester.

The UASBR was operated continuously, 24 hours a day, seven days a week for all the test periods. Initially, field data on flow rates, dissolved oxygen, nitrate, and temperature were collected daily. In June 1994, data collection was reduced to six days a week when weekend staffing was reduced. Electrical conductivity measurements were obtained weekly. The parameters of pH, sludge volume, and alkalinity were later added to the weekly field measurements at various times during the test program. Samples of the influent and effluent streams were collected weekly and sent to the university's laboratory for analyses of total selenium, selenite, total suspended solids, volatile to solids, total dissolved solids, and total organic carbon. Analyses for sludge were performed periodically to document its makeup over time. The volume of gas produced in the UASBR was recorded during Period 3. Gas samples were collected at various times during the later portion of Period 3 to determine constituent makeup of the gas and to perform mass balances.

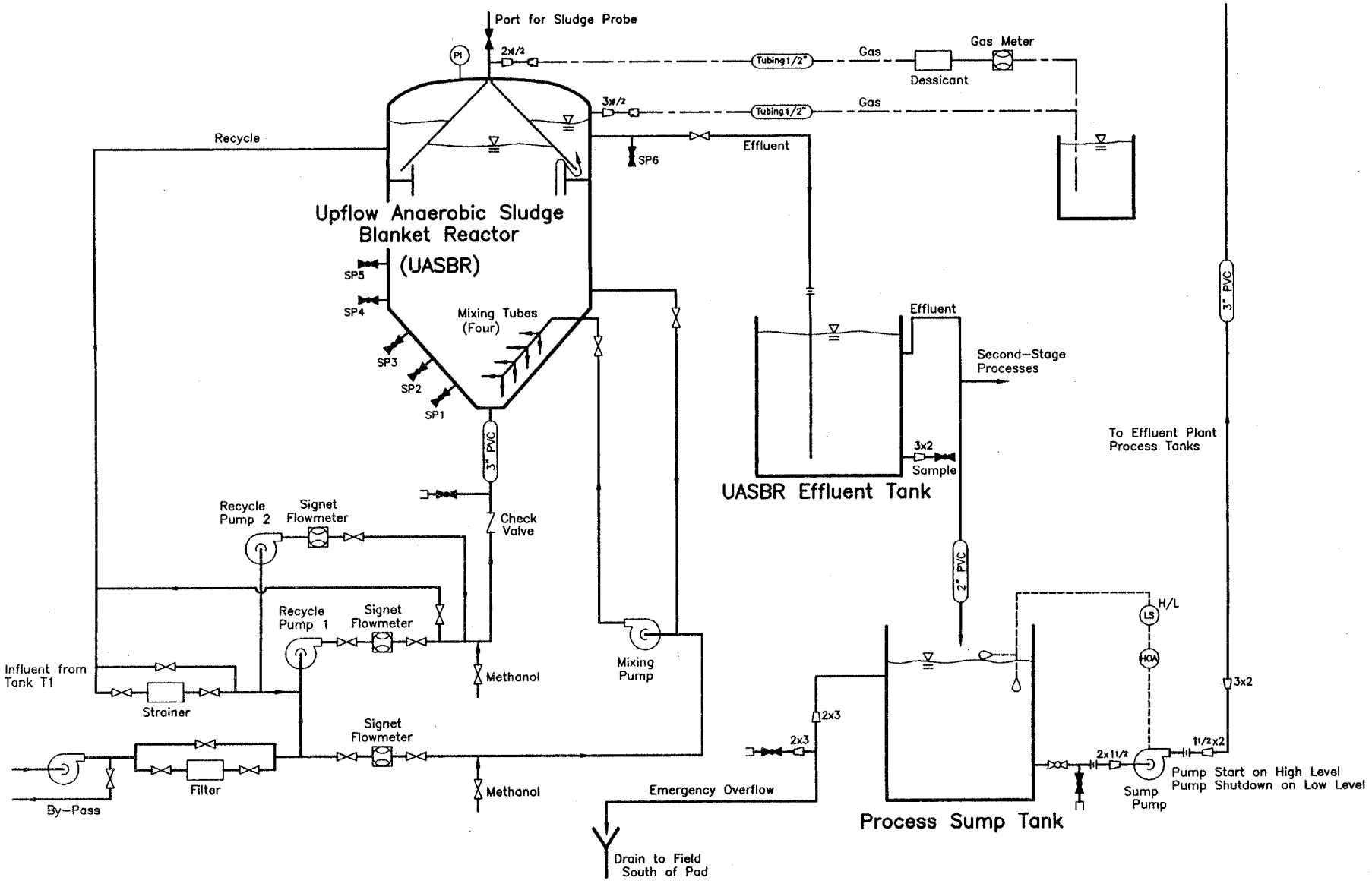


Figure 4. Upflow Anaerobic Sludge Blanket Reactor Schematic

Period 1 Operations - September 14, 1992 through April 29, 1993

A 6,000-gallon shipment of granular sludge arrived at the Adams facility from Kansas City, Missouri, on September 14 and the arrival marked the beginning of Period 1. This date is also defined as Day 0 for all testing at the Adams facility. Period 1 operations lasted through April 29, 1993 (Day 227). Granular sludge was obtained from a dormant UASBR that treated a high COD bakery waste. This saved months in start-up time that would have been needed to generate a new supply of sludge. Half of the sludge was put into the UASBR while the remainder was placed in two fiberglass tanks for use at a later date. The settled granules filled the bottom cone of the reactor tank and measured approximately 500 gallons.

The first 14 days of operation in Period 1 were spent acclimatizing the sludge to drainage water and modifying the effluent and recycle piping to prevent air-entrainment in those streams. Flow of drainage water through UASBR was gradually increased from 0.5gpm to 2gpm by October 19 and remained at this flow for the remainder of Period 1. The process was operated at an average upflow rate (influent flowrate added to the recycle flowrate) of 84 gpm, or at an average upflow velocity of 1.82 gallons per minute per square foot (gpm/ft^2) in the reactor throughout the period. The carbon required for denitrification to the influent stream averaged 355 mg of methanol per liter of drainage water (mg/L) throughout Period 1. The carbon dosage exceeded the amount required for denitrification (USEPA) to ensure the UASB process was not limited by carbon. Previous work by Binnie and others has shown that selenium reduction occurs after the nitrate has been reduced.

Modifications were made to the UASBR system throughout Period 1. On February 21, 1993, (Day 160), provisions were made for additional mixing of the sludge bed by diverting 20 gpm of the recycle flow and injecting the stream at various depths into the sludge bed with a PVC pipe inserted through the top of the reactor. This setup provided horizontal mixing of the sludge. Modifications were made to the influent and effluent piping at various dates to improve the control of flow through the reactor. Also, the methanol injection system was modified to improve system reliability. For Period 1, methanol dosages ranged between 177 and 660 mg/L with standard deviation of 70 mg/L. Control of the methanol feed system to maintain a constant dosage was a continuing problem until late in the testing program.

A series of events which were first documented on January 13, 1993, (Day 121), led to the eventual shut-down of the UASBR on April 29, 1993, (Day 227). Period 1 testing ceased because of the failure of the gas/solids separation cone and slippage of the baffle to the bottom of the UASBR.

Period 1 Results

The total and soluble selenium and selenite concentrations for the agricultural drainage water for Period 1 are shown by Figure 5. Total selenium (Tse) ranged between 433 ug/L and 592 ug/L and averaged 511 ug/L while soluble selenium (Sse) ranged between 360 ug/L and 564 ug/L and averaged 482 ug/L. Selenite concentrations for the period averaged 2 ug/L. These selenium values for the raw drainage water were typical for the entire testing program.

Figure 6 shows the UASBR effluent selenium values for the period. The effluent Sse concentration gradually increased until it leveled to above 300 ug/L on December 28, 1992. It remained at that level until January 15, 1993, when reduction improved and lowered to under 200 ug/L. As previously stated in the operations section, modifications to mix the sludge bed were made on February 15. From February 15, the effluent Sse concentration gradually improved and reached 57 ug/L on March 8. After March 8, the effluent Sse concentration increased, was erratic and appeared to be indicative of problems with the gas/solids separation cone in the reactor.

The percentage of soluble selenium reduced in the UASBR for Period 1 is shown in Figure 7. Sse removal was in excess of 80% until November 23. Between November 23 and February 26, 1993, Sse removal fluctuated from a high of 75% to a low of 32%. Again, removal rose above 80% from March 1 through March 8 before the apparent failure of the hypalon gas/solids cone. The field measurements for influent and effluent nitrate concentrations are shown in Figure 8. All values for nitrate concentration for the project and in this report are stated in mg/L as N. The influent concentration ranged between 19 mg/L and 50 mg/L and averaged 40 mg/L. The effluent residual was between 0 mg/L and 4 mg/L and averaged 2.2 mg/L until March 18 after which the effluent residual substantially increased. Again the effluent values indicated problems with the hypalon gas/solids cone. Laboratory measurements consistently corresponded to the field values.

Influent and Port 5 dissolved oxygen and Port 5 temperature values are shown in Figure 9. Port 5 corresponded to the 1,100-gallon level of the reactor and was 1.5 feet above the top of the reactor's conical bottom cone. The level of sludge was usually below Port 5 for the duration of the test program. The influent DO concentration ranged from a low of 5.5 mg/L to a high of 11 mg/L and averaged to 9.3 mg/L. The effluent concentration averaged 0.3 mg/L for the period. The reactor's temperature is shown to compare temperature to that of the other monitored data.

Influent and effluent total and volatile suspended solids concentrations are shown in Figure 10. The feed TSS and VSS concentrations averaged 26 mg/L and 15 mg/L, respectively. Until March 1, 1993, the effluent TSS and VSS values averaged 56 mg/L and 26 mg/L, respectively. After March 1, both effluent values increased and was thought to be attributed to the failure of the hypalon gas/solids cone.

The influent and effluent total organic carbon concentrations are shown in Figure 11, while methanol dosage is shown in Figure 12. The feed TOC concentration remained relatively stable through this test period and averaged 9 mg/L. The effluent TOC concentration averaged 21 mg/L and was always equal to or in excess of the influent concentration except on December 21, 1992, when the influent and effluent concentrations were 11 mg/L and 12 mg/L, respectively. A discussion of methanol dosage and the dosing system is provided in the previous operation section.

Period 2 Operations - July 19, 1993 through August 19, 1993

Testing resumed after the separation cone was repaired, the baffle was bolted to the side of the reactor, and other modifications were made. The gas extraction piping was modified and the

Figure 5
UASBR Period 1 - Influent Total Selenium, Soluble Selenium and Selenite

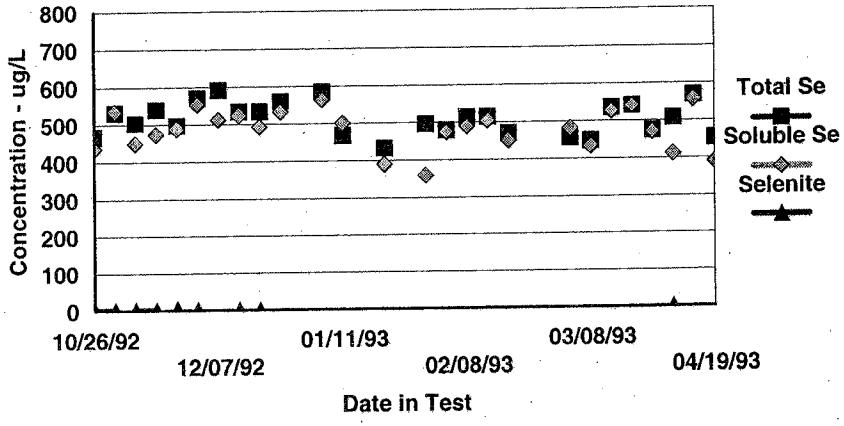


Figure 6
UASBR Period 1 - Effluent Total Selenium, Soluble Selenium and Selenite

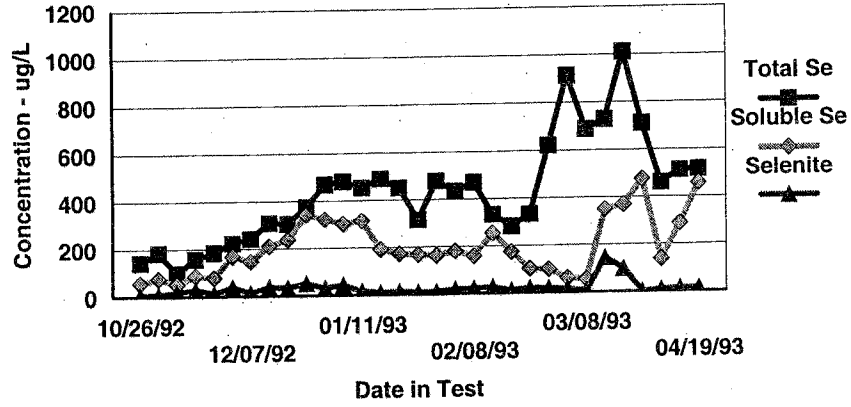


Figure 7
UASBR Period 1 - Percentage of Soluble Selenium Reduced

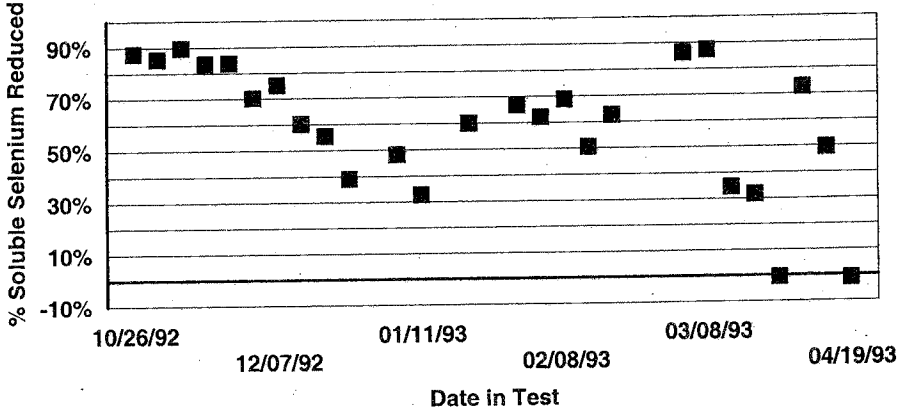


Figure 8
UASBR Period 1 - Influent and Effluent Nitrate

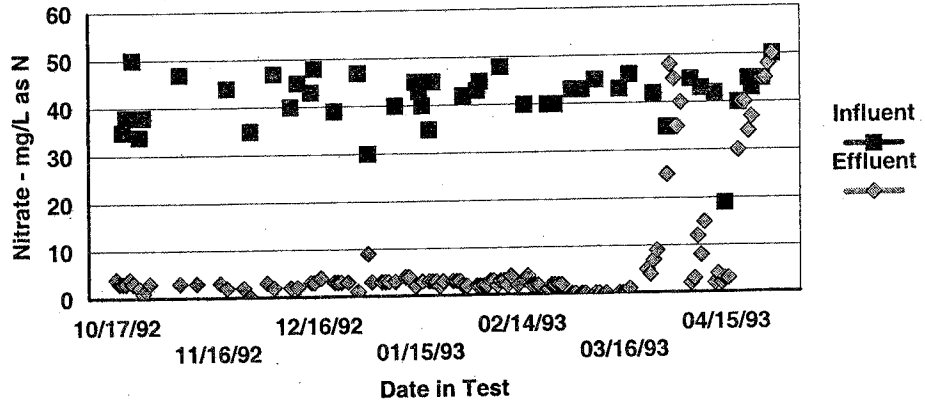


Figure 9
UASBR Period 1 - Influent and Port 5
Dissolved Oxygen and Port 5 Temperature

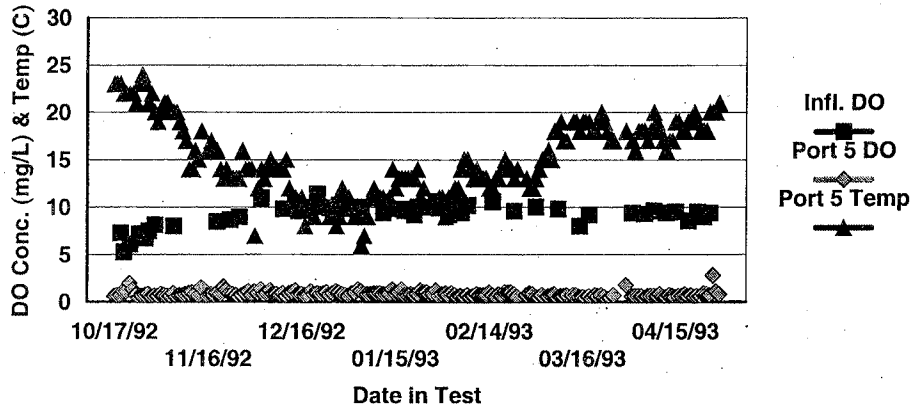


Figure 10
UASBR Period 1 - Influent and Effluent
Total & Volatile Suspended Solids

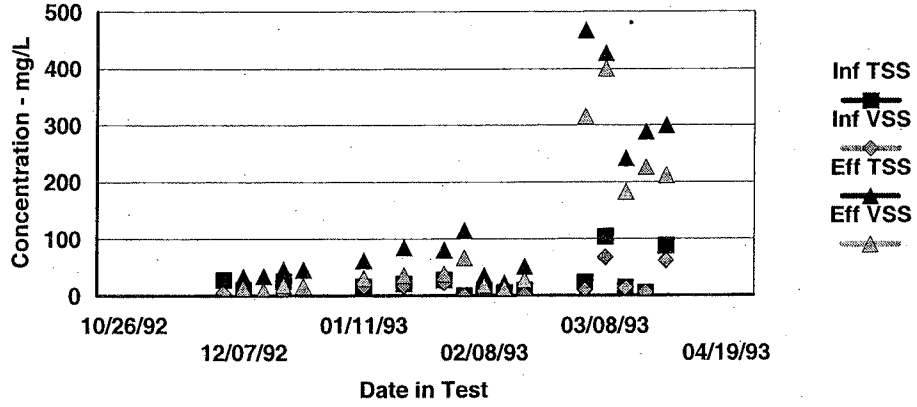


Figure 11
UASBR Period 1 - Influent and Effluent
Total Organic Carbon

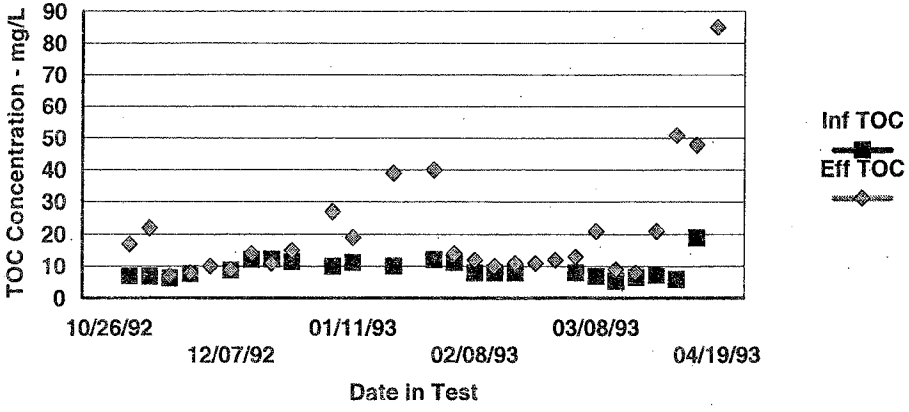
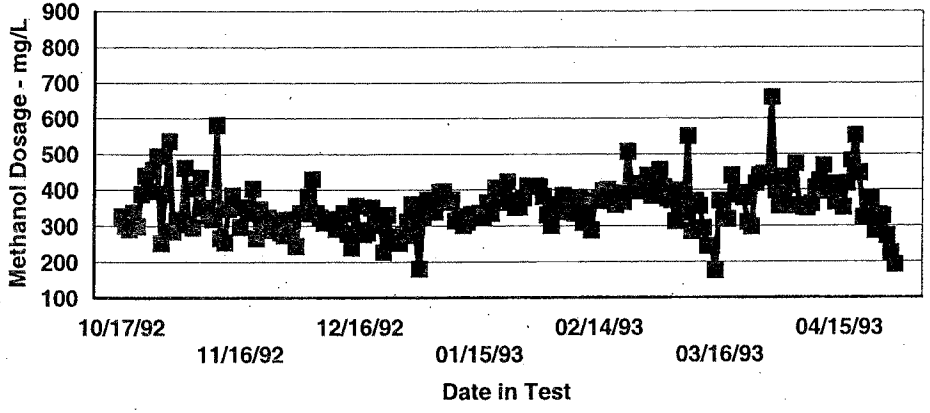


Figure 12
UASBR Period 1
Methanol Dosage



effluent and recycle piping were separated to operate independently of each other. Another recycling or sludge mixing system was added to the reactor. Lastly, an apparatus to optically probe the reactor to determine the interface of the sludge bed and settling zone was assembled, and ports to probe the opacity of the reactor's contents were installed on the reactor. The UASBR was restarted on July 19, 1993 (Day 308), with about 920 gallons of the granular, bakery sludge.

Period 2 testing was short-lived and ended on August 19, 1993 (Day 339). Sludge in the effluent and scum floating on top of the liquid in the reactor were observed throughout the period. The scum contained clumps of agglomerated sludge granules and gas.

Flow through the system for the first three weeks averaged 1.8 gpm, with an average recycle rate of 81 gpm, which corresponds to an effective average upflow velocity of 1.80 gpm/ft^2. On August 19 (Day 339), the sludge mixing system was put into operation at 76 gpm. Together with the recycle and throughput flows, this provided an effective upflow velocity of 3.42 gpm/ft^2. Methanol dosage averaged 375 mg/L, with a range between 61 and 646 mg/L and a standard deviation of 124 mg/L. The reactor was usually probed twice a week. Probes were performed daily for the last days of operations when readings measured approximately 100 gallons of sludge in the reactor. After shutdown, the remaining sludge was removed from the reactor and stored on site in 55-gallon plastic drums.

Period 2 Results

Period 2 operations lasted a month, from July 19 to August 19, 1993. This time frame was inadequate to achieve stable operations. Only a brief discussion of operation results is presented.

The average effluent Sse and nitrate concentrations for Period 2 were 180 ug/L and 7 mg/L as N, respectively. The percentage of Sse removed during the period ranged from a low of 6% to a high of 89%. The problem of keeping sludge in the reactor is evidenced by the effluent total and volatile suspended solids concentrations, which averaged 345 mg/L and 236 mg/L, respectively.

Period 3 Operations - September 1, 1993 through November 21, 1995

The UASBR was restarted on September 1, 1993 (Day 352), using anaerobic sludge obtained from the mixed-sludge digesters at Fresno's wastewater treatment plant. Unlike the granules of the bakery sludge previously tested, the digester sludge was composed of fine solids typically found in wastewater digesters. Only a minimal amount of sludge, about 200 gallons, could be maintained in the reactor despite periodic addition of sludge to the reactor throughout October and November. Upflow velocities through the reactor for October and November ranged between 0.05 and 0.87 gpm/ft^2. To provide a time reference when treatment trains were established, the two fluidized bed reactors and the two slow sand filters were put on-line in the second week of October 1993.

On December 20 (Day 462), approximately 1,700 gallons of activated sludge and 0.5 cubic feet of sand (to support biological growth) were added to the black, viscous digester sludge that remained in the reactor. The activated sludge was obtained from Selma-Fowler-Kingsburg wastewater treatment plant, which also supplied the sludge used in the investigations at Murrieta

Farm by Binnie. For the next eight days, while hair and other debris in the activated sludge were being flushed through the reactor, the influent flow rate into the reactor was incrementally increased from 2.5 to 5 gpm, and the upflow rate through the reactor was targeted at 40 gpm (upflow velocity 0.87 gpm/ft^2). On December 30, the target upflow rate was increased to 50 gpm (upflow velocity 1.08 gpm/ft^2) for a few days and then gradually decreased to 40 gpm on January 7, 1994. By December 31, the sludge volume had decreased to about 210 gallons. From January 7, the reactor operated at an influent rate of 5 gpm with an upflow rate of 40 gpm (upflow velocity of 0.87 gpm/ft^2) until January 31 when the testing was shut down for a day due to maintenance activities conducted by the electrical power purveyor. Sludge volume measured around 320 gallons.

The UASBR was restarted on February 2, 1994 (Day 506) at an influent flowrate approximately 5 gpm, with an upflow rate of 10 gpm (upflow velocity of 0.22 gpm/ft^2) and average carbon dosage of 453 mg/L. The reactor was turned off on April 26 (Day 589), due to loss of sludge from the reactor. Operations were restarted on May 4 at identical parameters previous to shut down on April 26. On June 15, the feed flow rate was incrementally increased and the recycle flow rate was decreased in identical increments until the entire upflow rate was that of the feed flow rate without a recycle flow. This change was accomplished on July 14 (Day 668). The UASBR was shut down from June 23 (Day 616) to June 25 to replace the failed hypalon gas/solids separator cone with a Lexan cylinder. The grommets holding the bottom of the hypalon cone in position ripped through the hypalon fabric.

For a short duration, from July 3, 1994 to August 1, 1994, the UASBR was operated to maintain a nitrate residual in the effluent. The target carbon dosage was lowered to 230 mg/L. This was done to provide nitrate reductase for the downstream reactors, fluidized bed reactor 1 and both slow sand filters, for they were not providing any additional selenium reduction. In other research, Macy (UCD 1992) found that the reduction of selenite to elemental selenium required nitrate reductase, the enzyme responsible for nitrate reduction. The slow sand filters were exhibiting nitrifying characteristics since March 1993.

From August 2, 1994 through November 1995, targeted carbon dosage for the UASBR varied and ranged between 300 mg/L and 400 mg/L. Table 3 shows dates, targeted dosages, actual average dosages, and standard deviation of actual dosages for the entire Period 3.

Table 3
UASBR Period 3 Methanol Dosages*

Date		Target	Actual	Standard
From	To	Dosage	Average	Deviation
08/31/93	05/30/93	500	406	132
05/31/94	06/08/94	600	578	143
06/08/94	06/14/94	475	500	99
06/15/94	06/16/94	400	476	10
06/17/94	06/28/94	325	525	96
06/29/94	07/04/94	285	289	11
07/05/94	07/12/94	250	256	31
07/13/94	08/01/94	250	236	72
08/02/94	08/19/94	300	307	24
08/20/94	10/10/94	400	382	33
10/11/94	04/02/94	350	354	46
04/03/95	05/01/95	325	335	18
05/02/95	11/21/95	400	385	24

*Dosage units are mg/L as methanol

The UASBR was operated with a feed flow rate of 10 gpm (upflow velocity of 0.22 gpm/ft^2) without a recycle flow from July 14 through February 13, 1995 (Day 882), when all plant operations were shut down due to flooding of the discharge field. During this period, on August 1, 1994 (Day 686), the phosphate feed to the incoming drainage water was reduced to 0.25 mg/L as P from 0.5 mg/L. On February 1, 1995 (Day 870), a dye test was performed on the UASBR to investigate channeling and short-circuiting.

The UASBR was restarted on February 18 (Day 887), at a feed flow rate of 10 gpm without recycle (upflow velocity 0.22 gpm/ft^2). The feed flow rate was decreased to 5 gpm with a 5 gpm recycle flow rate producing an upflow velocity of 0.22 gpm/ft^2 on February 23. The UASBR was operated at these parameters until March 10 (Day 907), when all operations at the Adams facility were suspended due to flooding at the site from storms that devastated the western side of the San Joaquin Valley and washed out a bridge on Interstate 5 that crossed Arroyo Pasajero.

Testing with UASBR resumed on March 27 (Day 924), with a feed flow rate of 2 gpm without recycle. A few days later, the feed flow rate was increased to 5 gpm and recycle was added at a flow rate of 5 gpm. It remained at those parameters until July 7 (Day 1026), when the reactor was shut down to install a pre-manufactured high-density polyethylene gas/solids separation cone fabricated by Precision Plastics of Fresno, California to meet the demand of the reactor. The cone was made to collect and to adequately measure the gas produced so that a mass balance for selenium could be conducted for the UASBR. Data for mass balance calculations were collected during September, October, and November 1995.

The installation of the cone was completed in three days. The level of water in the reactor was lowered below the Lexan cylinder and baffle, two pre-formed angle support rings were bolted

around and to the side of the tank at the top of the reactor, the tank was cut between the support rings, and the top of the tank was removed to install the cone. This was the first time the interior of the reactor could be fully observed. Previous observations and work performed inside the UASBR had to be accomplished through a 24-inch-diameter port. Balls of agglomerated biomass ranging from 1 to 2 inches in diameter, which covered the surface of the remaining water in the reactor, were removed before the HDPE cone was installed.

The reactor was restarted on July 10 (Day 1029) at a feed flow rate of 5 gpm and a 10 gpm upflow rate (upflow velocity of 0.22 gpm/ft^2) until July 14, when the UASBR operations were suspended to repair the cone. A kink in the gas line to the gas meter caused a buildup of gas pressure under the cone, which resulted in slippage of a few of the cone's holddown angles from the reactor tank's retention angles. The cone tilted and buckled. Repairs were completed on July 20 (Day 1039), and the operations resumed at previous parameters.

The influent flow rate was maintained at 5 gpm (0.10 gpm/ft^2) until August 23 (Day 1073) when it was increased to 18 gpm (0.39 gpm/ft^2) without a recycle flow. The Lincoln pump station pump discharge line ruptured, and the UASBR was shut down from August 29 through September 1 for repair. The phosphate dosage for the raw drainage water was increased to 1.3 mg/l as P from 0.25 mg/L when the UASBR was restarted on September 2 (Day 1083), at a feed flowrate of 5 gpm and an upflow rate of 20 gpm (upflow velocity of 0.43gpm/ft^2). Operation remained at those parameters until all testing at the Adams facility was stopped on November 21, 1995 (Day 1164).

Period 3 Results

The selenium values for agricultural drainage water were fairly consistent with those of Period 1. Period 3 selenium values for the influent drainage water are shown in Figure 13. Tse ranged between 411 ug/L and 706 ug/L and averaged 523 ug/L, while Sse ranged between 393 ug/L and 736 ug/L and averaged 506 ug/L. Selenite concentrations for the period averaged 3 ug/L. The UASBR effluent selenium concentrations for Period 3 are shown in Figure 14, while the percentage of Sse reduced is shown in Figure 15. The best Sse removal in Period 3 occurred during a three week period from May 9 through June 1, 1994, and hovered around 80%. This removal was accomplished when the reactor was fitted with the hypalon g/s cone. The hypalon cone failed later that month and on June 23 (Day 616) was replaced with a Lexan cylinder. The only other occurrence when Sse removal breached the 80% removal level was on August 3, 1994. On August 10, Sse removal dropped to 34%. After August 10 through to the end of testing on November 21, 1995, the Sse removal values fluctuated weekly, but the slope of the trend line was positive. During this 16-month period, Sse removal rose above 60% on six occasions. Installation dates for Lexan cylinder and HDPE cone are shown by upper triangles in Figure 14.

Figure 16 shows the influent and effluent nitrate field measurements. Again, all nitrate concentration values for the project and in this report are in terms of mg/L as N. Influent nitrate concentration varied from a low of 9 mg/L to a high of 47 mg/L and averaged 29 mg/L, which resulted in a standard deviation of 6 mg/L. The effluent nitrate concentration averaged 9 mg/L with a standard deviation of 7 mg/L.

Figure 13
UASBR Period 3 - Influent Total Selenium, Soluble Selenium and Selenite

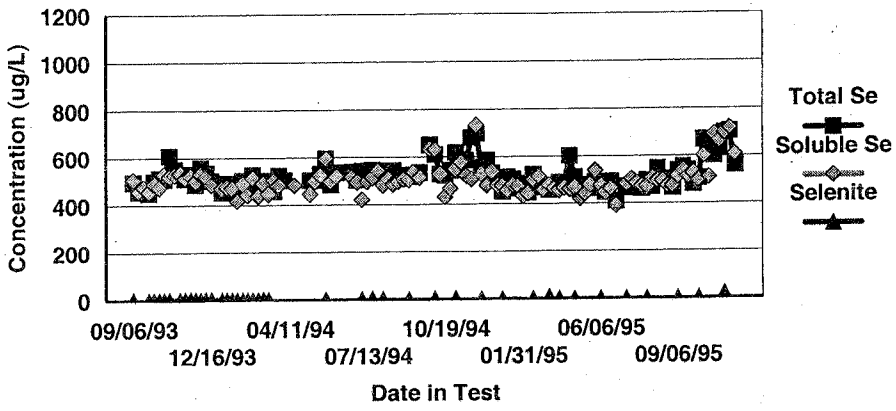


Figure 14
UASBR Period 3 - Effluent Total Selenium, Soluble Selenium and Selenite

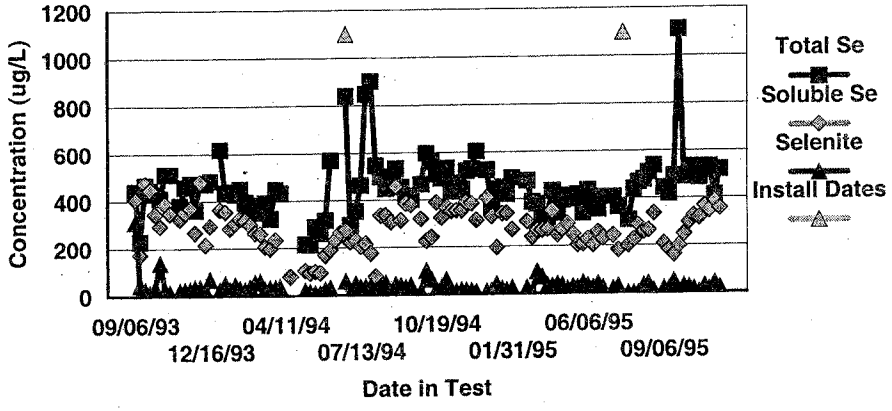


Figure 15
UASBR Peroid 3 - Percentage of Soluble Selenium Reduced

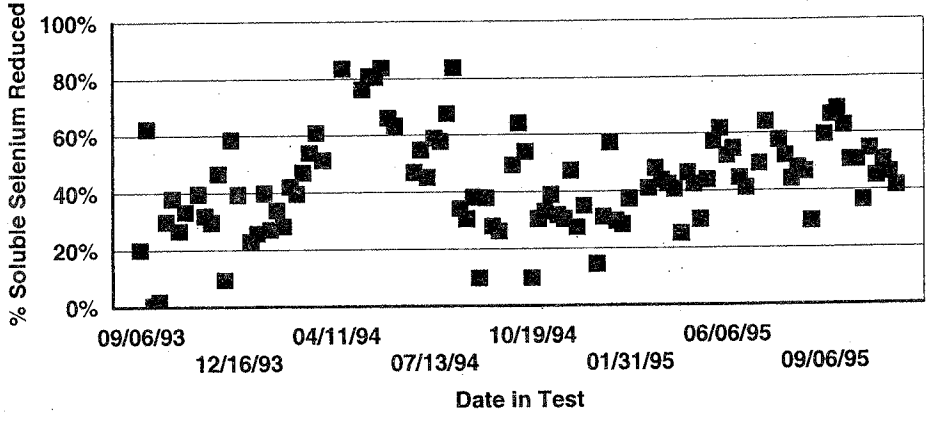
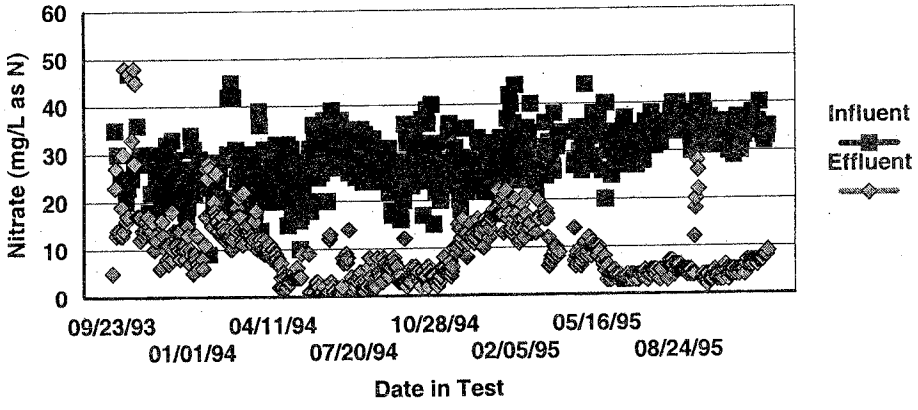


Figure 16
UASBR Period 3 - Influent and Effluent Nitrate



Influent and Port 5 dissolved oxygen and Port 5 temperature values are shown in Figure 17, while Figure 18 compares Port 5 to ambient temperatures. The influent DO concentration averaged 8.8 mg/L, while Port 5's DO concentration averaged 0.8 mg/L. The reactor's temperature did not experience the extreme highs and lows of the ambient temperature, but was parallel with a time offset.

The influent and effluent total organic carbon concentrations are shown in Figure 19, while methanol dosage is shown in Figure 20. The feed TOC concentration averaged 9 mg/L with a standard deviation 6 mg/L. The effluent TOC concentration was continuously in excess of the feed TOC and averaged 61 mg/L with a standard deviation of 24 mg/L. Figure 20 shows the results of the modifications made to the carbon dosing system. Dosing became more stable as operations progressed.

Figure 21 shows the influent and effluent alkalinity concentrations for Period 3. Alkalinity analyses were performed on a weekly basis and began at the end of December 1994 and continued until the end of the project in November 1995. Influent and effluent alkalinity concentrations averaged 191 mg/L as $CaCO_3$ and 391 mg/L as $CaCO_3$, respectively.

The UASBR volumes of sludge plotted in Figure 22 are calculated values. Measurements were taken with a photoelectric probe, which detected the depth of the sludge bed. From the geometry of the reactor, the volume was determined from the measured depth. Since the volume was measured by a photoelectric cell, a correlation between sludge volume and sludge density could not be determined. The average sludge volume for Period 3 operations was 550 gallons.

Figure 23 shows the total dissolved solids concentrations of the influent and effluent. Throughout the entire period, there was a reduction of TDS concentration from the influent to the effluent. The influent and effluent TDS concentrations averaged 8,228 mg/L and 8,002 mg/L, respectively.

Influent and effluent volatile suspended solids concentrations are shown in Figure 24. The influent and effluent VSS concentrations averaged 5 mg/L and 20 mg/L, respectively. Although not shown, the influent and effluent total suspended solids concentrations increased through the process and averaged 18 mg/L and 37 mg/L, respectively.

Figure 17
UASBR Period 3 - Influent and Port 5
Dissolved Oxygen and and Port 5 Temperature

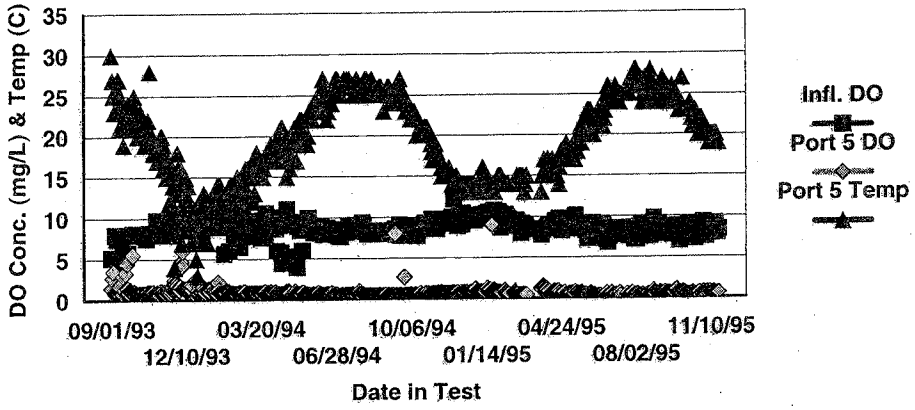


Figure 18
UASBR Period 3
Port 5 and Ambient Temperature

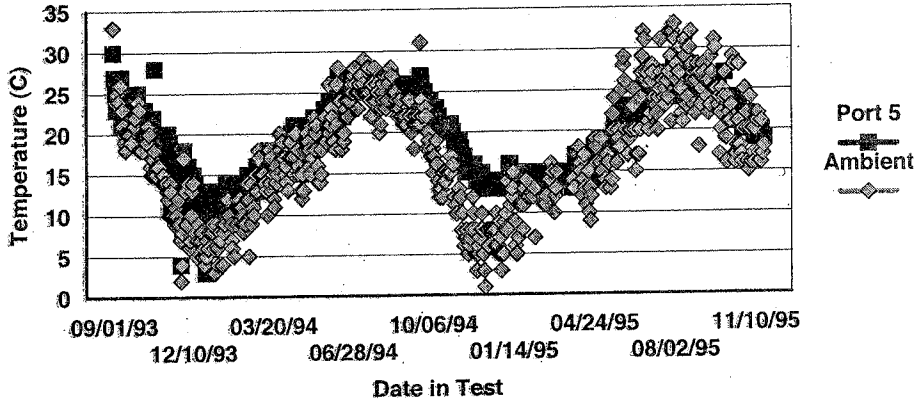


Figure 19
UASBR Period 3 - Influent and Effluent
Total Organic Carbon

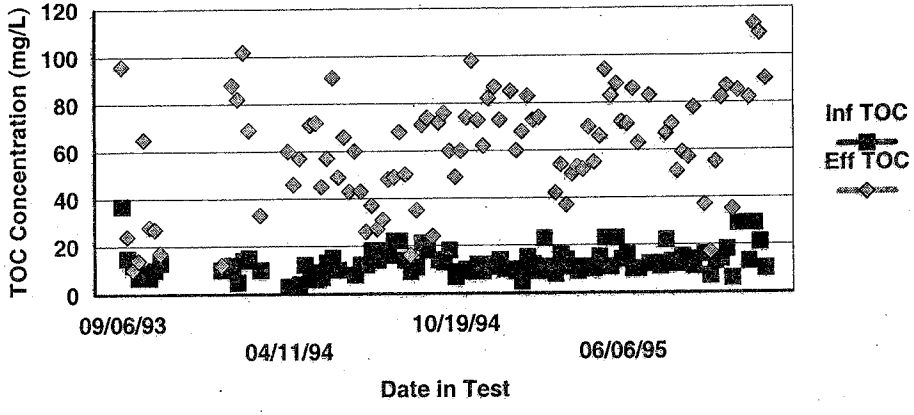


Figure 20
UASBR Period 3
Methanol Dosage

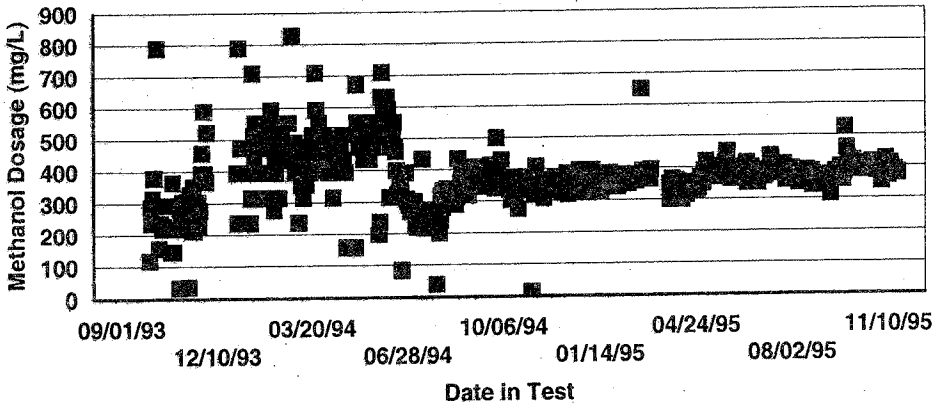


Figure 21
UASBR Period 3
Influent and Effluent Alkalinity

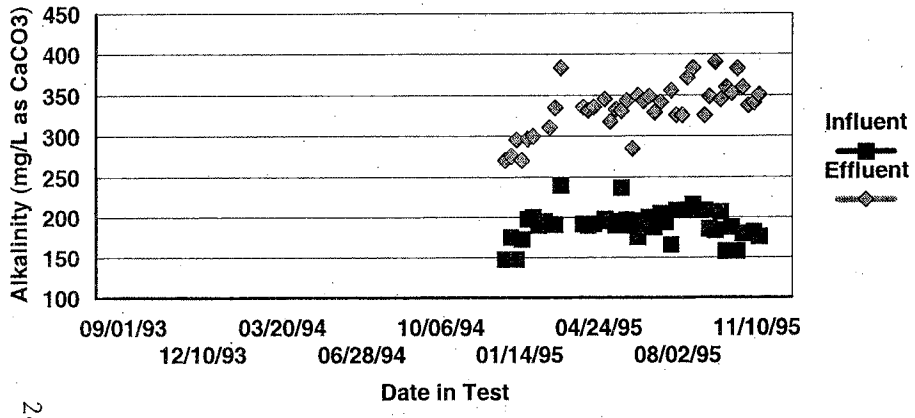


Figure 22
UASBR Period 3
Sludge Volume

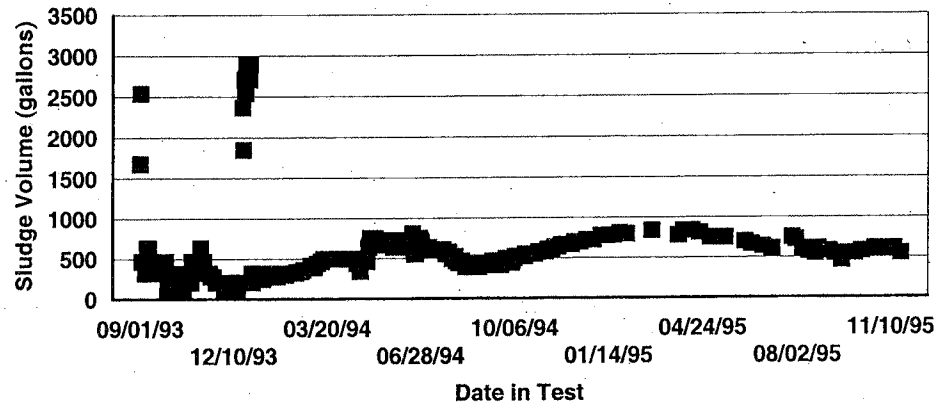


Figure 23
UASBR Period 3 - Influent and Effluent
Total Dissolved Solids

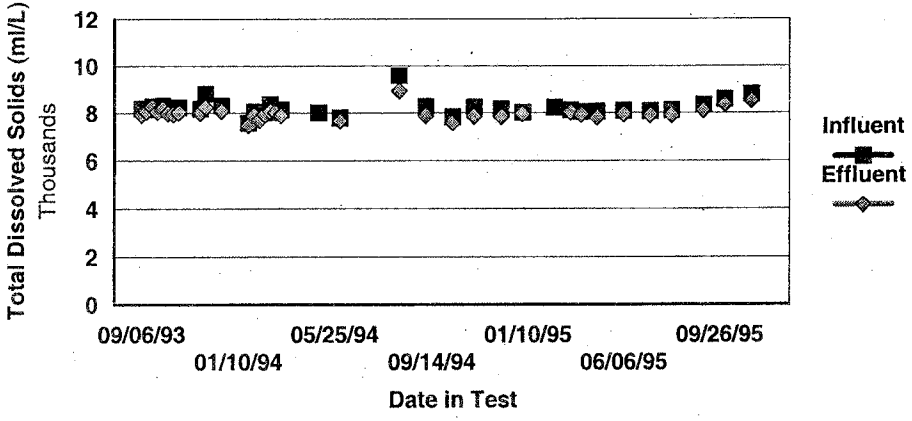
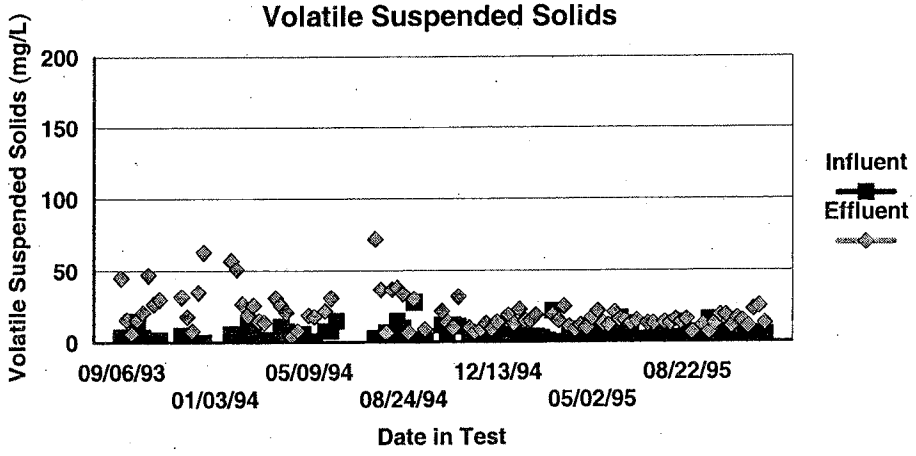


Figure 24
UASBR Period 3 - Influent and Effluent
Volatile Suspended Solids



FLUIDIZED BED REACTOR TEST

Fluidized Bed Reactor Test Units

Two fluidized bed reactors were tested at the Adams facility. The fluidized bed reactor process consists of processing wastewater in a closed vessel containing media, such as sand or activated carbon. The fluidized bed is a biological, attached growth process where micro-organisms grow on support media. Wastewater is passed up and through the vessel at a rate to suspend or fluidize the media on which bacteria grow. In denitrification, carbon is added to the influent wastewater to carry out the metabolic processes of the bacteria. The bacteria reduce nitrate or nitrite to nitrogen gas through respiratory action, as the wastewater passes around the fluidized media. The use of small sand particles as support media provides a vast surface area for bacteria growth as compared to fixed-bed systems.

Both the FBRs used at Adams Avenue were physically identical to one another except that FBR2 was fitted with a methanol injection system. Each FBR consisted of a 22-gallon cylindrical reactor vessel, 100-gallon recycle tank, influent pump, recycle pump, associated flowmeters, and other appurtenances. The reactor vessels were clear acrylic columns, 6 feet high with an inner diameter of 9.5 inches. A schematic of the FBR is shown by Figure 25.

Fluidized Bed Reactor 1 Operations - October 12, 1993 through November 21, 1995

Testing with FBR1 commenced in October 1993. With the exception of four extended periods of downtime for maintenance to make piping and reactor modifications and to solve operational problems, the reactor was operated continuously until November 21, 1995, when operations ceased. For the entire period, FBR1 was the second stage of process Train 1 and treated the effluent of from UASBR.

The independent operation variables tested during the course of operations were feed flow rate and depth of media. The initial feed flow rate through the reactor was targeted at 1.0 gpm, with a upflow rate (influent + recycle) of 14 gpm. The target feed flow rate remained at 1.0 gpm until it was lowered to 0.5 gpm on January 20, 1995 (Day 858). The feed flow rate was lowered once more to 0.25 gpm on August 19, 1995 (Day 1069) and remained at that rate until plant shutdown on November 21. The upflow rate was adjusted to maintain 50 percent bed expansion and ranged between 8 gpm and 62 gpm. FBR1 operations were suspended for four extended periods: April 27, 1994 (Day 590) through May 9, 1994 due to problems with the UASBR; March 10, 1995 (Day 907) through March 29, 1995 due to flooding of the site; July 8, 1995 (Day 1027) through July 21, 1995 to install the HDPE cone in the UASBR; and August 29, 1995 (Day 1079) through September 5, 1995 to repair the influent line at the Lincoln pump station.

The reactor was started with media consisting of #20 sand at a settled depth of 24 inches. Media depth was changed four times during the course of operations: lowered to 12 inches on April 19, 1994 (Day 582); again lowered to 6 inches on November 3, 1994 (Day 780); raised to 12 inches on January 5, 1995 (Day 843); and again raised to 24 inches on February 10, 1995 (Day 879). Changes in media depth occurred when modifications and maintenance activities were performed on the system.

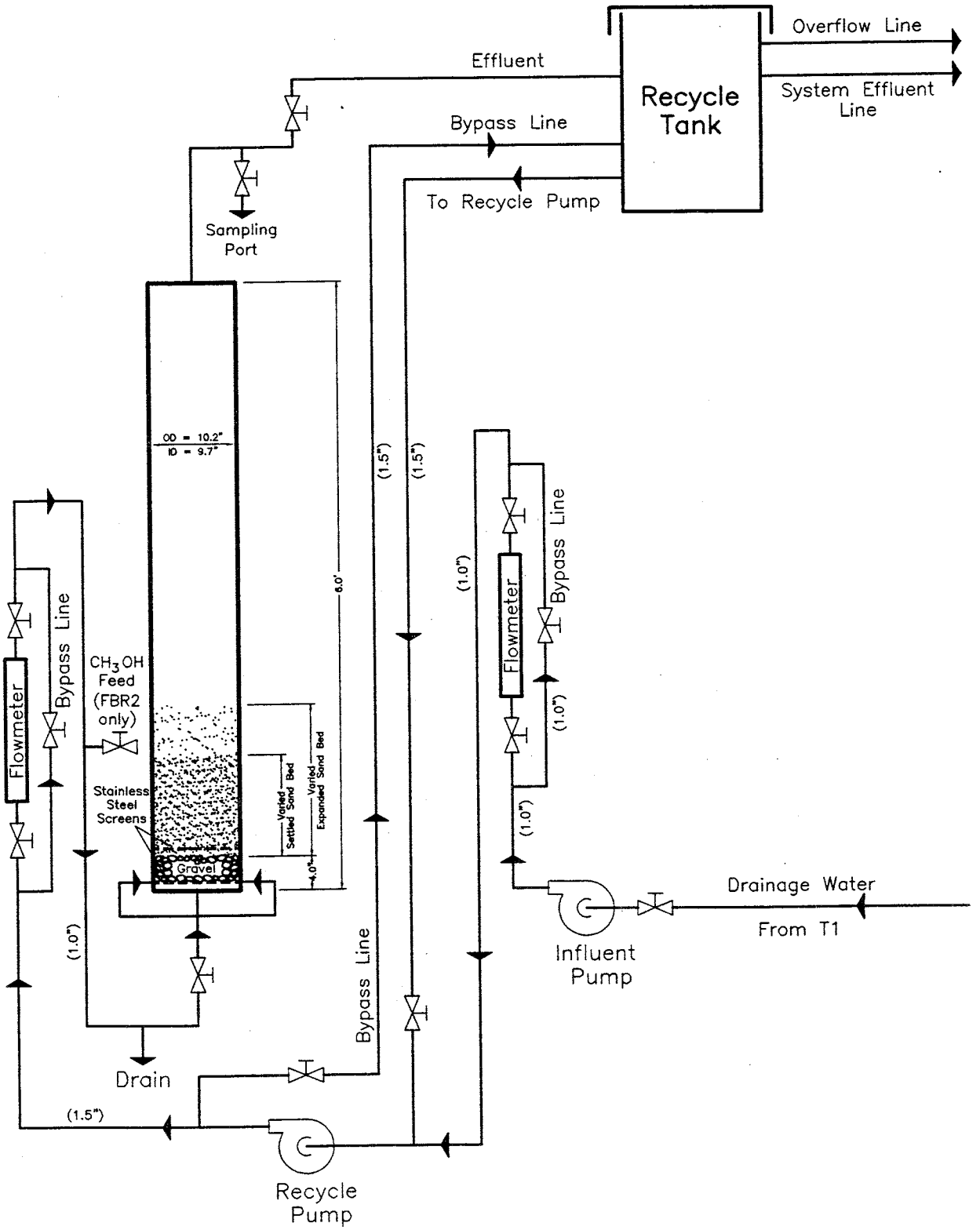


Figure 25. Fluidized Bed Reactor Schematic
(Typical for FBR1 and FBR2)

Several modifications were made to FBR1 during the test period. The influent piping from the UASBR was replumbed in the third week of August 1994 to eliminate aeration of the reactor's feedwater. The influent manifold was modified twice, the first time in April 1994 and second time in January 1995, to improve feedwater distribution into the reactor.

Operation of FBR1 was labor intensive. The feed flow rate would decrease as the particulate carryover from the UASBR accumulated in the strainer. As a result, the influent strainer was cleaned and the feed flow rate was adjusted on a daily basis. Also, the influent line between the strainer and reactor was flushed daily to remove gas and biological growth that accumulated during operations.

Other maintenance activities included cleaning of the reactor, recycle tank, and piping. Biological growth was removed from the walls of the reactor column above the fluidized bed, recycle tank, and piping. The growth in the reactor measured up to a quarter-inch thick before cleaning. The reactor and recycle tank were cleaned six and three times respectively during the 26-month testing period. Manifold modifications were primarily made because of the biological growth on the manifold and associated distribution plates and screens that caused blockage and uneven flow distribution.

Fluidized Bed Reactor 1 Results

FBR1 was the second stage of process train 1 and treated the effluent of the UASBR. FBR1's influent and effluent selenium concentrations are shown in Figures 26 and 27, respectively. Even though the FBR1's influent values are those of the UASBR's effluent, they are again shown in Figure 26 for ease of comparison with FBR1's effluent values. The influent Tse, Sse, and selenite concentrations averaged 458 ug/L, 258 ug/L, and 31 ug/L, respectively. The effluent values for Tse, Sse, and selenite were 382 ug/L, 200 ug/L and 51 ug/L.

Influent and effluent nitrate and dissolved oxygen concentrations are shown in Figures 28 and 29, respectively. Dates when the depth of media was changed (the lower, lighter shaded triangles) and when modifications were made to the influent manifold or manifold piping (the upper, darker shaded triangles) are also indicated on the top portion of both figures. From restart of the FRB1 after the project site was flooded on March 31, 1995 (Day 928) to the end of operations on November 21, 1995, effluent averaged 156 ug/L, 1.9 mg/L as N, and 0.5 mg/L for Sse, nitrate, and DO, respectively. Even though the FBR1 was wrapped with an insulation blanket, the reactor's temperature was strongly influenced by the ambient temperature. The reactor and ambient temperatures are shown in Figure 30. The average difference between these two temperatures throughout the testing period was 8.1 °C. The recycle pump was the source of the heat that raised the reactor's water temperature above that of the influent. The reactor's temperature ranged between 4 °C and 40 °C.

Alkalinity analyses began on February 21, 1995. The change in alkalinity between the influent and the effluent was minimal. The influent and effluent alkalinity concentrations are shown in Figure 31 and averaged 335 mg/L as $CaCO_3$ and 357 mg/L as $CaCO_3$.

Influent and effluent total organic carbon total and suspended solids concentrations are shown in Figures 32 and 33. From March 31, 1995 through November 21, 1995, the influent and effluent

Figure 26
FBR1 - Influent Total Selenium,
Soluble Selenium and Selenite

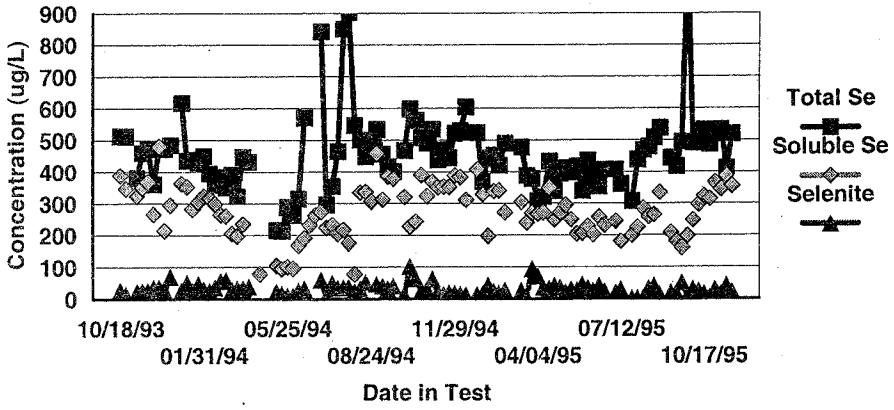


Figure 27
FBR1 - Effluent Total Selenium,
Soluble Selenium and Selenite

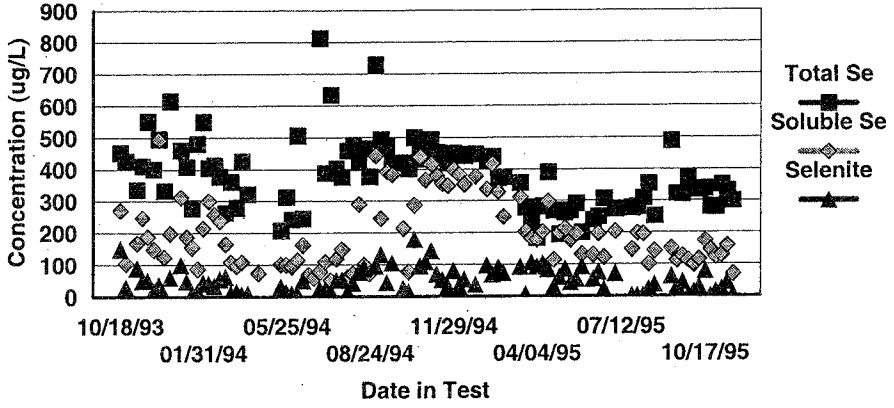


Figure 28
FBR1 - Influent and Effluent
Nitrate

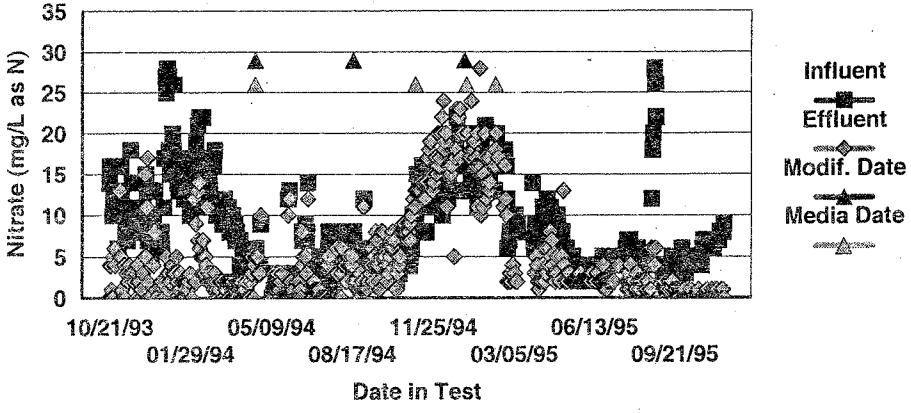


Figure 29
FBR1 - Influent and Effluent
Dissolved Oxygen

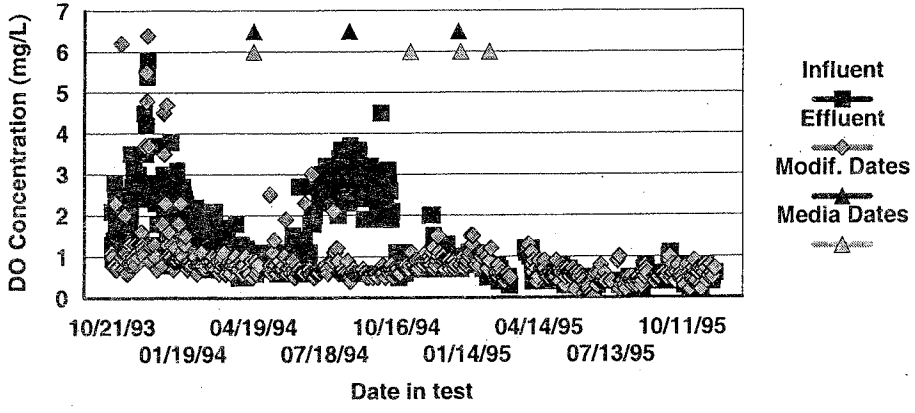


Figure 30
FBR1 - Reactor and Ambient Temperature

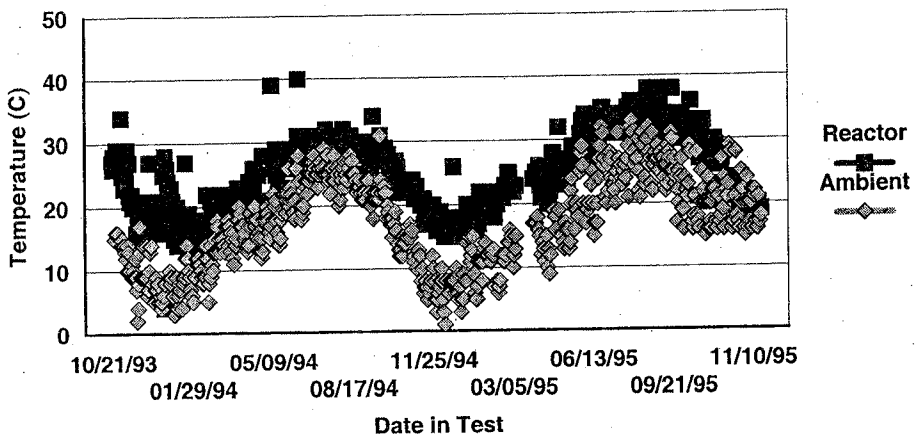


Figure 31
FBR1 - Influent and Effluent Alkalinity

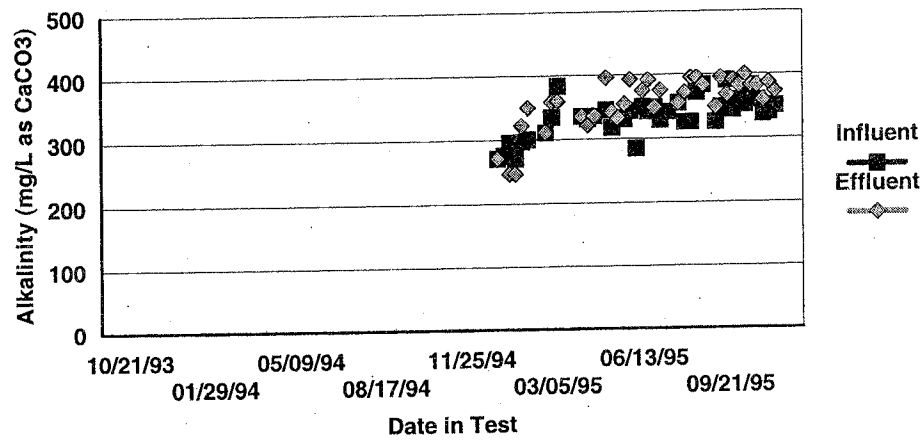


Figure 32
FBR1 - Influent and Effluent
Total Organic Carbon

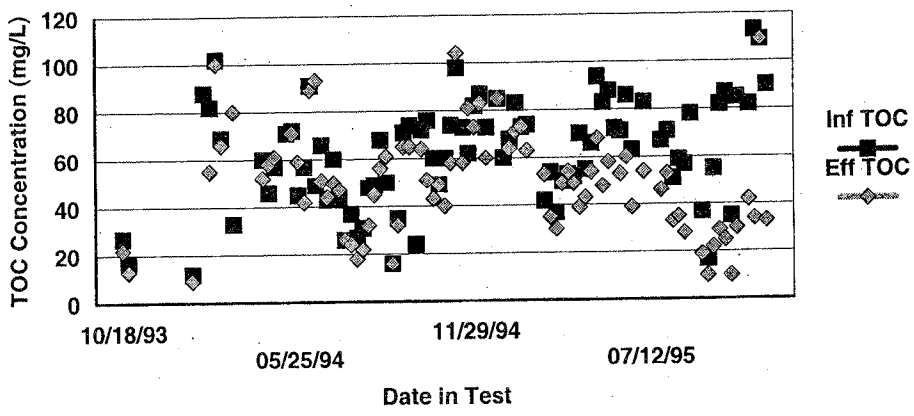
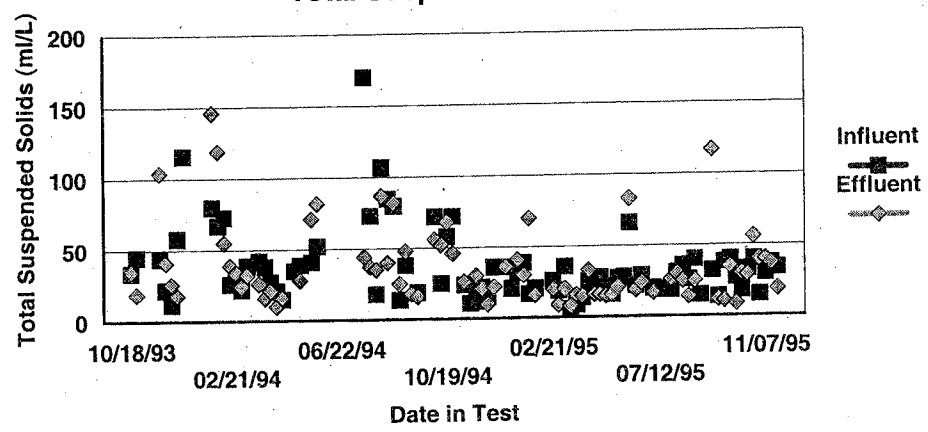


Figure 33
FBR1 - Influent and Effluent
Total Suspended Solids



TOC concentrations averaged 70 mg/L and 42 mg/L, while the influent and effluent TSS averaged 26 mg/L and 29 mg/L. Even though not shown in the figures, the influent and effluent volatile suspended solids concentrations remained fairly consistent and averaged 14 mg/L and 12 mg/L for the same period.

Fluidized Bed Reactor 2 Operations - October 13, 1993 through November 21, 1995

The period of testing with FBR2 corresponded with FBR1's time frame, which lasted 26 months from October 1993 through November 1995. FBR2 was operated as a first-stage treatment process to reduce both nitrate and selenium. FBR2 operations were continuous except for four periods of extended downtime for maintenance activities to make piping and reactor modifications and to solve operational problems. These four periods and reasons for the shutdowns were: December 17, 1993 (Day 459) through December 30, 1993 to replace recycle pump (seal failure) and to clean reactor; January 11, 1995 (Day 849) through February 2, 1995 to modify the reactor's distribution system; March 10, 1995 (Day 907) through March 30, 1995 due to flooding of the site; and April 7, 1995 (Day 935) through April 10, 1995 due to an electrical problem with the recycle pump.

The physical set-up for FBR2 was identical to that of FBR1, except that FBR2 was fitted a with chemical injection system to add methanol into the feedwater as a source of carbon required for denitrification.

Like FBR1, independent operation parameters tested for FBR2 were feed flowrate and depth of media. FBR2 was started at a feed flowrate of 1 gpm with a recycle flowrate that produced a 50 percent bed expansion. At 1 gpm, little or no denitrification occurred in the reactor, so on December 7, 1993, (Day 449), the inflow was reduced to 0.1 gpm. Inflow into FBR2 remained at 0.1gpm for the rest of the testing period. The upflow rate (influent rate added to recycle rate) for the entire testing period ranged between 7 and 55 gpm, with an average of 24 gpm.

Testing commenced with a media depth of 24 inches of #20 sand. Problems arose shortly after start-up. Effluent from the reactor was milky. On December 1, 1993 (Day 443), the reactor was shut-down for maintenance activities. The distribution plate, which was found to be 80 percent plugged, was changed and the support media was replaced with 25 inches of #12 sand (a finer sand). On December 7, operations resumed with an influent flowrate of 0.1 gpm. Operation notes from December 14 stated that the support media was being broken down and was carried out in the effluent. On December 17, the reactor was shut down due to a seal failure in the recycle pump. Again the distribution plate pores were found to be plugged with the support media fines. Scouring inside the column was also observed. The reactor was cleaned and put back into operation on December 30 (Day 472) with 12 inches of # 20 sand and at a feed flow rate of 0.1 gpm. The depth of media was changed three more times during the course of testing: reduced to 6 inches of #20 sand on November 11, 1994 (Day 788); increased to 12 inches on January 6, 1995 (Day 844); and again increased to 24 inches on February 24, 1995 (Day 893).

Like those for FBR1, operations for FBR2 were labor intensive. Problems arose due to biological growth and chemical precipitation in the piping, reactor, and recycle tank. As a result, the system required periodic cleaning that was usually performed when the system was modified or when the support media or media depth were changed.

The numerous modifications made to the influent manifold to improve flow distribution through the reactor were attributable to bacteria growth. Growth in the reactor was reduced and low dissolved oxygen levels were maintained in the reactor after placement of an insulator blanket around the reactor in February 1994. Distribution of flow into the reactor was improved when the distribution plate was replaced with a #6 mesh stainless steel screen in June 1994.

The methanol dosage system was a high maintenance item from the onset of operations. Numerous modifications were made to the methanol injection system during the first two months of operation to prevent blockage of the dosage line at the control metering valve. Placement of a back-pressure valve on the discharge line of the dosing pump in January 1994 helped alleviate some problems, but the dosing system still remained problematic. The targeted dosage rate was 300 mg/L from January 10, 1994 (Day 483) through July 25, 1994 (Day 679) when it was lowered to 240 mg/L. On August 1, 1994 (Day 686) the target rate was increased to 270 mg/L and remained the target rate for the remainder testing. The calculated dosage rates for these four periods in sequential order were 300 mg/L, 282 mg/L, 250 mg/L, and 274 mg/L.

Another problem area in operations was the maintenance of a realistic operating temperature inside the reactor. FBR2's temperature ranged between 17 and 42^{0}C, with an average of 30^{0}C. The reactor's temperature was influenced by the size of the recycle pump. The 2-horsepower recycle pump was changed to a 3/4-HP one on June 14, 1994, to lower the reactor operating temperature. On September 13, 1994, the 3/4-HP recycle pump was replaced with a 2-HP pump to improve bed expansion. The recycle pump was changed back to a 3/4-HP one on June 26, 1995, and was used for the remainder of the testing.

Fluidized Bed Reactor 2 Results

FBR2 was operated as a single-stage reactor to reduce both selenium and nitrate and was run in parallel with the UASBR. The influent selenium concentrations were those of the UASBR and were previously presented previously in the UASBR Period 3 section, Figure 13. The average influent Tse, Sse and selenite concentrations for the entire FBR2 operation period were 522 ug/L, 507 ug/L, and 3 ug/L, respectively. The effluent selenium values for the entire operation period are shown in Figure 34 and averaged 383 ug/L, 275 ug/L, and 36 ug/L for Tse, Sse, and selenite, respectively.

Figure 35 shows percentage of Sse reduced and dates on which the depth of the media and phosphate dosage were changed. Overall for the entire period, Sse reduction averaged 35%. The best reduction for an extended period was 68% that occurred between January 31, 1994 (Day 504) and September 14, 1994 (Day 730) at a media depth of 12 inches. Sse reduction averaged 50% from restart of the reactor on March 31, 1995 (Day 928) after flooding of the site until the end of operations on November 21, 1995 (Day 1163). Phosphate was dosed into the plant's influent at three rates during the course of testing. Phosphate was added to the influent to ensure adequate nutrients for biological growth. Initially, phosphate dosage was 0.5mg/L as P until August 1, 1994 (Day 710) when it was lowered to 0.25 mg/L as P. Then, on August 2, 1995 (Day 1052), the phosphate dosage was raised to 1.3 mg/L as P for the remainder of operations. Sse reduction for these three periods were 50.2%, 39%, and 55.3%. Sse reduction of 68.9% was

Figure 34
FBR2 - Effluent Total Selenium, Soluble Selenium and Selenite

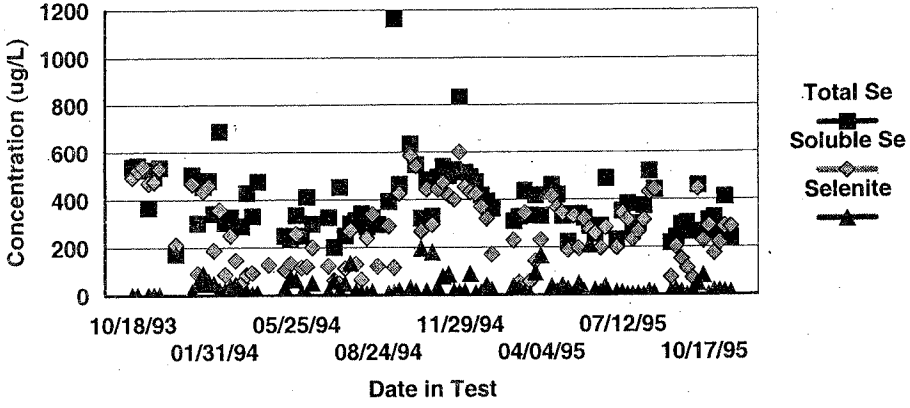


Figure 35
FBR2 - Percentage of Soluble Selenium Reduced and Dates for Media & Phosphate Dosage Changes

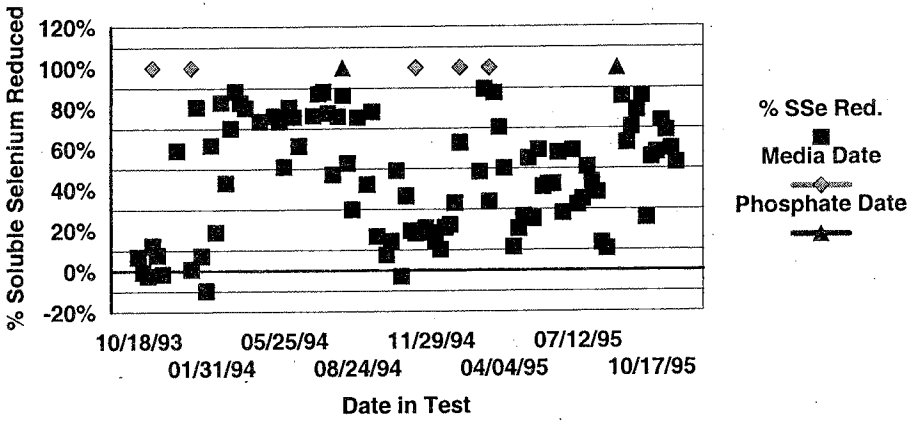


Figure 36
FBR2 - Influent and Effluent Nitrate

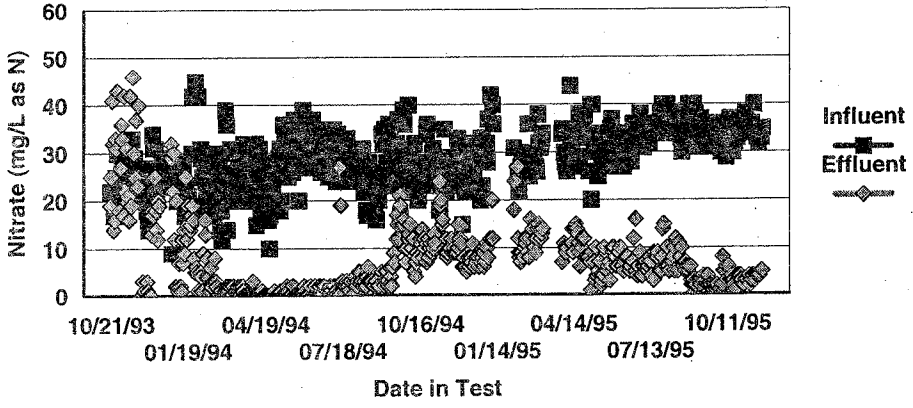
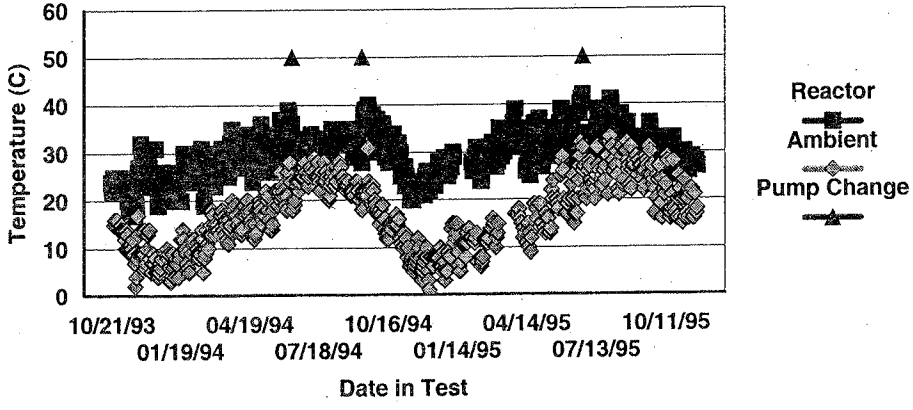


Figure 37
Reactor and Ambient Temperatures and Date for Recycle Pump Change



achieved from January 31, 1994 through August 1, 1994 when the phosphate dosage was 0.5 mg/L as P and media depth was 12 inches.

Influent and effluent nitrate concentrations for the entire operation period are shown in Figure 36 and averaged 29 mg/L as $CaCO_3$ and 7 mg/L as $CaCO_3$, respectively. From January 31, 1994 through September 14, 1994 when Sse reduction was best, the average nitrate effluent concentration was 2 mg/L as $CaCO_3$, while the effluent nitrate averaged 8 mg/L as $CaCO_3$ for the remainder of operations from September 15, 1994 to November 21, 1995.

Figure 37 shows reactor and ambient temperatures along with the identification of dates when the recycle pump was changed. The average temperature difference between the reactor and ambient temperatures were 14 °C and 16 °C for two periods when a 2-HP pump was used from October 21, 1993 through June 13, 1994 and September 12, 1994 through June 25, 1995, while the average temperature difference ranged between 7 °C and 8 °C for the two periods with a 3/4-HP pump.

Influent and effluent dissolved oxygen concentrations are shown by Figure 38. The influent DO concentration averaged 8.8 mg/L for the entire test period. Until February 11, 1994 (Day 515), the effluent DO concentration fluctuated and averaged 2.4 mg/L. After February 11, the effluent DO concentration stabilized and averaged 0.7 mg/L for the remainder of operations. Figure 39 shows methanol dosage into the influent stream of FBR2. As previously stated, there were four targeted rates during the course of testing. The operation of the injection system was problematic and tended to improve as modifications were made as testing progressed. The standard deviation four the four dosage periods in sequential order were 158 mg/L, 65 mg/L, 26 mg/L, and lastly 40 mg/L for the last 16 months of operation.

The influent and effluent total organic carbon concentrations are shown by Figure 40. Effluent was almost always in excess of the influent. Influent TOC averaged 47.7 mg/L, while the effluent averaged 12.8 mg/L for the entire test period. The effluent TOC concentration averaged 23.9 mg/L from January 31, 1994 through August 1, 1994, when the percentage of Sse reduction was the best at 68.9%. For this period the calculated methanol phosphate dosages were 282 mg/L and 0.5 mg/L as P, respectively, and the depth of media was 12 inches.

Figures 41 and 42 show influent and effluent volatile and total suspended solids concentrations, respectively. The effluent VSS concentration remained relatively constant for the last 18 months of operation, while the effluent TSS concentration varied considerably throughout the program. Overall for the test period, the influent and effluent VSS values averaged 5 mg/L and 22 mg/L and the influent and effluent TSS concentrations averaged 18 g/L and 52 mg/L, respectively.

Influent and effluent alkalinities are shown by Figure 43. On the average, alkalinity increased 59% through the reactor. For the entire testing period, the influent and effluent alkalinity averaged 186 mg/L as $CaCO_3$ and 295 mg/L as $CaCO_3$, respectively.

Influent and effluent electrical conductivities and total dissolved solids concentrations are shown in Figures 44 and 45, respectively. Surprisingly, the effluent EC was continuously greater than the influent. From March 8, 1994 through to the end of testing, influent and effluent EC values averaged 8,658 uS/cm and 9,956 uS/cm, respectively. The device to measure EC was replaced

Figure 38
FBR2 - Influent and Effluent
Dissolved Oxygen

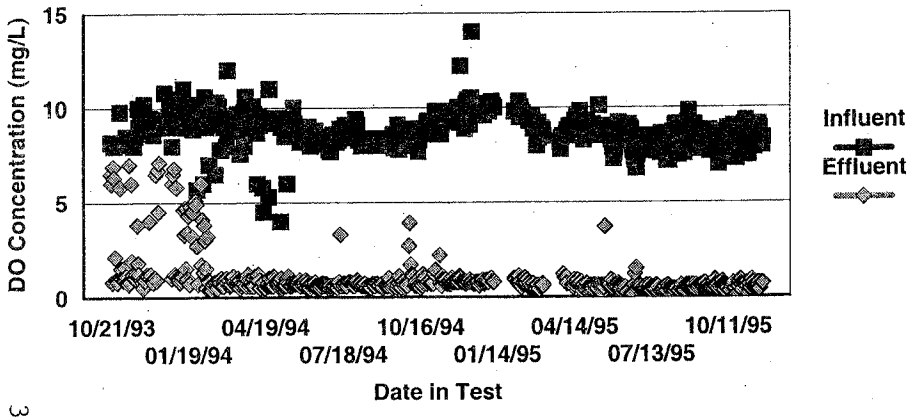


Figure 39
FBR2
Methanol Dosage

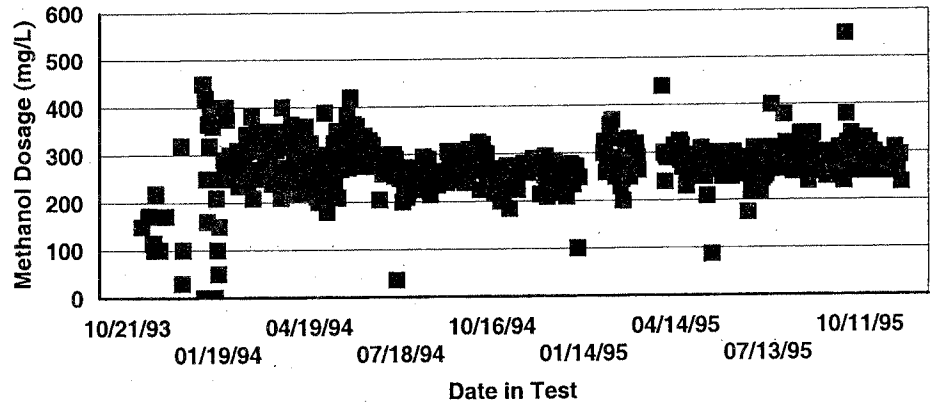


Figure 40
FBR2 - Influent and Effluent
Total Organic Carbon

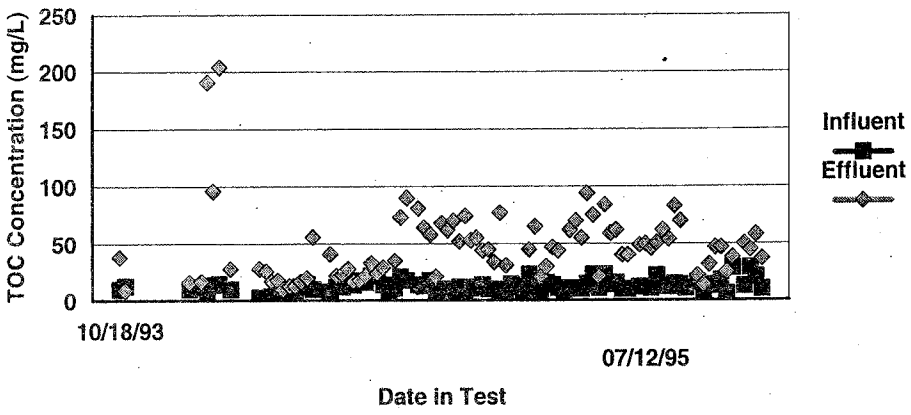


Figure 41
FRB2 - Influent and Effluent
Volatile Suspended Solids

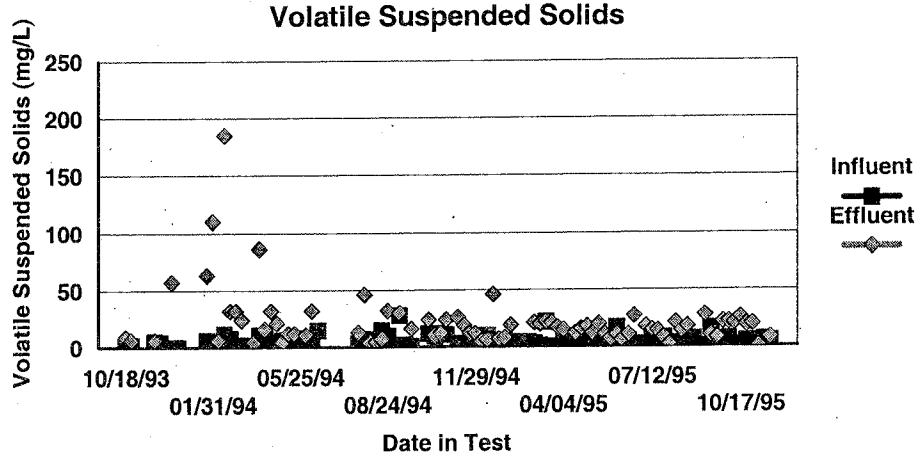


Figure 42
FBR2 - Influent and Effluent
Total Suspended Solids

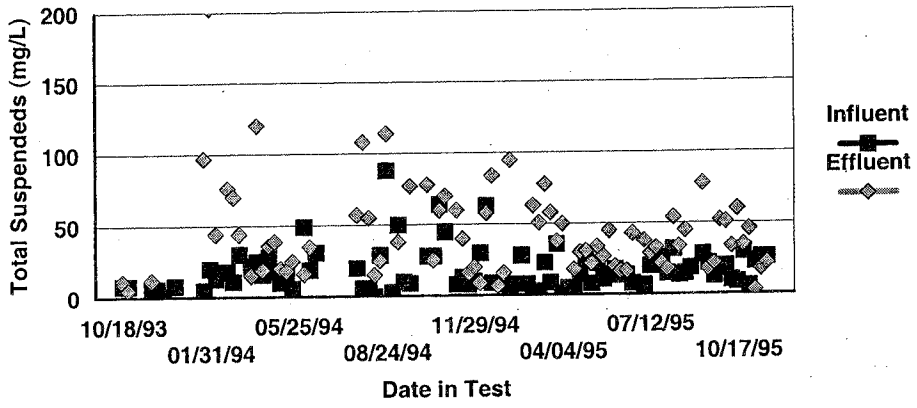


Figure 43
FBR2
Influent and Effluent Alkalinity

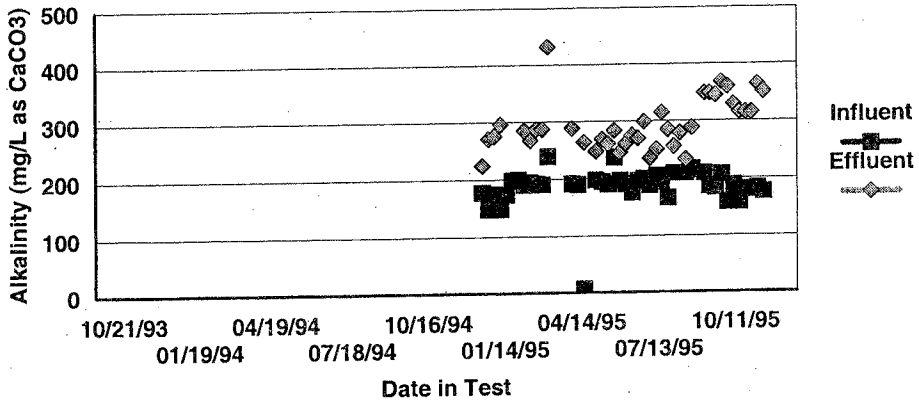


Figure 44
FBR2 - Influent and Effluent
Electrical Conductivity

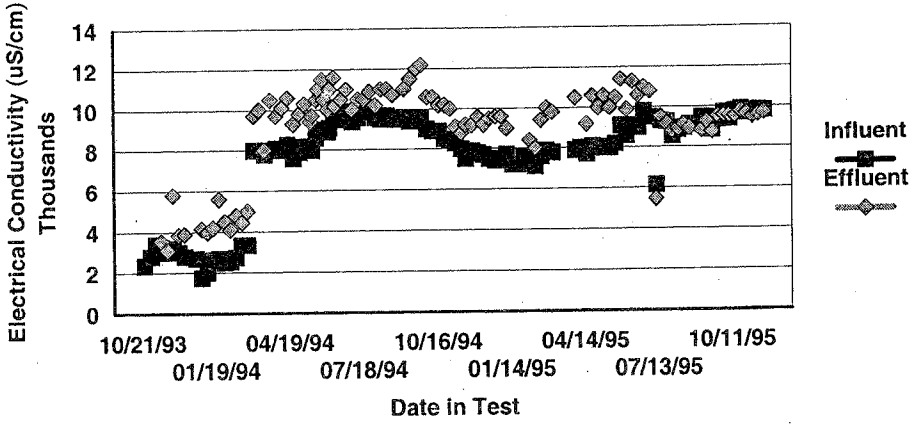
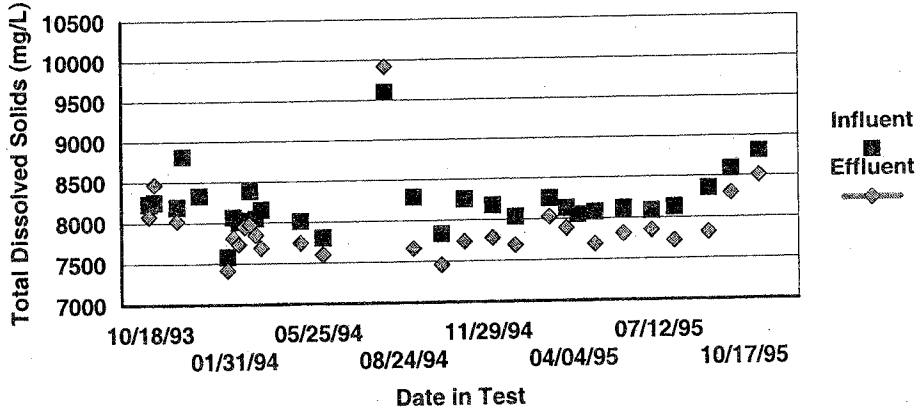


Figure 45
FBR2 - Influent and Effluent
Total Dissolved Solids



on March 1, 1994 because the EC measurements did not correlate to the laboratory TDS values. The influent and effluent TDS concentrations averaged 8,258 mg/L and 7,116 mg/L, respectively.

SLOW SAND FILTER TEST

Slow Sand Filter Test Units

The purpose of the slow sand filter in the process trains was to act as a final polishing step to remove particulate selenium from the drainage water. Particulate selenium is elemental selenium and selenium that is incorporated into bacterial cells or other particulates. The treatment process(es) upstream of the sand filters reduce the selenate and selenite forms of selenium to the particulate state. Selenium in raw agricultural drainage water is 85 percent to 95 percent in the selenate state, the most soluble form of selenium. The sand filter removes the particulate selenium as the water passes though the filter. Additional biological selenium reduction occurs in the filter as the water passes through the schmutzdecke, the biological mat which forms on the surface of the sand filter.

Both slow sand filters used in testing at the Adams facility were identical to one another. Each consisted of a clear acrylic column with nominal diameter of 14 inches and height of 60 inches. The filter media consisted of 18 inches of coarse sand over 12 inches of a gravel base. The unit was fitted with an influent strainer, influent pump, feed flowmeter, backwash pump, and other appurtenances. A schematic for the slow sand filter is shown in Figure 46.

Sand Filters 1 and 2 Operations - October 14, 1993 through November 2, 1994

Testing with the SSFs began on October 14, 1993 (Day 395) and ended in November 2, 1994 (Day 779). SSF1 treated the effluent of FBR1 and was the third stage of Process Train 1. SSF2 treated the effluent of the UASBR and was the second stage of Process Train 2. Operation of the filters paralleled one another. The feed flow rate into each filter was maintained at 0.5 gpm throughout the testing period. The filter media was changed once, on October 25, 1993 (Day 406), from a #20 sand to a coarser #12 sand to help minimize rate of head loss through the filters to decrease the need to backwash. On July 14, 1994 (Day 638), the source of backwash water was changed to water in tank T3 from the Adams facility's service water system. Tank T3 contained effluent from all the process trains and was of a lower dissolved oxygen concentration than water from the service water system.

Since the filters treated the effluent from either FBR1 or the UASBR, filter operations were coordinated with the operation of those upstream processes. Problems of the upstream processes were, in many instances, carried to the filters. Operations were labor intensive. Backwash was required daily. Gas, which accumulated in the filter media and reduced flow through the filter, would periodically have to be relieved by tapping the side of the column with a rubber mallet. Also, the filters required cleaning to remove growth and precipitant. Due to the amount of work required to keep the filters in operation, testing with the SSFs was discontinued at the beginning of November 1994 to concentrate on the operation and development of the UASBR and FBR processes.

Slow Sand Filter 1 Results

Slow sand filter 1 was the third and final stage of Process Train 1 which treated the effluent of FBR1. Even though some biological reduction of selenium occurred in the filter, the primary

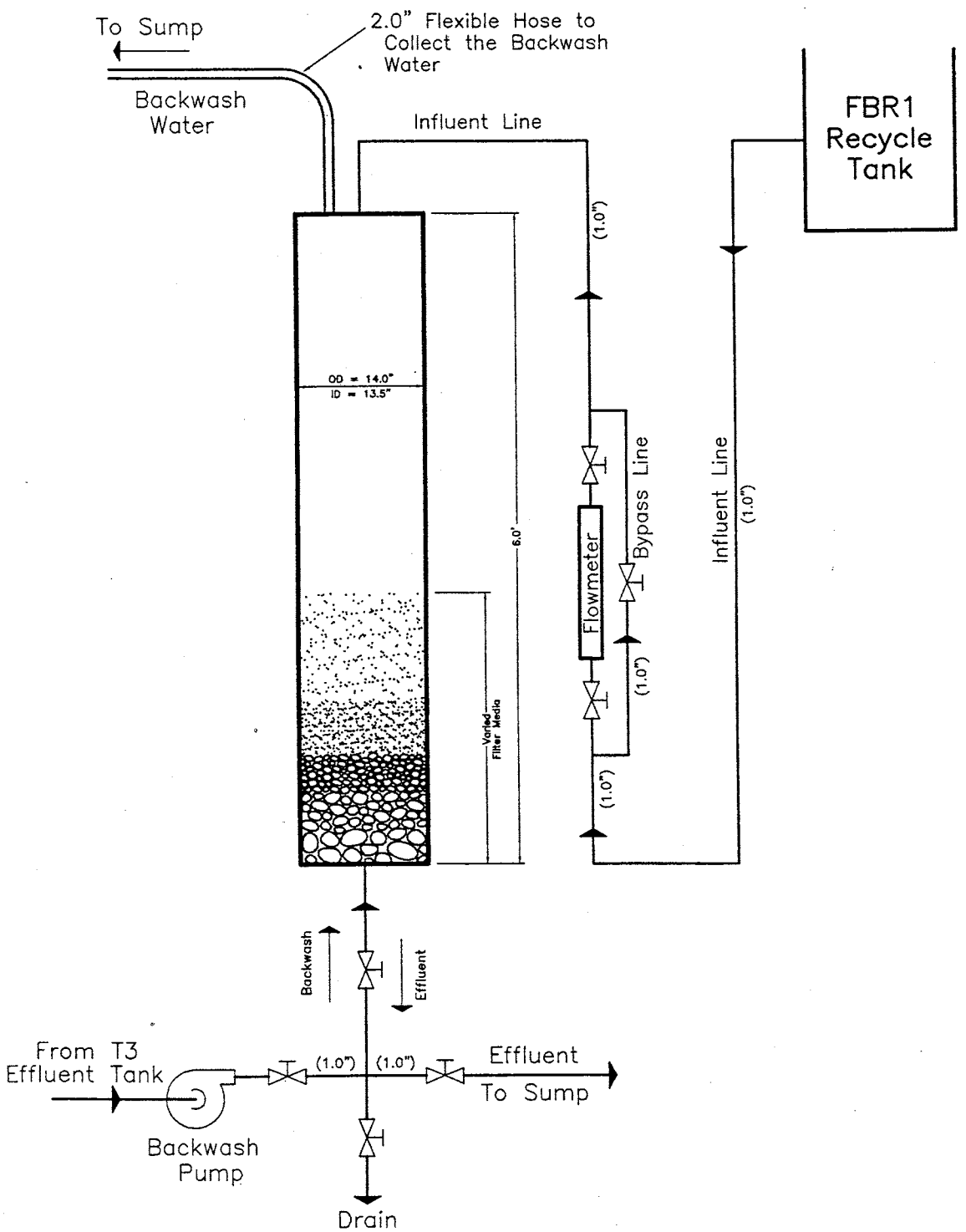


Figure 46. Slow Sand Filter Schematic
(Typical for SSF1 and SSF2)

purpose of the filter was to remove particulate selenium. As described in Table 1, Pse is elemental selenium and selenium incorporated into bacterial cells or other particulates. Pse is equal to total selenium (Tse) minus soluble selenium (Sse). SSF1 was shut down for two prolonged periods from February 27, 1994 (Day 531) through March 15, 1994 (Day 547) for repair and maintenance activities and from April 27, 1994 (Day 590) through May 9, 1994 (Day 602) due to operational problems with the UASBR.

Influent and effluent total and soluble selenium concentrations are shown in Figures 47 and 48. For the 12-month test period, the influent and effluent Tse concentrations averaged 430 ug/L and 236 ug/L, and the influent and effluent Sse concentrations averaged 190 ug/L and 107 ug/L, respectively. The influent and effluent Pse concentration is shown by Figure 49 and averaged 241 ug/L and 102 ug/L for the period. This represents a Pse removal of 57.7% by the filter.

Total treatment by the filter process is determined by the Tse removed. The percentage of Tse removed is shown by Figure 50 and averaged 45.1% for the 12-month period.

Influent and effluent nitrate and total organic carbon concentrations are shown by Figures 51 and 52, respectively. Except for a few instances, the effluent was less than the influent for both constituents. Influent and effluent nitrate concentrations averaged 3.1 mg/L and N and 2.9 mg/L as N, and the influent and effluent TOC concentrations averaged 51 mg/L and 33 mg/L, respectively.

Influent and effluent total and volatile suspended solids are shown in Figures 53 and 54. Influent and effluent TSS concentrations averaged 52 mg/L and 26 mg/L, respectively, while VSS concentrations averaged 31 mg/L and 11 mg/L for the duration of testing.

Slow Sand Filter 2 Results

Slow sand filter 2 was the second and final "polishing" stage of Process Train 2 and treated the effluent of the UASBR. The primary purpose of the filter was to remove particulate selenium even though additional biological reduction of selenium occurred in the filter. SSF2 was shut down for one prolonged period from April 27, 1994 (Day 509) through May 9, 1994 (Day 602) due to operational problems with the UASBR.

Influent and effluent total and soluble selenium concentrations are shown by Figures 55 and 56. For most of the time, the effluent concentration was less than the influent. One major spike occurred on July 13, 1994 (Day 667) where Tse and Sse effluent values reached 1373 ug/L and 720 ug/L, respectively. The operation log noted problems due to green biological growth on top of the filter media and stated that the backwash water was suspect. On July 14, a new backwash technique was instituted using processed water from tank T3 in lieu of the plant's service water. Tank T3 contained the treated effluent (low dissolved oxygen concentration) from the process trains and single stage processes. The influent and effluent Tse concentrations averaged 459 ug/L and 279 ug/L (includes spike value) throughout the entire testing period. The influent and effluent Sse concentrations averaged 268 ug/L and 182 ug/L, respectively.

Figure 47
SSF1 - Influent and Effluent
Total Selenium

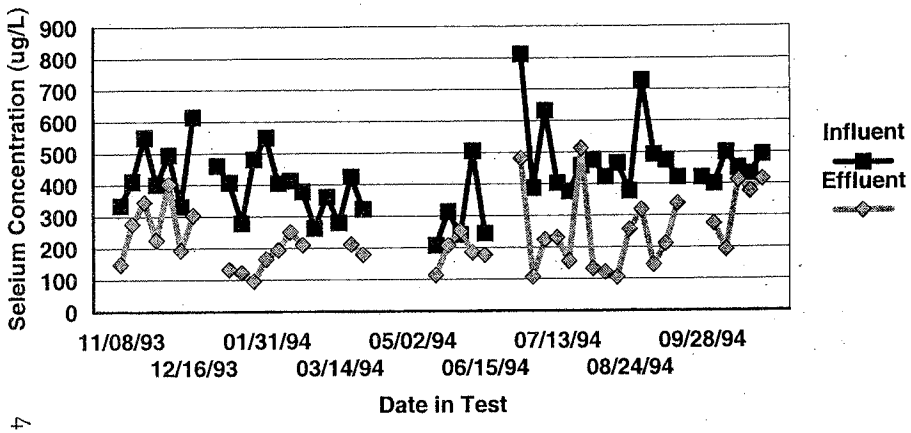


Figure 48
SSF1 - Influent and Effluent
Soluble Selenium

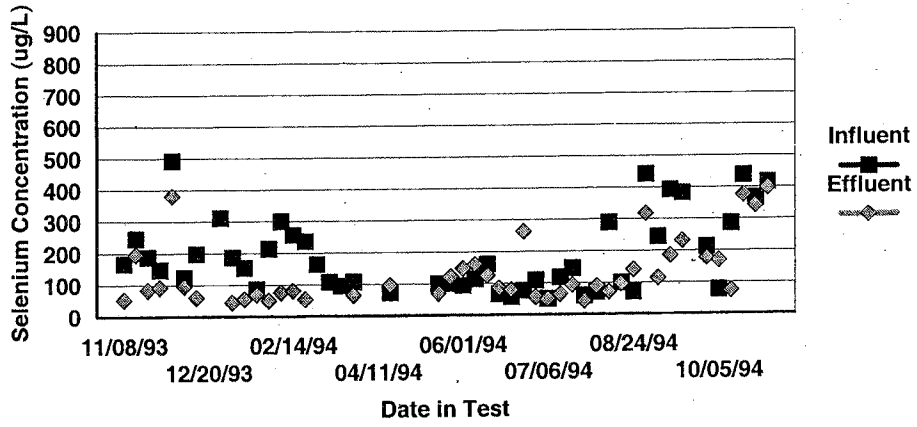


Figure 49
SSF1 - Influent and Effluent
Particulate Selenium

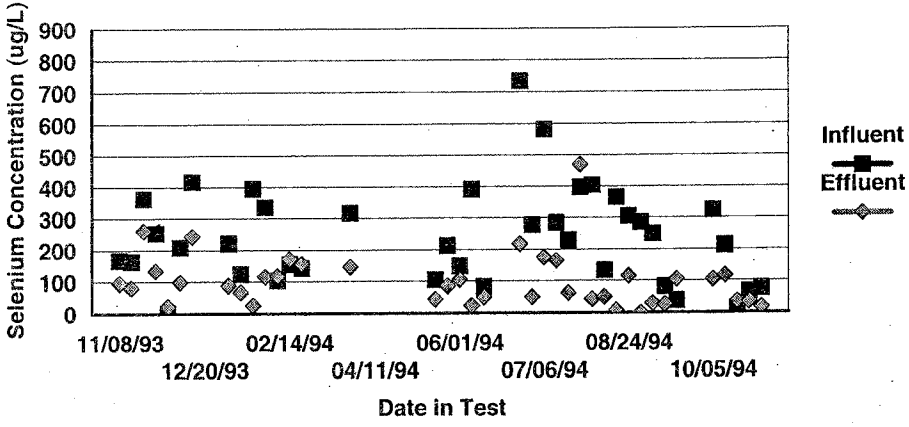


Figure 50
SSF1 - Percentage of
Total Selenium Removed

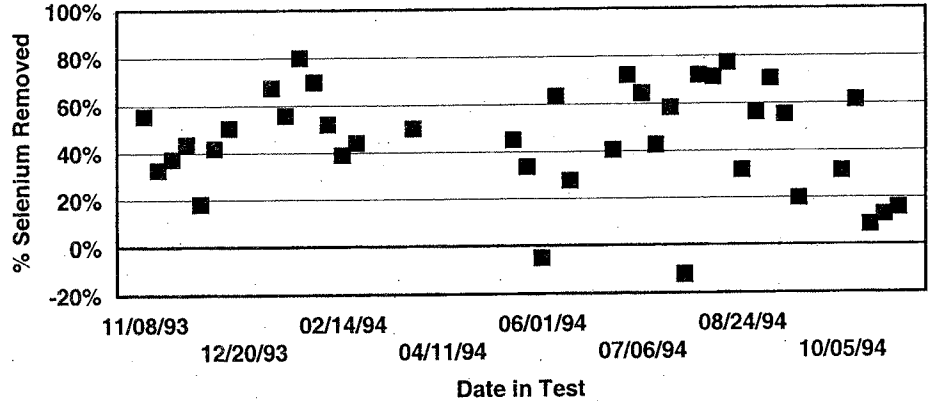


Figure 51
SSF1 - Influent and Effluent
Nitrate

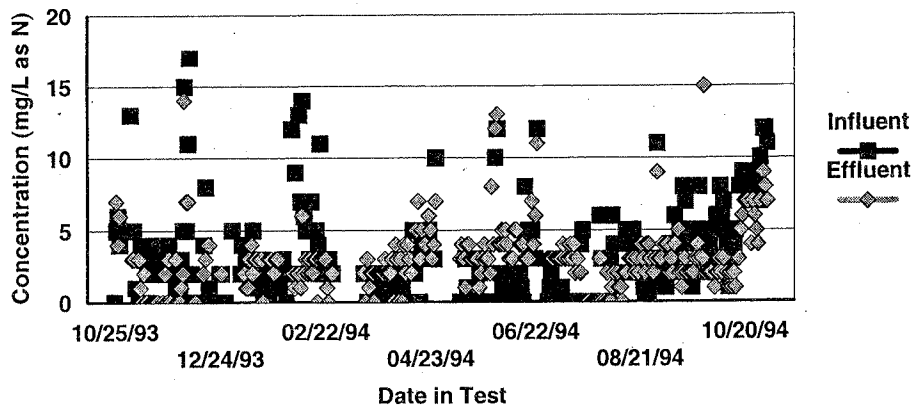


Figure 52
SSF1 - Influent and Effluent
Total Organic Carbon

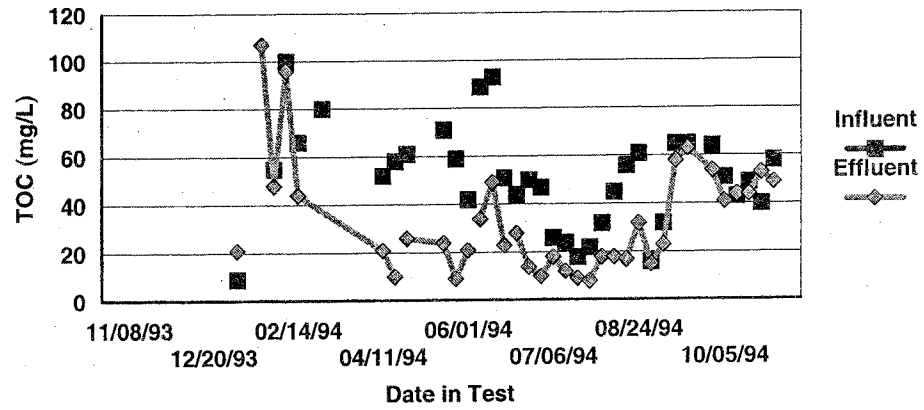


Figure 53
SSF1 - Influent and Effluent
Total Suspended Solids

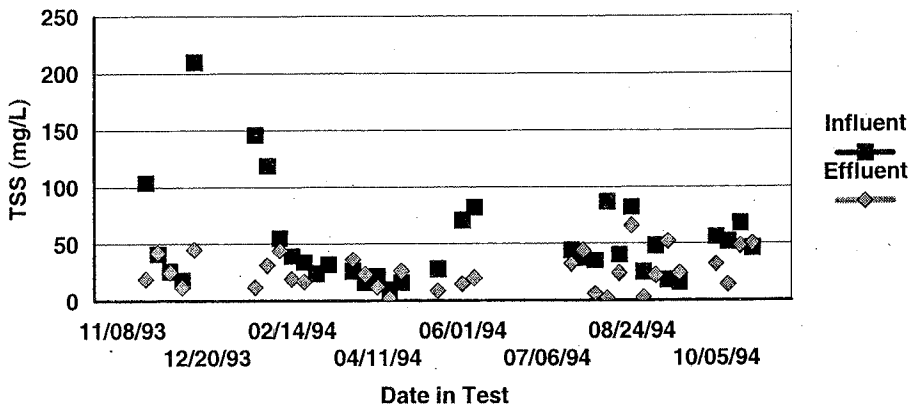
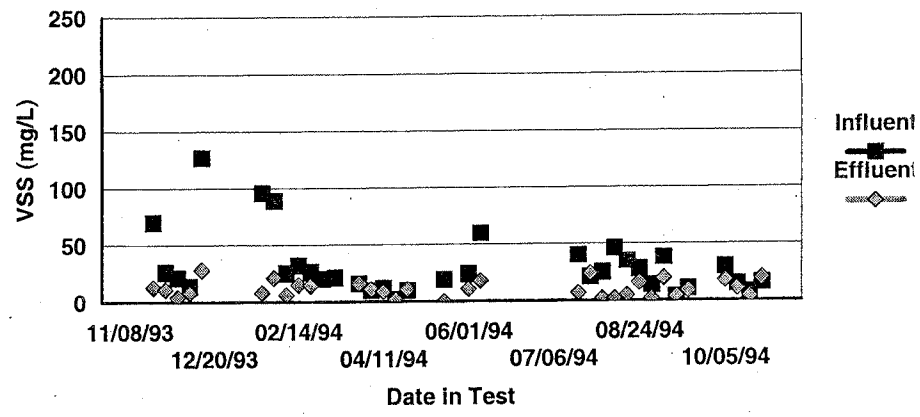


Figure 54
SSF1 - Influent and Effluent
Volatile Suspended Solids



The particulate selenium values are shown by Figure 57, and Figure 58 shows the percentage of Tse removed by the filter. Pse influent and effluent concentrations averaged 184 ug/L and 93 ug/L (79 ug/L excluding spike), respectively. The percentage of Tse removed by the filter averaged 35.5% including the spike value and 41.1% excluding the spike value.

Influent and effluent nitrate and total organic carbon concentrations are shown by Figures 59 and 60, respectively. Generally the effluent values were lower than the influent ones. The influent and effluent nitrate concentrations averaged 7.5 mg/L as N and 3.8 mg/L as N and the influent and effluent TOC values averaged 55 mg/L and 41 mg/L, respectively.

Influent and effluent concentrations for total and volatile suspended solids are shown in Figures 61 and 62. TSS influent and effluent concentrations average 51 mg/L and 26 mg/L, and the VSS concentrations averaged 26 mg/L and 11 mg/L, respectively for the 12-month test period.

Figure 55
SSF2 - Influent and Effluent
Total Selenium

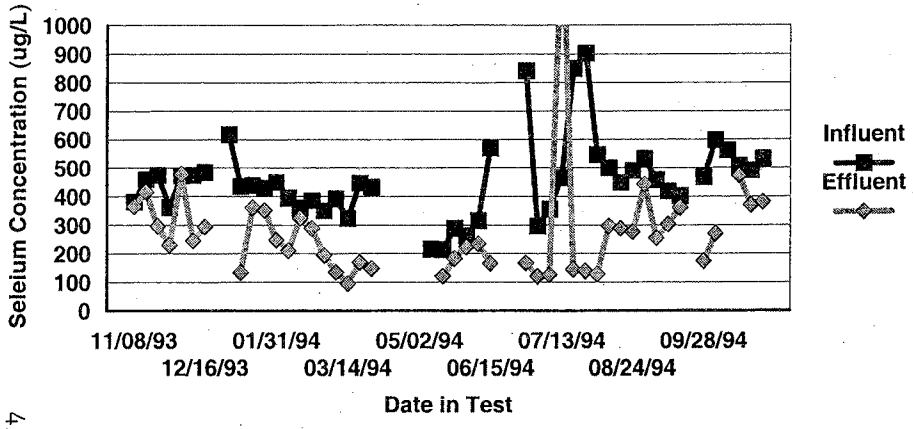


Figure 56
SSF2 - Influent and Effluent
Soluble Selenium

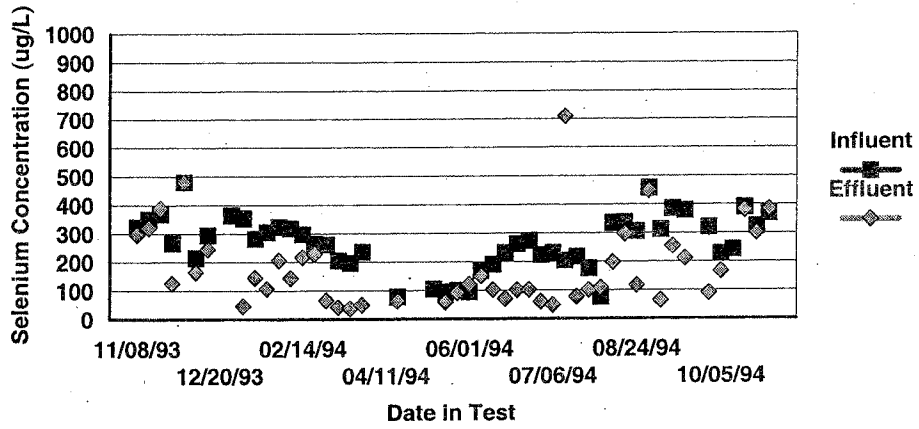


Figure 57
SSF2 - Influent and Effluent
Particulate Selenium

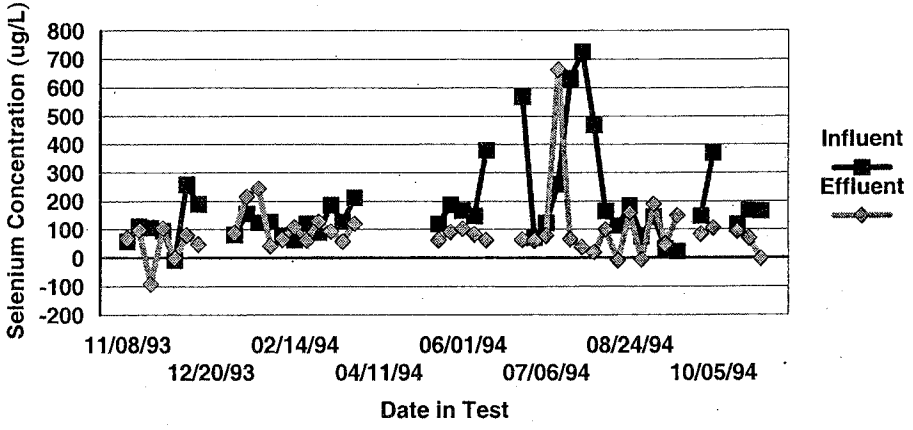


Figure 58
SSF2 - Percentage of
Total Selenium Removed

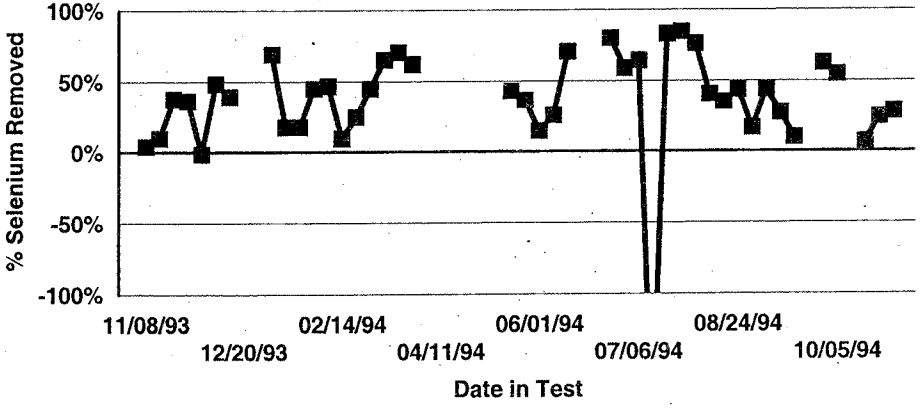


Figure 59
SSF2 - Influent and Effluent
Nitrate

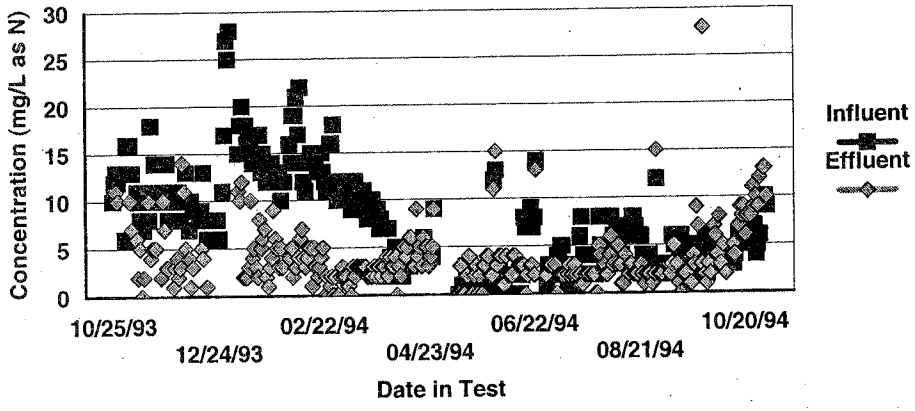


Figure 60
SSF2 - Influent and Effluent
Total Organic Carbon

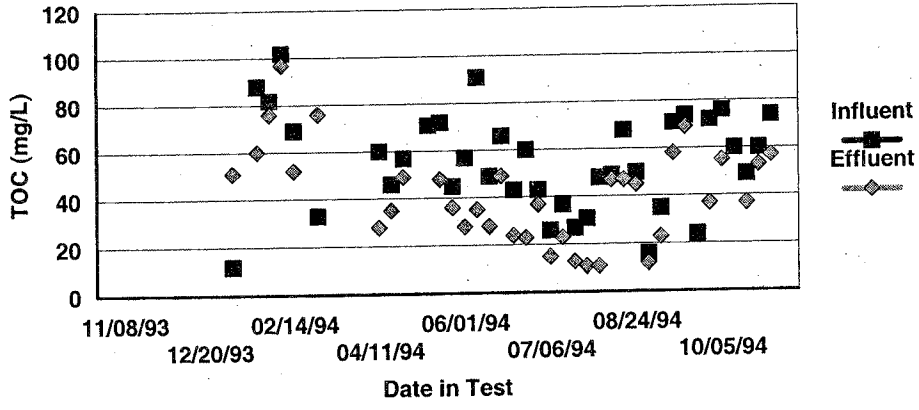


Figure 61
SSF2 - Influent and Effluent
Total Suspended Solids

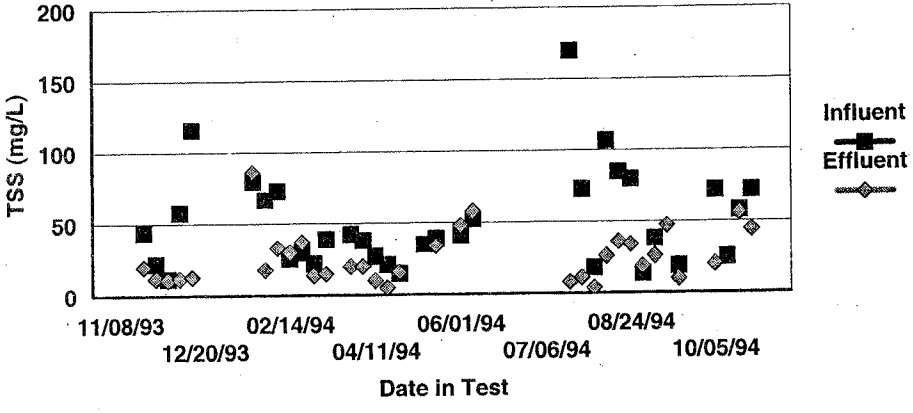
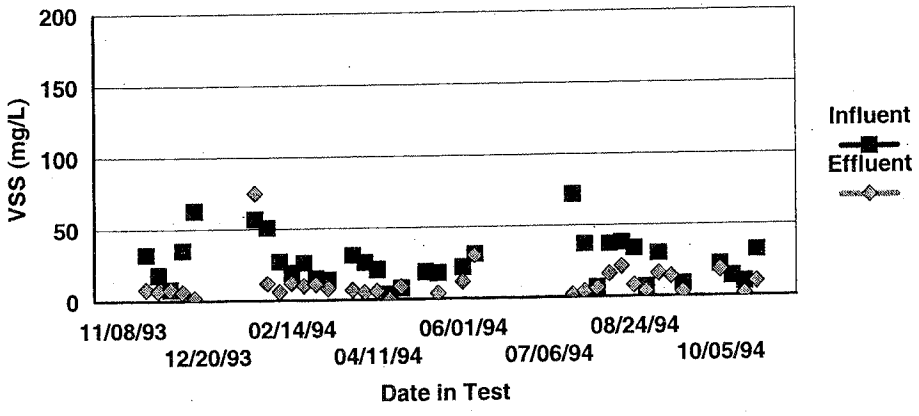


Figure 62
SSF2 - Influent and Effluent
Volatlile Suspended Solids



PACKED BED REACTOR TEST

Packed Bed Reactor Test Unit

The packed bed reactor is a fixed media system. Treatment occurs through biological activity from the organisms attached to the support media as the wastewater passes through the media.

The PBR tested at the Adams facility was an upflow system and consisted of a 9-foot section of schedule 80 PVC pipe, with a diameter of 10 inches. The PBR system was fitted with an influent pump, feed flowmeter, methanol injection system, and other appurtenances. The support media, for biological growth, were 1-inch-diameter, plastic Jaeger Tri-pack spheres with a void volume of 90 percent, a surface area of 85 square feet per cubic foot of spheres, and a weight of 6.2 pounds per cubic foot of spheres. A schematic of the PBR tested at the Adams facility is shown in Figure 63.

Packed Bed Reactor Operations - December 16, 1993 through November 21, 1995

After the PBR was inoculated with effluent from the UASBR, testing commenced on December 16, 1993 (Day 458), at a feed flow rate targeted at 0.1 gpm and a methanol dosage rate of 300 mg/L. Data collection commenced on January 1, 1994. The feed flow rate remained targeted at 0.1 gpm for the entire testing period, while the targeted methanol dosage rate was reduced to 200 mg/L on March 17, 1994 (Day 549), and then increased to 250 mg/L on August 1, 1994 (Day 549). The phosphate dosage for the influent drainage water to the Adams facility was increased to 1.3 mg/L from 0.25 mg/L on August 29, 1995 (Day 1079).

PBR operations were suspended for two prolonged periods from March 10, 1995 (Day 907) through March 30, 1995 (Day 927) due to flooding of the site and from August 30, 1995 (Day 1080) through September 15, 1995 (Day 1096) for maintenance activities. Problems were encountered in maintaining consistent influent flow and methanol dosage rates into and through the PBR throughout the testing period. On February 21, 1994 (Day 525), the influent flow rate, measured by graduated cylinder and stopwatch, was determined to be 0.02 gpm.

The flow problems were related to buildup of gas, biological growth, and precipitation of salt inside the PBR, the influent lines, and the effluent lines. Modifications made to resolve the flow problems included replacing a pressure regulating valve on the discharge line of the dosing pump on February 21, 1994 (Day 525); installing a gas relief valve on top of the PBR in March 1994 ; relocating the PBR's control valve and flow meter to the influent line from the effluent line on April 1, 1994 (Day 564), and October 10, 1994 (Day 756), respectively; and separating the PBR's feed line from the line that also fed the UA2 and FBR2 on September 22, 1995 (Day 1103). Regular maintenance activities were instituted to flush the influent and effluent lines of biological growth, gas, and precipitated salt as well as to clean the PBR and distribution plate to remove biological growth and precipitated salt.

Packed Bed Reactor Results

The PBR was operated as a single-stage reactor, ran parallel to the UASBR and FBR2, and reduced both selenium and nitrate. The feed selenium concentrations were previously presented

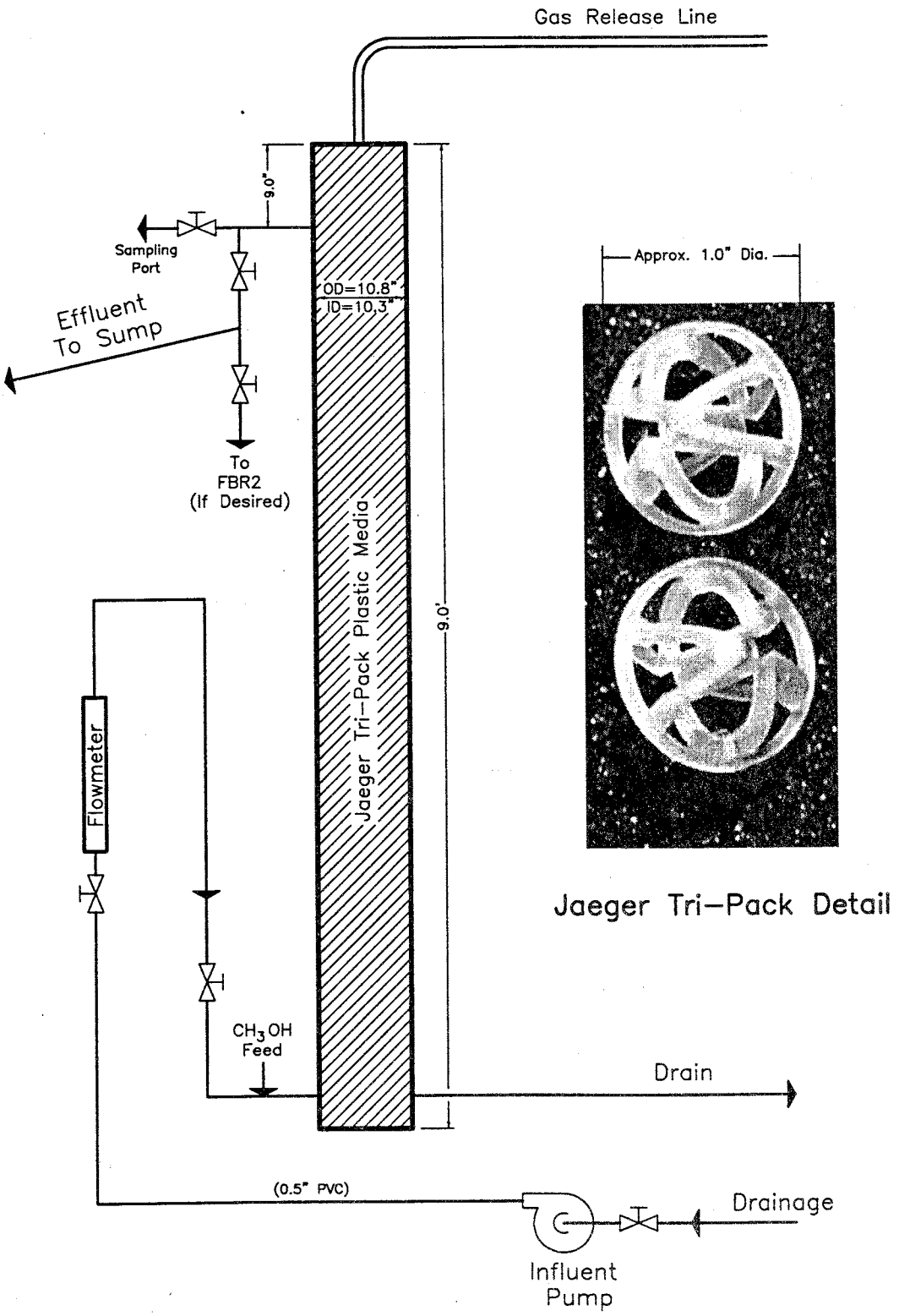


Figure 63. Packed Bed Reactor Schematic

in the UASBR Period 3 section, Figure 13. The average influent Tse, Sse, and selenite concentrations for the entire PBR operation period from January 1, 1994 through November 21, 1995 were 524 ug/L, 506 ug/L and 3 ug/L, respectively. Figure 64 shows the effluent concentrations for Tse, Sse, and selenite and averaged 387 ug/L, 243 ug/L, and 30 ug/L, respectively, for the entire 23-month operation period.

Figure 65 shows the percentages of Tse and Sse reduced and dates when targeted methanol dosage rates were changed. The reduction percentages fluctuated throughout the testing period and averaged 26% and 51% for Tse and Sse, respectively.

Influent and effluent nitrate concentrations are shown by Figure 66. The effluent concentration fluctuated during the course of operations and at times was greater than that of the influent. The influent and effluent concentrations for the operation period averaged 29 mg/L and 11 mg/L, respectively.

The ambient and reactor temperatures are shown by Figure 67. The reactor temperature basically followed the ambient temperature. The average ambient from reactor temperature difference was 1.6°C.

Figure 68 shows influent and effluent dissolved oxygen. Effluent DO from the PBR remained stable throughout the entire testing period and averaged 0.8 mg/L. The influent averaged 8.8 mg/L.

Methanol dosage and the two dates for when the target rate was changed are shown by Figure 69. Even though a stable dosage rate was difficult to maintain, the average dosage rate for the three periods were 321 mg/L, 218 mg/L, and 269 mg/L for target rates of 300 mg/L, 200 mg/L, and 250 mg/L, respectively.

Influent and effluent total organic carbon concentrations are shown by Figure 70. Aside from a period at the beginning of operations, the effluent TOC concentrations remained relatively stable and averaged 32 mg/L (without the beginning period previous to February 21, 1994), while the influent averaged 13 mg/L for the same period.

Figures 71, 72, and 73 show influent and effluent total suspended solids, volatile suspended solids, and total dissolved solids, respectively. Even though the influent and effluent TSS concentrations varied throughout the operation period, they both averaged 19 mg/L. The influent and effluent VSS concentrations also fluctuated throughout the entire operation period, but averaged 5 mg/L and 8 mg/L, respectively. The effluent TDS concentration was consistently less than the influent and averaged 6,710 mg/L, while the influent averaged 8,200 mg/L for the period.

Influent and effluent alkalinity and electrical conductivity and are shown by Figures 74 and 75. Influent alkalinity was always lower that the effluent, and the difference between the two

Figure 64
PBR - Effluent Total Selenium, Soluble Selenium and Selenite

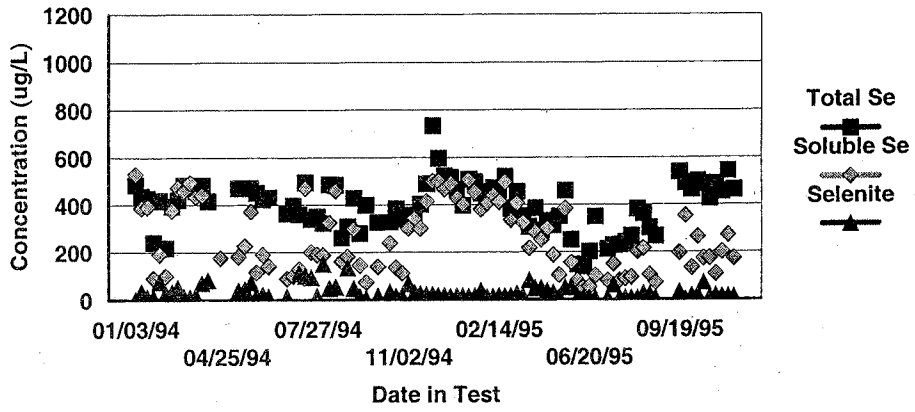


Figure 65
PBR - Percentage of Total & Soluble Selenium Reduced and Dates for Methanol Dosage Change

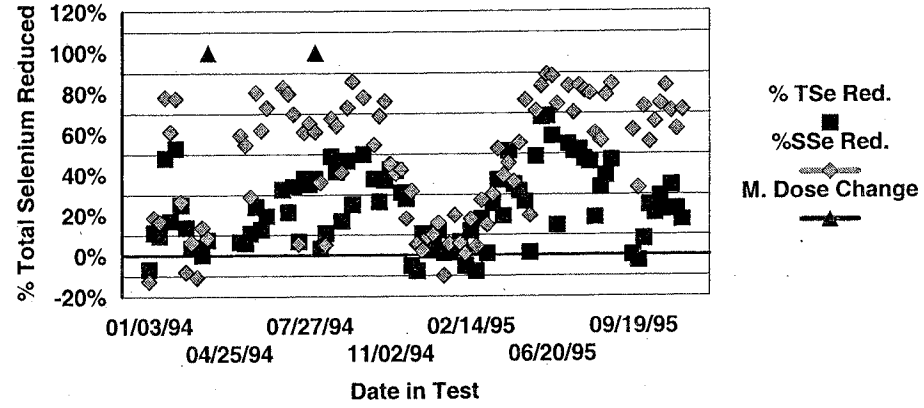


Figure 66
PBR - Influent and Effluent Nitrate

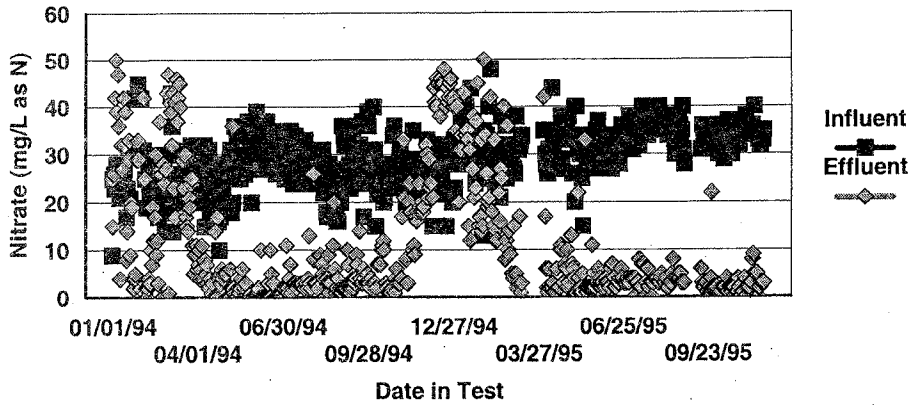


Figure 67
Reactor and Ambient Temperatures

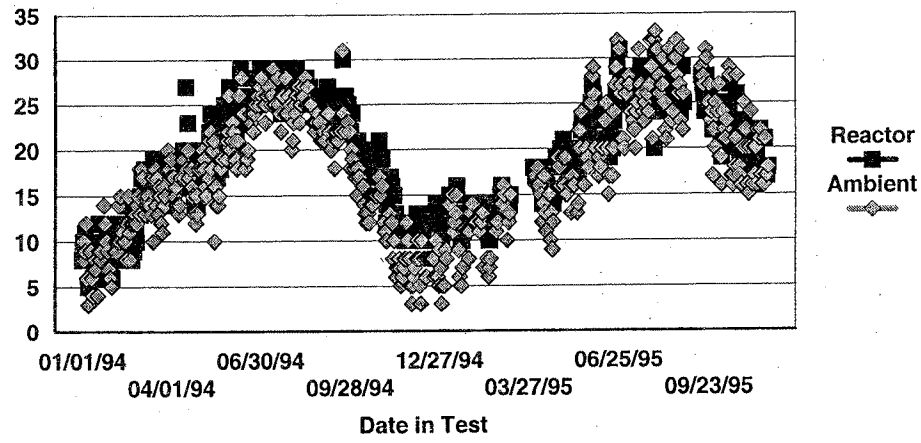


Figure 68
PBR - Influent and Effluent
Dissolved Oxygen

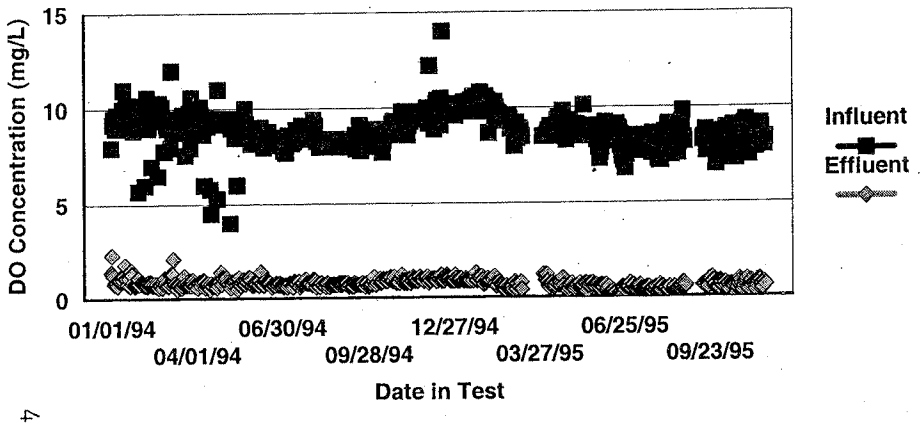


Figure 69
PBR - Methanol Dosage and Date
for Change of Target Dosage Rate

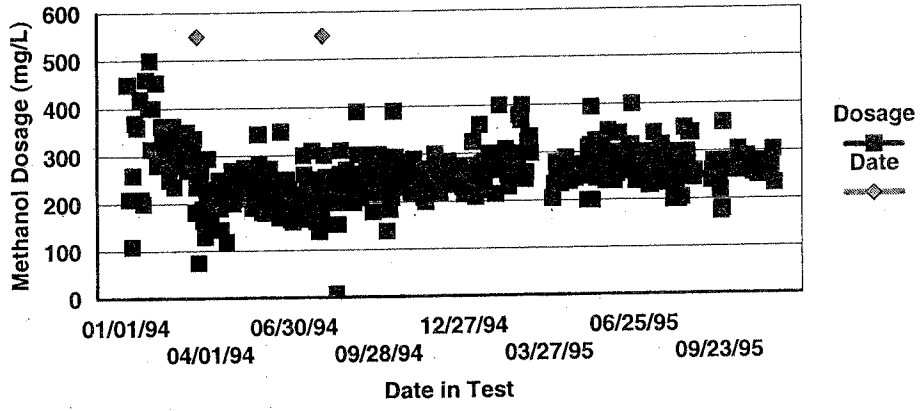


Figure 70
PBR - Influent and Effluent
Total Organic Carbon

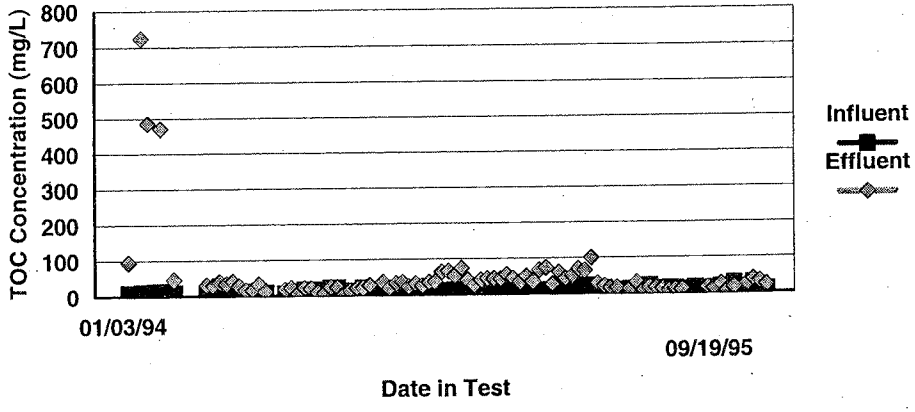


Figure 71
PRB - Influent and Effluent
Total Suspended Solids

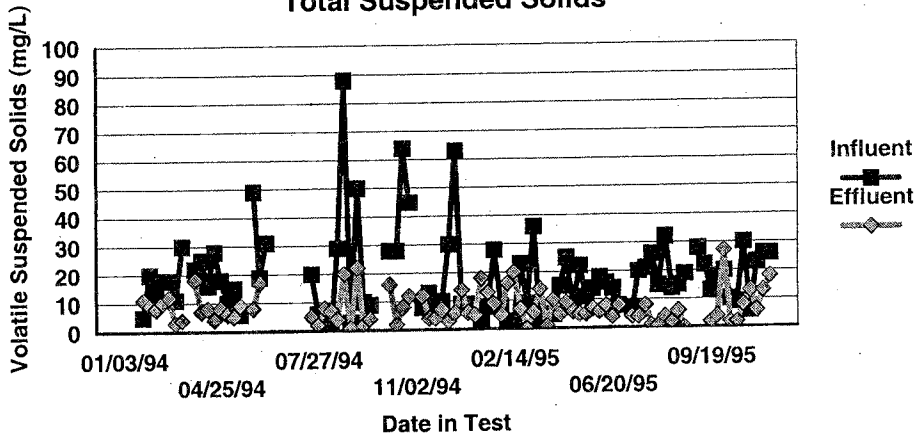


Figure 72
PBR - Influent and Effluent
Volatile Suspended Solids

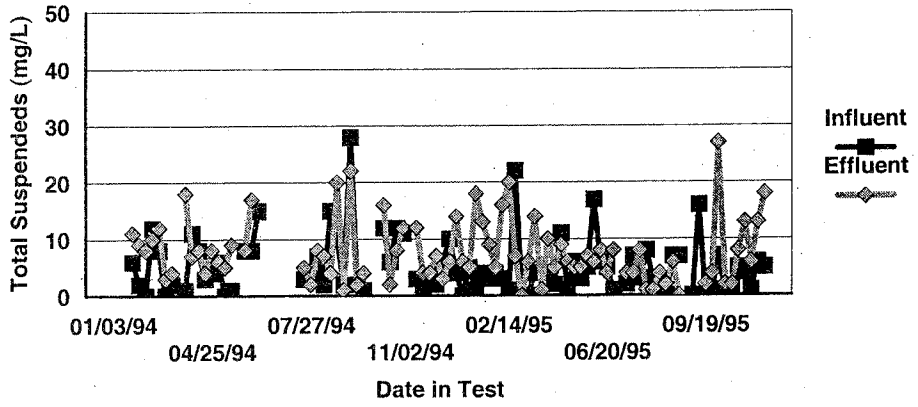


Figure 73
PBR - Influent and Effluent
Total Dissolved Solids

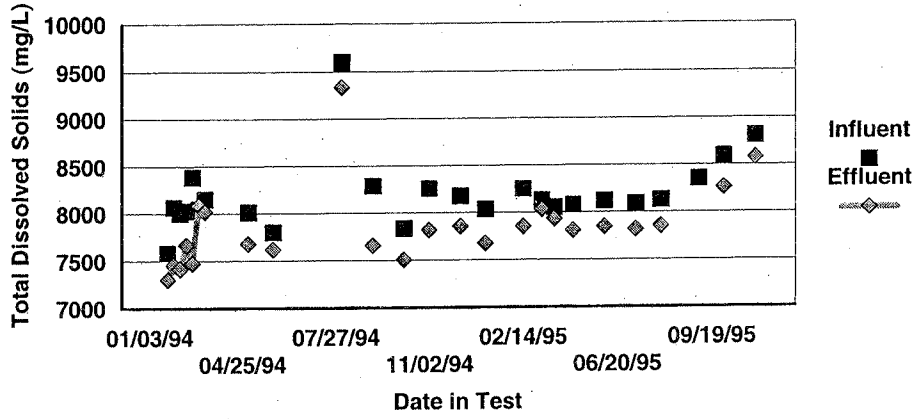


Figure 74
PBR
Influent and Effluent Alkalinity

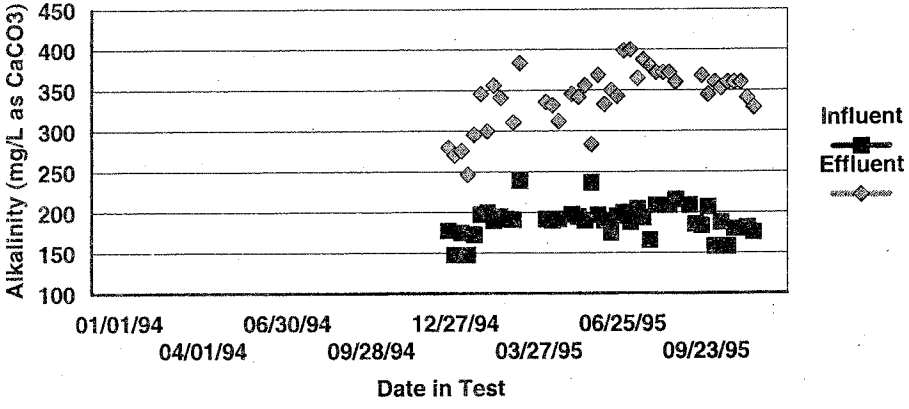
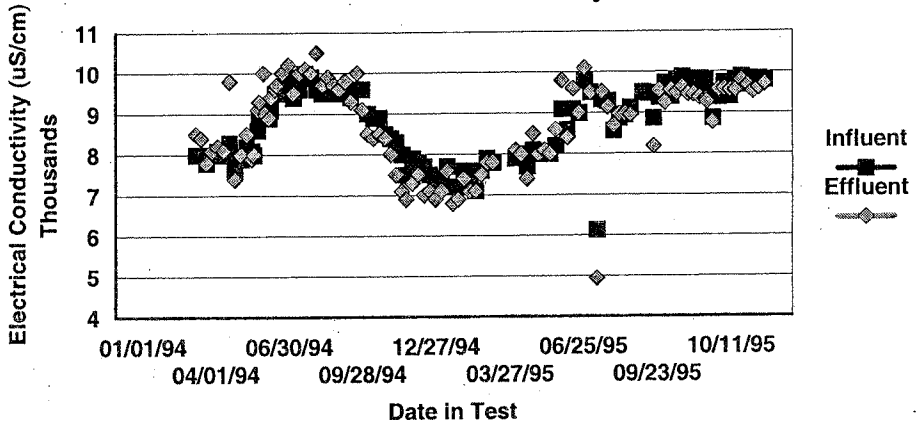


Figure 75
PBR - Influent and Effluent
Electrical Conductivity



averaged 15.3 mg/L as $CaCO_3$ for the entire operation period. The EC remained relatively constant between the influent and effluent values and the difference between the two, effluent from the influent, averaged 22 uS/cm.

PILOT UPFLOW ANAEROBIC SLUDGE BLANKET REACTOR (UA2) TEST

UA2 Test Unit

The pilot UASBR or UA2 complimented the operation of the main UASBR. The primary objective of the UA2 was to develop operation parameters for the main UASBR. The UA2, a transparent column, visually represented the main UASBR where sludge could be monitored for color and size and where the effects of a change in operational parameter such a upflow velocity could be observed prior to making operational changes to the main unit. Also, at the end of the testing period, the UA2 was used to treat low selenium drainage water from Firebaugh Canal Water District.

The UA2 consisted of a 10-inch diameter Plexiglas column, 6 feet high and fitted with a gas/solids separator cone, baffle and a recycle line. The UA2 system was fitted with influent and recycle pumps, influent and recycle flow meters, and a methanol injection system. The schematic for the UA2 system is shown in Figure 76.

UA2 Operations - March 16, 1994 through November 16, 1995

Maintaining the integrity of the sludge and sludge bed throughout the entire program testing of the UASBR process was a continual problem. Gas is generated in the sludge bed as a result of the process. The gas posed two basic problems. Gas bubbles would be entrapped in the sludge bed, forming pockets that in turn caused short circuiting through the unit. The second problem occurred as gas bubbles floated up through the unit. The bubbles attracted sludge granules, sludge fines, and other bubbles and formed a mass or "clumps" as the bubbles passed up through the sludge bed and floated to the surface. These clumps contained organisms that are vital in the treatment process. For the process to be effective, these organisms must remain in the sludge bed and be available to treat the incoming water. The primary concerns of operations were to ensure an even distribution of flow through the sludge bed; to prevent degradation of the sludge granules; to release gas from the sludge bed; to prevent agglomeration of the gas and sludge that would form into clumps; and to break up the agglomeration once it occurred. Almost all operational decisions were based on these concerns. As a standard daily maintenance practice, operation personnel tapped the outside of the reactor at the sludge bed level with a rubber mallet to relieve gas that had accumulated.

Operation of the UA2 commenced on March 16, 1994 (Day 548), and ceased on November 16, 1995 (Day 1158). The first seven weeks of operation involved shake-down of the pilot system and testing the stability of sludge. Recording of operational data started on May 10, 1994 (Day 603) while laboratory analyses commenced on June 1, 1994 (Day 625).

From March 16 (Day 548) through April 27 (Day 590), the UA2 was operated to test the stability of the granular bakery sludge. It was loaded with 8 gallons of the black bakery sludge and started at a feed flow rate of 0.12 gpm (upflow velocity of 0.231gpm/ft^2) with a methanol dose of 275 mg/L. On March 23 (Day 556), the black granules had turned brown and white, likely because of the oxygen content of the influent drainage water. The unit was turned off for 24 hours then restarted with influent limited to 0.1 gpm for 30 minutes a day with a pure methanol

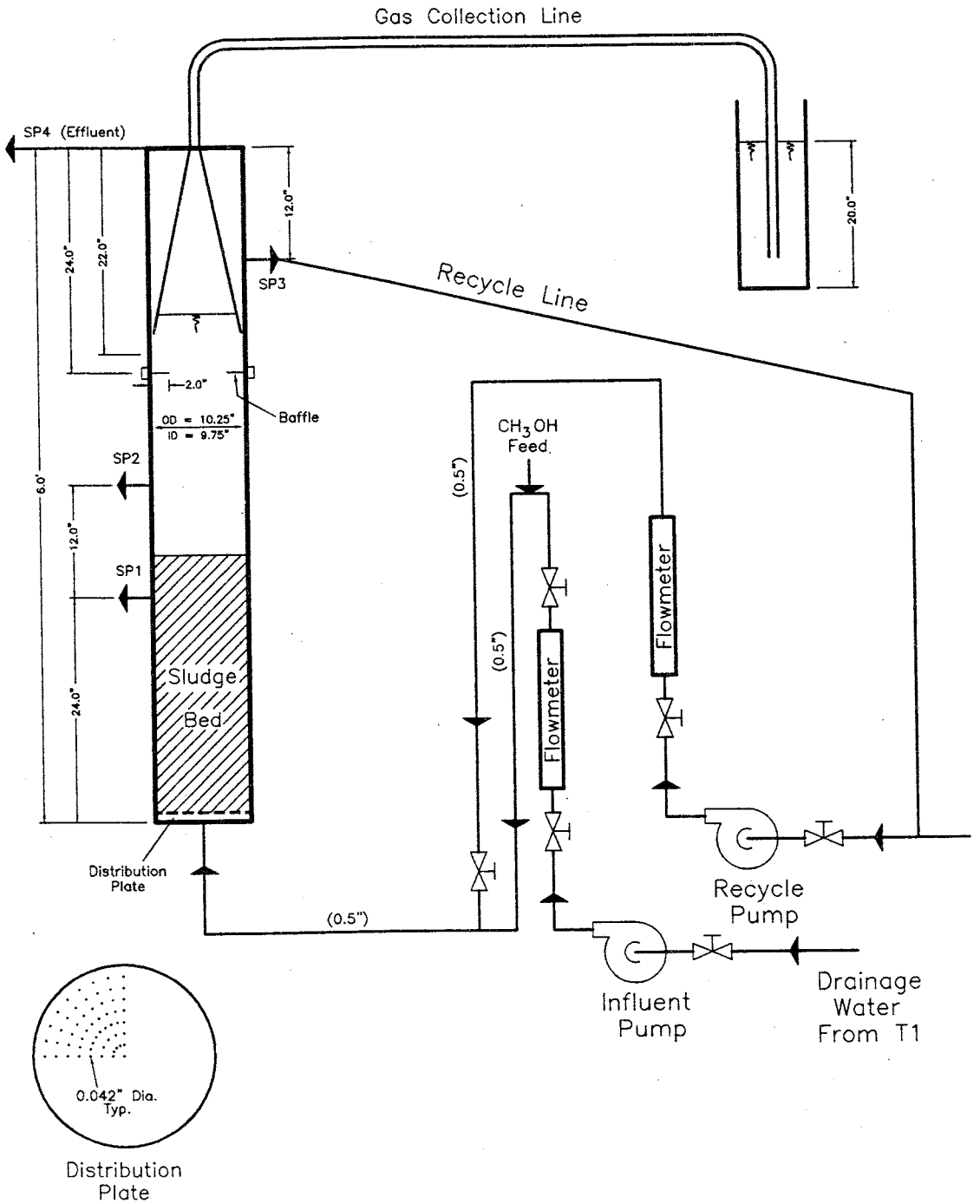


Figure 76. Pilot - Scale Upflow Anaerobic Sludge Blanket Reactor Schematic (UA2)

dosage of 25 mL per day and a recycle flow of 0.1 gpm. The recycle flow was turned off on April 17 while the influent rate and pure methanol dosage remained unchanged. When this test was complete, on April 27, the sludge granules gradually had turned gray and black and exhibited decent settling characteristics. Fines were present in the water above the sludge bed for the entire period.

On April 27, 1994, the UA2 was shut down to replace the bakery sludge with a composite sludge taken from three locations of the main UASBR: port 2, port 3 and surface scum of the UASBR. The sludge volume placed into the UA2 was 7.4 gallons (28 liters) with a settled sludge depth of 17 inches. The UASBR sludge was a mixture of anaerobic digester sludge from the Fresno Wastewater Treatment Plant and activated sludge from the Selma-Kingsburg-Fowler Treatment Plant. From April 27 to May 9, 1994, the UA2 was operated with only a recycle flow of 0.12 gpm (upflow velocity of 0.231 gpm/ft^2). It was observed that gas bubbles generated in the sludge bed attracted sludge fines and particles as the bubbles rose to the surface. A portion of the sludge particles would then fall back on top of the sludge bed as the bubbles dispersed at the surface. On May 9, 1994 (Day 602), testing with drainage water commenced, during which influent flow was added at 0.05 gpm and the recycle flow rate was doubled to 0.2 gpm (upflow velocity of 0.483 gpm/ft^2). In this mode, nitrate and dissolved oxygen concentrations both decreased. The recycle flow rate had to be adjusted daily because sludge fines and gas accumulated in the recycle line and restricted the recycle flow. The recycle flow rate often dropped to zero overnight. Sludge fines and granules would agglomerate and form into clumps in the reactor during normal operations. To agitate the sludge bed and break down these clumps of sludge and gas, the recycle rate was increased to 1.0 gpm for five minutes. At the end of this test period, the sludge bed was about 21 inches deep and consisted of brown granules at the bottom of the bed with black fine on top of the granule layer.

From May 24 (Day 617) through September 14, 1994 (Day 730), the UA2 was operated to mimic operation of the main UASBR. The feed flow rate ranged between 0.1 and 0.12 gpm (upflow velocity of between 0.193 and 0.231 gpm/ft^2), the recycle was off, and the methanol dosage was targeted at 300 mg/L. The sludge bed was agitated daily to release gas generated during operations.

During the first month of this test period, the sludge bed's depth decreased 3 inches but an increase in the depth of the brown granules was observed. The granules at the bottom of the bed had a reddish tint. Fines were noticed to be moving throughout the reactor and accumulating on the outside of the cone (gas/solids separator) and along the reactor wall by the bottom of the cone. The wall of the reactor above the sludge bed was a red and orange color. The sludge bed had increased from 15 inches to 21 inches during the last month of this period. The top 2 to 3 inches of the sludge bed contained fines that were black and dark brown, and the remainder of the bed consisted of granules that were brown.

The next test period was from September 15, 1994 (Day 731) through November 2, 1995 (Day 1144), during which the primary goals were to evaluate the treatment efficiency of the process at a higher flow rate and observe the stability of the sludge under the new parameters. Initially, the UA2 was operated at an influent flow rate of 0.2 gpm (upflow velocity of 0.386 gpm/ft^2), without a recycle flow. The sludge bed was mixed daily for about 2 minutes using the recycle system. Actual methanol dosage rates ranged between 182 mg/L and 485 mg/L.

Problems were encountered maintaining a uniform flow through the sludge bed. One means to accomplish this was to agitate and mix the sludge bed on a daily basis by pulsing additional flow through the reactor using the recycle system. Pulse duration was changed twice during this period from the initial daily duration of 2 minutes. On March 3, 1995 (Day 900), the duration was increased to 5 hours per day, but on April 14 (Day 942) it was decreased to 20 minutes per day because of sludge granule disintegration at the longer duration.

A recycle flow was added to the operation parameters on two occasions during this test period. The primary purposes of the recycle flow were to prevent sludge granules, sludge fines, and gas from agglomerating into clumps and to help break up the clumps once they were formed. The first occasion was for eight days, starting January 7, 1995 (Day 845). The second occasion was for one week, starting February 23, 1995 (Day 892). On both occasions, the recycle flow was terminated because the sludge granules decreased in size as result of the recycle flow. Problems were also encountered in maintaining a constant recycle flow rate because sludge fines and gas restricted flow at various locations in the recycle system.

The sludge bed expanded about 8 inches during the first month of the test. On October 20, 1994 (Day 766), 3 gallons of brown granules were removed from the middle of the sludge bed to improve mixing of the bed and distribution of flow through the bed. The remaining sludge bed depth measured 17 inches settled and expanded 6 inches when operations resumed.

Sludge was removed from the reactor on three other occasions to improve the mixing of the bed. Four gallons were removed on January 30, 1995, (Day 868); 2 gallons were removed on June 15, 1995 (Day 1004); and another 2 gallons were removed on October 5, 1995 (Day 1116). On June 29, 1995 (Day 1018), the entire bed was replaced with sludge obtained from the main UASBR to compare treatment efficiency of the UA2 with that of the main UASBR.

Testing with the UA2 was temporarily stopped for three weeks, starting March 10, 1995 (Day 907), and due to flooding of the Adams Avenue site. On another note, the UA2 was taken apart and cleaned on three occasions in 1995: January 30, May 2, and October 5. Also the phosphate feed dosage into the raw drainage water was increased from 0.25 mg/L to 1.3 mg/L on September 29, 1995 (Day 1079).

Testing using low-selenium drainage water was performed from November 2 (Day 1144) through the end of testing operations on November 16, 1995. Drainage water with selenium concentrations averaging 35 ug/L was trucked from Firebaugh Canal Water District. The feed flow rate into the unit was 0.2 gpm (upflow velocity of 0.386 gpm/ft^2) until November 11, when it was decreased to 0.1gpm (upflow velocity of 0.193 gpm/ft^2). Methanol dosage ranged between 370 mg/L and 500 mg/L. The unit was operated without a recycle flow.

UA2 Results

The testing period for the UA2 is divided into four periods. Period 1, from May 24, 1994 through September 14, 1994, was when the UA 2's influent flow rate was between 0.1 and 0.12 gpm. Period 2, from September 15, 1994 through March 9, 1995, when the unit was shut down due to site flooding, was when the UA2's influent rate was targeted at 0.2 gpm. Period 3, from April 1, 1995 though October 31, 1995, was when the UA2 resumed operations after flooding at

an influent rate of 0.2 gpm. And lastly Period 4, from November 3, 1995 through November 16, 1995, was when the UA2 treated drainage water with a low concentration of selenium (total selenium concentration under 40 ug/L). Due to its short duration, Period 4 is not discussed and its operation and analyses data are absent from the figures. Period 4 data are included in the Appendixes Report. The Appendixes Report A through K contains operation and analytical results data for the project.

The overall results for selenium reduction are shown by Figures 77 and 78. Figure 77 shows the effluent concentration for total selenium, soluble selenium, and selenite, while Figure 78 shows the percentage of soluble selenium reduced and the dates for beginning of Periods 2 and 3. Influent selenium concentration data were previously presented in Figure 13. The best percentage Sse removal occurred in Period 1 and averaged 74%, while removal for Periods 2 and 3 averaged 24% and 57%, respectively.

The influent and effluent nitrate concentrations are shown on Figure 79. Nitrate reduction was best and most stable for Period 3. The effluent concentration averaged 5.6 mg/L as N, 11.3 mg/L as N, and 5.4 mg/L as N for Periods 1, 2, and 3, respectively, while the standard deviation for the three periods averaged 8.1 mg/L as N, 8.3 mg/L as N , and 5.4 mg/L as N.

Figure 80 shows the influent and effluent dissolved oxygen concentrations. The effluent DO concentration was consistently low for all three periods and averaged 0.6 mg/L, 0.7 mg/L, and 0.4 mg/L. Influent and effluent total organic carbon concentrations are shown by Figure 81. The influent TOC concentration was consistent through the entire testing period and averaged 13 mg/L. The effluent varied and averaged 27 mg/L, 65 mg/L, and 50 mg/L for the three periods. Figure 82 shows the influent total dissolved solids concentration was consistently greater than that of the effluent. The influent and effluent TDS concentrations averaged 8,239 mg/L and 7,924 mg/L, respectively, for the entire period.

Figure 83 shows influent and effluent alkalinity concentrations. The influent averaged 186 mg/L as $CaCO_3$, while the effluent averaged 342 mg/L as $CaCO_3$. The average difference, the influent value from the effluent value, was 152 mg/L as $CaCO_3$.

The influent and effluent electrical conductivity values are shown by Figure 84. Except for a few instances, the influent was greater than the effluent value. The influent averaged 8,700 uS/cm for the entire period, while the effluent averaged 8,432 uS/cm.

Figure 77
UA2 - Effluent Total Selenium, Soluble Selenium and Selenite

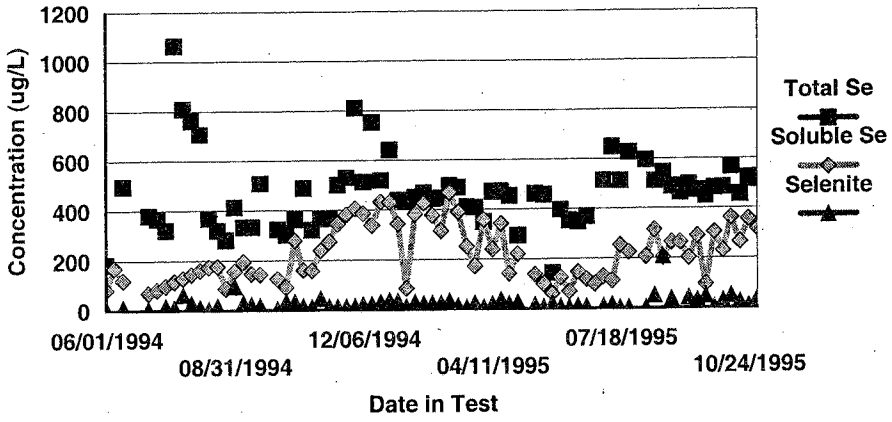


Figure 78
UA2 - Percentage of Soluble Selenium Reduced and Dates for Influent Flow Change and Restart after Flooding

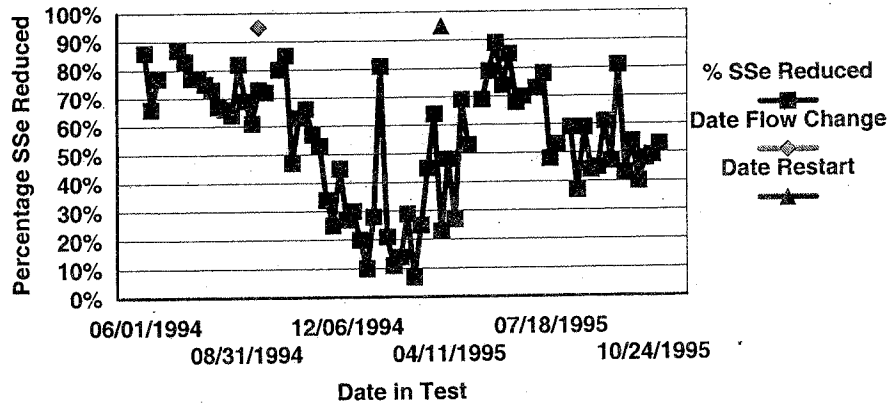


Figure 79
UA2 - Influent and Effluent Nitrate

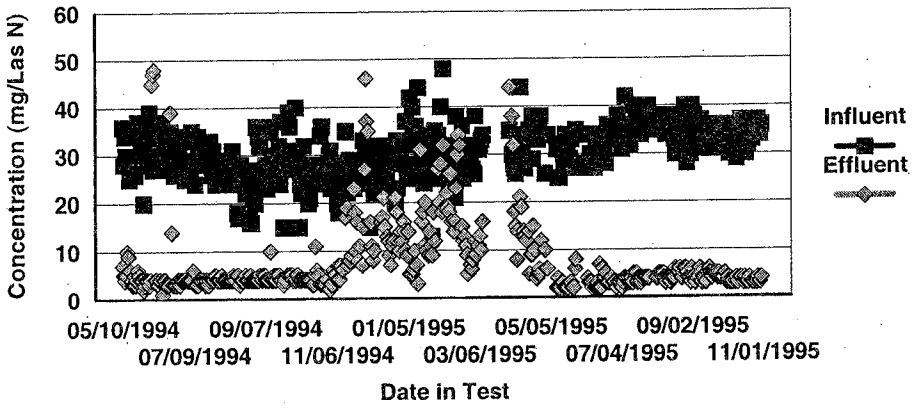


Figure 80
UA2 - Influent and Effluent Dissolved Oxygen

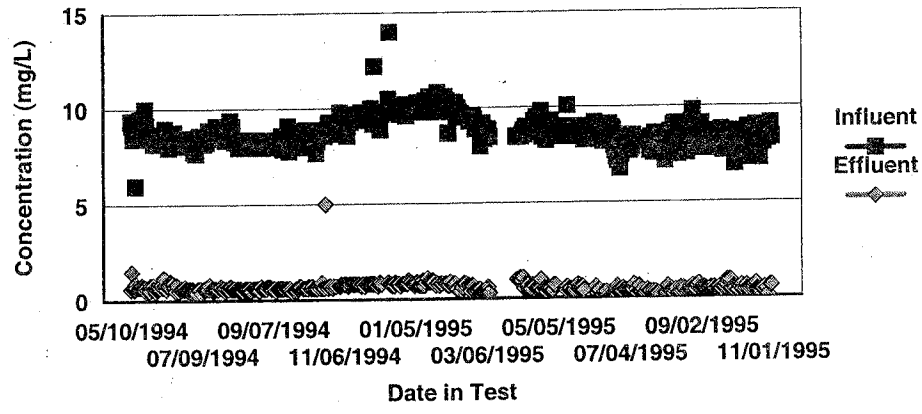


Figure 81
UA2 - Influent and Effluent
Total Organic Carbon

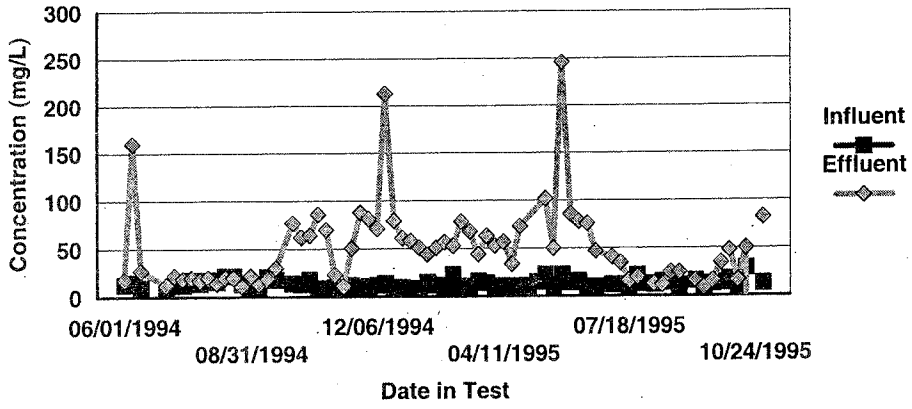


Figure 82
UA2 - Influent and Effluent
Total Dissolved Solids

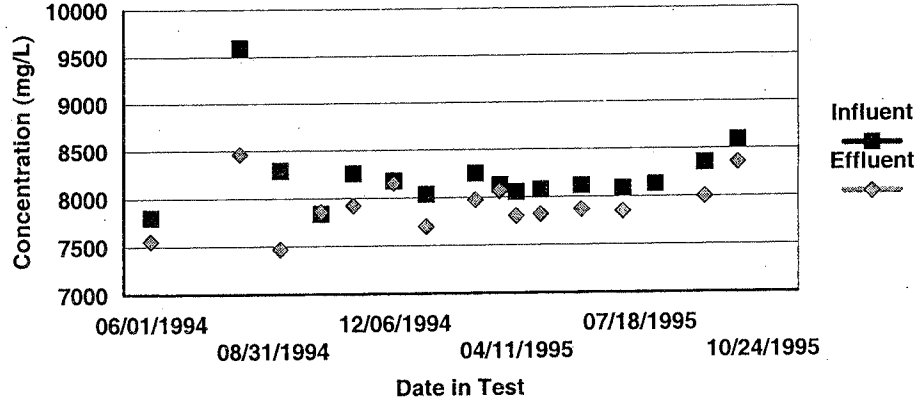


Figure 83
UA2 - Influent and Effluent Alkalinity

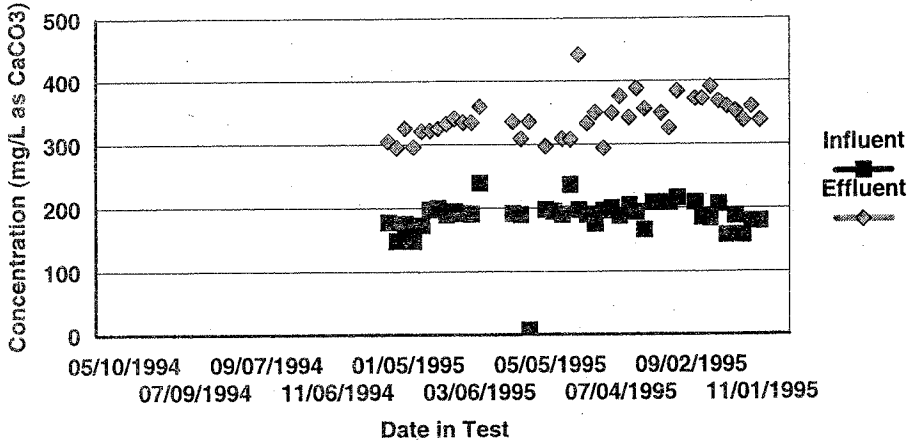
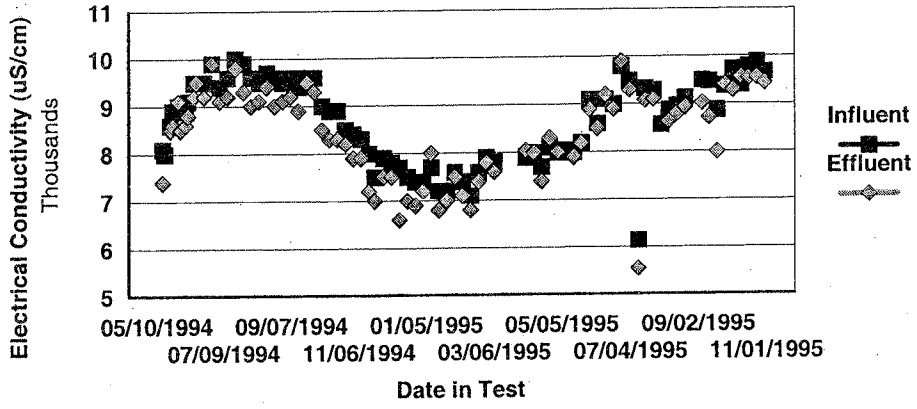


Figure 84
UA2 - Influent and Effluent
Electrical Conductivity



EVALUATION

A total of seven processes were tested at the Adams facility which included four first-stage processes, two second-stage processes, and one third-stage process. The processes were operated for a number of parameters. The processes are evaluated according to the stages and the process trains. Periods for evaluation of the individual processes and trains are grouped around dates on which significant events occurred. These events include the installation of the cylinder and cone in UASBR, change in methanol dosage rates for the process, change in phosphate dosage rate into feedwater, weather conditions, and start-up and operations of second and third-stage processes. The values in the summary tables are average values for the period that were collected or determined from data collected on a regular basis. Care should be taken when using the period average values for evaluation due to the number of data available for the period and may be heavily influenced by one data value.

First-stage Processes

The UASBR, UA2, FBR2 and PBR were the four first-stage processes tested at the facility. The primary purpose for the first-stage processes was to evaluate the processes and trains to reduce/remove selenium from agricultural drainage water. Since 85 to 95% of selenium in drainage water is in selenate (Se+6) state, selenium's most soluble form, the primary objective of a first-stage process was to reduce soluble selenium (selenate) to selenite (Se+4) or further to the particulate state (elemental). An ideal first-stage process would entirely remove all forms of selenium through volatilization.

To evaluate the processes on an equal basis (i.e., identical feedwater, operation of methanol dosing system, temperature, etc.), the periods used in the following tables were primarily based upon UASBR's Period 1 testing (two periods in Table 4), start of UA2 testing on June 1, 1994 , the phosphate dosage rate (changes on August 1, 1994 and August 29, 1995), installation of cylinder (June 1994) and cone (July 1995) in the UASBR, and flooding at the facility (March 1995). Dates for these significant events are listed in the Appendix of this report.

Table 4 compares percentage reduction of Sse that occurred in the first-stage processes. The highest reduction of soluble selenium occurred when the UASBR was initially put into operation using the bakery sludge in September 1992. Sse reduction was consistently above 80% for six weeks until December 7, 1992 with a retention time of 30 hours. The primary problem identified for this period and through the entire testing program was maintaining a uniform flow through the sludge bed. During this period, high upflow velocities (1.8 gpm/ft2) were used to elevate and mix the sludge bed, but in time proved inadequate. Mixing systems using various recycling schemes were instituted during all the periods of UASBR testing, but results varied.

As shown in Table 4, the UA2 demonstrated the best Sse reduction at the lowest retention time of all the first-stage processes for all periods except for the last one from September 2 through November 21, 1995. During this last 10-week period, both the PBR's and FBR's Sse reductions were higher at 65.4% and 64.9%, respectively, but the retention times were 3.4 and 2 times than that of the UA2. The FBR's retention time is based upon only the reactor volume and does not include the volume of the 100-gallon recycle tank.

Table 4
First-stage Processes
Reduction of Soluble Selenium and Retention Time

DATE		UASBR		UA2		FBR2		PBR	
From	To	Soluble Se Reduction %	Retention Time hours	Soluble Se Reduction %	Retention Time hours	Soluble Se Reduction %	Retention Time hours	Soluble Se Reduction %	Retention Time hours
10/26/92	12/07/92	80.8	29.9	-	-	-	-	-	-
12/07/92	03/09/93	58.0	29.9	-	-	-	-	-	-
02/02/94	05/31/94	58.6	9.6	-	-	66.8	3.7	25.7	6.5
06/01/94	06/23/94	65.1	9.6	80.1	3.6	73.4	3.7	74.5	6.5
07/13/94	08/01/94	56.8	5.2	75.0	3.6	66.9	3.7	43.9	6.5
08/02/94	02/15/95	36.1	5.2	47.7	2.1	35.4	3.7	34.7	6.5
03/27/95	07/07/95	45.1	7.6	63.5	1.9	44.3	4.0	60.4	6.5
07/10/95	08/29/95	48.8	9.1	53.9	1.9	32.0	4.0	74.5	6.5
09/02/95	11/21/95	52.7	10.3	52.7*	1.9	64.9	4.0	65.4	6.5
	Average**	47.0		55.4		49.2		48.8	

*

Period from 09/02/94 through 11/02/94
** Averages are weighted according to number of analyses per period

Table 5 shows the increase in alkalinity concentration along with the decrease in the pH value for all four first-stage processes. The values in the table are averages for the period. The increase in alkalinity is a result of the denitrification process. Alkalinity increases for the last period in Table 5 for all four processes were on par with the calculated increase of 198 mg/L as CaCO3 when using IC analyzed nitrate data (see Nitrate Analyses section) from August 1, 1995 through November 21, 1995.

Table 5
First-stage Processes
Change in Alkalinity and pH

From	To	Alkalinity	pH	Alkalinity	pH	Alkalinity	pH	Alkalinity	pH
10/26/92	12/07/92		na		na		na		na
12/07/92	03/09/93		na		na		na		na
02/02/94	05/31/94		-0.1		na		0.1		0.4
06/01/94	06/23/94		-0.1		0.1		0.1		0.2
07/13/94	08/01/94		0.1		0.1		0.1		0.0
08/02/94	12/19/94		-0.0		-0.1		0.2		2.0
12/20/94	02/15/95	112	-0.2	140	0.0	98	0.5	123	-0.1
03/27/95	07/07/95	138	-0.2	141	-0.1	71	0.2	151	0.0
07/10/95	08/29/95	140	-0.3	158	-0.4	71	0.0	172	-0.2
09/02/95	11/21/95	172	0.0	178	-0.5	159	-0.1	174	0.0

pH analyses began in March 1994
Alkalinity analyses began in December 1994
Alkalinity units are mg/L as $CaCO_3$. na is not available

Two summary tables for the first-stage processes are presented in Tables 6 and 7. Table 6 summarizes operation parameters of phosphate and methanol dosage rates, detention time and upflow velocity, average effluent dissolved oxygen and nitrate concentrations, and average nitrate and soluble selenium percent reduction values for periods of operation similar to those in Tables 4 and 5. Table 7 summarizes the effluent total, soluble and particulate selenium concentrations and percentage reduction of Tse and Sse and for each of the first-stage processes.

Table 6
First-stage Processes
Operation Parameters, Effluent Concentrations and Reduction of Nitrate and Soluble Selenium

Date From To	Phosphate Dosage mg/L as P	Methanol Dosage mg/L as methanol	Retention Time hours	Upflow Velocity gpm/ft2	Effluent D.Oxygen mg/l	Efluent Nitrate mg/L as N	Nitrate Reduced percent	Soluble Se Reduced percent
UASBR-Period 1								
10/17/92 - 03/08/93	0.05	349	29.9	1.821	1	1.3	94.4	66
UASBR-Period 3								
02/02/94 - 06/23/94	0.5	464	9.6	0.212	1	6.9	64.9	60.3
07/13/94 - 08/01/94	0.5	248	5.2	0.227	2.8	3.4	81.1	56.8
08/02/94 - 02/15/95	0.25	355	5.2	0.216	1.7	10	62.9	36.1
03/27/95 - 07/07/95	0.25	364	7.6	0.216	0.9	9.1	67.7	45.1
07/10/95 - 08/29/95	0.25	377	9.1	0.245	0.4	7.7	78.6	48.8
09/02/95 - 11/21/95	1.3	390	10.3	0.433	0.5	5	85.5	52.7
UA2								
06/01/94 - 08/01/94	0.5	319	3.6	0.234	0.6	6.8	77.7	77.9
08/02/94 - 08/14/94	0.25	304	3.6	0.202	0.6	4.1	84.6	66.3
08/15/94 - 03/09/95	0.25	336	2.1	0.442	0.7	10.3	62.9	46.2
04/01/95 - 08/29/95	0.25	340	1.9	0.386	0.4	6.1	81.1	60.2
09/02/95 - 11/02/95	1.3	400	1.9	0.4	0.5	3.9	87.9	52.7
FBR2								
10/21/93 - 12/17/97	0.5	147	0.82	30.7	2.3	21.5	21	12.5
12/31/93 - 08/01/94	0.5	282	3.7	36.5	1.1	3.1	88.4	62.1
08/02/94 - 01/10/95	0.25	260	3.7	51.3	0.8	8.4	68.5	32.5
02/03/95 - 03/09/95	0.25	287	3.7	60.4	0.7	13	60	66
04/01/95 - 09/01/95	0.25	279	4	63.5	0.5	7.4	77	40.2
09/02/95 - 11/21/95	1.3	284	4	42.4	0.5	3	91.2	64.9
PBR								
01/01/94 - 03/17/94	0.5	321	6.5	0.17	0.9	23.5	-0.3	24.3
03/18/94 - 08/01/94	0.25	218	6.5	0.17	1	4.7	81	56.2
08/02/94 - 03/09/95	0.25	260	6.5	0.17	0.8	16.3	40.7	32.8
04/01/95 - 08/29/95	0.25	271	6.5	0.17	0.5	4.5	86.1	65.5
09/16/95 - 11/21/95	1.3	264	6.5	0.17	0.6	2.6	92.3	65.4

*as methanol

Table 7
First-stage Processes
Effluent Selenium Concentrations and Selenium Reductions

Date From To	Effluent Total Se ug/L	Effluent Soluble Se ug/L	Effluent Part Se ug/L	Effluent Selenite ug/L	Total Se Reduced percent	Soluble Se Reduced percent
UASBR-Period 1						
10/26/93 - 03/08/93	379	168	211	23	27.2	66.0
UASBR - Period 3						
10/21/93 - 02/01/94	447	341	108	52	11.0	30.9
02/02/94 - 05/31/94	346	197	129	33	30.8	58.6
06/01/94 - 06/23/94	576	226	365	40	-9.0	58.8
07/13/94 - 08/01/94	739	199	540	36	-36.1	61.4
08/02/94 - 11/02/94	407	319	178	43	8.8	37.8
11/03/94 - 02/15/95	476	336	140	20	19.7	39.2
03/27/95 - 07/07/95	388	256	133	36	18.6	45.0
07/10/95 - 08/29/95	444	250	193	18	10.3	48.8
09/02/95 - 11/21/95	541	282	282	24	5.7	52.7
Weighted Average**	456	281	172	35	13.6	44.5
UA2						
06/01/94 - 06/23/94	354	111	263	9	35.4	79.0
07/13/94 - 08/01/94	665	114	551	31	-23.9	77.1
08/02/94 - 11/02/94	388	164	225	27	28.2	68.0
11/03/94 - 02/15/95	521	359	162	24	3.8	28.9
03/27/95 - 07/07/95	391	164	242	17	18.6	64.6
07/10/95 - 08/29/95	561	226	336	48	-15.1	53.9
09/02/95 - 11/01/95	492	268	223	29	11.7	51.9
Weighted Average**	470	223	248	26	10.2	55.5
FBR2						
10/21/93 - 02/01/94	431	400	45	44	23.0	26.4
02/02/94 - 05/31/94	331	155	191	30	27.2	67.3
06/01/94 - 06/23/94	323	141	182	20	39.2	73.3
07/13/94 - 08/01/94	288	171	116	67	46.9	66.9
08/02/94 - 11/02/94	469	321	147	46	20.9	43.3
11/03/94 - 02/15/95	475	362	113	38	15.7	31.5
03/27/95 - 07/07/95	332	277	55	50	35.5	44.3
07/10/95 - 08/29/95	378	335	44	6	23.2	32.0
09/02/95 - 11/21/95	299	212	87	22	49.5	64.9
Weighted Average**	382	275	109	36	28.7	44.7
PBR						
01/03/94 - 02/01/94	403	319	84	28	15.9	32.4
02/02/94 - 05/31/94	398	340	79	43	13.5	29.1
06/01/94 - 06/23/94	419	134	285	17	22.2	75.5
07/13/94 - 08/01/94	396	287	108	70	26.8	43.9
08/02/94 - 11/02/94	363	212	150	51	37.5	61.1
11/03/94 - 02/15/95	488	430	58	20	9.5	14.4
03/27/95 - 07/07/95	274	171	110	28	38.8	60.4
07/10/95 - 08/29/95	286	126	160	19	42.1	74.5
09/02/95 - 11/21/95	487	205	282	21	17.9	65.4
Weighted Average**	390	259	135	32	27.0	49.7

*All values are average for period
**Weighted average is for entire testing period

Second-stage Processes

FBR1 and SSF2 were the two second-stage processes tested at the Adams facility. Due to the nature of the processes and their position in the treatment train, their treatment objectives were different. With FBR1 being the second stage of a three-stage process, its objective was to further reduce selenium to an elemental or particulate state. Since SSF2 was the final stage of Treatment Train 2, its primary objective was to remove particulate selenium.

Table 8 provides a summary of operation parameters and resulting nitrate and soluble selenium reduction percentages for FBR1. The best SSe reduction of 51.1% was achieved at the end of testing from September through November 1995 when the reactor was operated at the longest retention time of 1.5 hours and occurred when the plant's feedwater phosphate dosage rate was 1.3 mg/L.

Table 8
Second-stage Processes
Operation Parameters and Nitrate
and Soluble Selenium Reduced

Date From	Date To	Phosphate Dosage mg/L as P	Retention Time hours	Upflow Velocity gpm/ft2	Average Effluent DO mg/L	Average Effluent Nitrate mg/L as N	Nitrate Reduced Percent	Soluble Selenium Reduced Percent
Fluidized Bed Reactor 1								
10/21/93	02/01/94	0.5	0.3	17.2	1.4	2.9	77.6	40.4
02/02/94	05/31/94	0.5	0.3	24	0.8	2	65.1	21.8
06/01/94	06/23/94	0.5	0.3	28.8	0.7	2.7	47.8	44.8
07/13/94	08/01/94	0.5	0.3	31.3	0.8	1.1	84.5	46.5
08/02/94	01/19/95	0.25	0.3	48	0.7	9.9	-6.2	5.3
01/20/95	02/13/95	0.25	0.6	72	10	16.2	-5.6	5.6
03/31/95	07/07/95	0.25	0.6	67	0.6	2.8	47.5	28.9
07/22/95	08/18/95	0.25	0.6	67	0.4	1.8	65.7	32.8
09/06/95	11/21/95	1.3	1.5	61.1	0.5	1.2	79.9	51.5
Slow Sand Filter 2								
11/08/93	02/01/94	0.5	1.5	na	1.1	4.9	60	31
02/02/94	05/31/94	0.5	1.5	na	0.7	3.1	*	47.4
06/01/94	06/23/94	0.5	1.5	na	0.6	3.1	*	37.1
07/13/94	08/01/94	0.5	1.5	na	0.6	21	22.5	-46.7
08/02/94	11/02/94	0.25	1.5	na	0.5	4.7	1.8	31.3

The other second-stage process, slow sand filter 2, was operated for a 1-year period from November 1993 to November 1994. The SSF2 was operated at feed flow rate of 0.5 gpm, which equates to a retention time (or empty bed contact time) of 1.5 hours. Table 9 is summary of the results for the second-stage processes and provides effluent selenium concentrations and percentages of selenium reduced. The negative % values in the table show that the constituent increased from the influent to the effluent concentration. As previously stated in the report, particulate selenium is the difference of soluble selenium from total selenium. For this report, it should be noted that in all calculations for Pse reduction and Pse concentration averages, Pse was taken to be 1 when the Pse value was 0 or a negative number.

Table 9
Second-stage Processes
Effluent Selenium Concentrations and
Percentages of Selenium Reductions

Date From To	Total. Selenium ug/L	Soluble Selenium ug/L	Particulate Selenium ug/L	Selenite ug/L	Total Se Reduced percemt	Soluble Se Reduced percent	Part. Se Reduced percent
FBR1							
10/21/93 - 02/01/94	444	207	237	51	3.9	39.7	-113.0
02/02/94 - 05/31/94	338	115	175	28	5.4	21.8	-38.9
06/01/94 - 06/23/94	452	95	340	23	2.0	44.8	-26.6
07/13/94 - 08/01/94	413	109	304	40	1.7	53.6	-112.0
08/02/94 - 11/02/94	469	272	198	89	4.9	18.6	-45.0
11/03/94 - 02/15/94	429	357	71	63	10.9	-9.0	51.9
03/27/95 - 07/07/95	263	182	82	67	30.5	26.3	34.1
07/10/95 - 08/29/95	296	157	139	14	31.1	35.5	23.1
09/02/95 - 11/21/95	339	127	212	30	33.6	51.5	-41.0
Weighted Average**	382	200	178	51	15.0	28.6	-21.7
SSF2							
11/08/93 - 02/01/94	311	230	90	65	30	31.0	13.9
02/02/94 - 05/31/94	187	100	87	40	46.9	47.4	21.7
06/01/94 - 06/23/94	198	109	78	9	48.0	37.1	63.7
07/13/94 - 08/01/94	552	297	52	29	83.8	53.1	9.8
08/02/94 - 11/02/94	309	233	78	85	40.9	31.3	8.0
Weighted Average**	279	182	95	56	37.6	32.3	18.6

*All values average for period
**Weighted average is for entire period

For FBR1, particulate selenium increased in six out of the nine analysis periods of Table 7. The lowest average total selenium concentrations of 263 ug/L and 296 ug/L occurred during two consecutive periods from March through September 1995 when the particulate selenium was reduced 34.1% and 23.1%. As for SSF1, the lowest effluent total selenium concentration averaged 187 ug/L and 198 ug/L for two consecutive periods that encompassed February through May 1994 and occurred when particulate removal was highest at 21.7% and 63.7%.

Third-stage Process

Slow sand filter 1 was the solitary third-stage process tested at the Adams facility. Testing with the SSF1 was identical to the SSF2's testing time frame from November 1993 to November 1994 and at identical operation parameters. A summary of effluent selenium concentrations and selenium reduction results for SSF1's operation is shown by Table 10. The effluent total selenium concentration averaged 195 ug/L from February through May 1994. During this period, additional selenium reduction occurred as evidenced by the 66.6% increase of Pse through the filter.

Table 10
Third-stage Process
Effluent Selenium Concentrations and
Percentages of Selenium Reductions

Date From To	Effluent Total Se ug/L	Effluent Solublel Se ug/L	Effluent Part. Se ug/L	Effluent Selenite ug/L	Total Se Reduced percent	Soluble Se Reduced percent	Part. Se Reduced percent	Selenite Reduced percent
SSF 1								
11/08/93 - 02/01/94	220	108	112	25	50.4	48.5	12.4	12.4
02/02/94 - 05/31/94	195	81	120	24	44.2	34.0	23.4	23.4
06/01/94 - 06/23/94	275	144	100	21	31.8	-62.6	57.8	57.8
07/13/94 - 08/01/94	301	68	233	37	29.7	36.2	32.2	32.2
08/02/94 - 11/02/94	254	199	53	84	45.0	8.7	35.0	35.0
Weighted Average**	236	132	102	46	45.1	15.9	24.1	24.1

*All values average for period
**Weighted average is for entire period

Process Trains 1 and 2

There were two process trains tested at the Adams facility. Process Train 1 consisted of the UASBR>FBR1>SSF1 and Train 2 was the UASBR>SSF2. Both trains were operated for approximately one year and ended on November 2, 1994 when testing the filtration process ceased. A summary of effluent selenium concentrations and selenium reduction results for both trains is shown by Table 11.

Table 11
Process Trains 1 and 2
Effluent Selenium Concentrations and
Percentages of Selenium Reductions

Date From To	Effluent Total Se ug/L	Effluent Soluble Se ug/L	Effluent Part. Se ug/L	Effluent Selenite ug/L	Total Se Reduced percent	Soluble Se Reduced percent
Process Train 1: UASBR>FBR1>SSF1						
11/08/93 - 02/01/94	220	108	112	25	57.5	78.8
02/02/94 - 05/31/94	196	81	120	24	61.4	83.4
06/01/94 - 06/23/94	281	143	98	23	46.6	64.1
07/13/94 - 08/01/94	301	68	233	37	44.5	86.8
08/02/94 - 11/02/94	254	199	53	84	53.2	60.8
Weighted Average**	235	133	102	46	56.6	73.3
Process Train 2: UASBR>SSF2						
11/08/93 - 02/01/94	311	230	90	65	44.2	58.5
02/02/94 - 05/31/94	187	100	87	40	66.1	80.9
06/01/94 - 06/23/94	189	106	70	9	63.4	76.7
07/13/94 - 08/01/94	552	297	255	47	-3.1	41.3
08/02/94 - 11/02/94	309	233	78	85	43.1	53.9
Weighted Average**	279	182	95	56	49.2	64.5

*All values average for period.
**Weighted average is for entire period.

For the overall operation, Train 1 had marginally better results than Train 2. Overall, Tse and Sse reductions for Train 1 were 56.6% and 73.3%, respectively, while the Tse and Sse reductions for Train 2 were 49.2% and 64.4%, respectively.

SUMMARY

The work summarized in this report has focused on the reduction of selenium from the selenate state to selenite or elemental state through a number of biological processes and process trains.

The four first-stage processes achieved soluble selenium reduction between 47 percent and 55 percent and the two second-stage processes reduced SSE between 41 percent and 87 percent. The lowest soluble selenium concentration achieved was 68 ug/L and that was for Train 1, UASBR>FBR1>SSF1. Even though none of the processes or trains reduced selenium to the target Water Quality Objective of 5 ug/L concentration as established by the State of California's Central Valley Regional Board for the San Joaquin Basin, the report has identified where additional work is needed to further develop the processes and trains in which they may be applicable for a specific role in the reduction and removal of selenium from agricultural drainage water.

The major overall operation problems encountered included precipitation of salt in piping and process units, attached biological growth in the piping and process units, and consistent and uniform operation of the chemical injection systems. The precipitation and growth are chemical and biological issues and are complex and more difficult to address than the mechanical issues of chemical injection systems.

Most of the time and effort at the Adams facility was spent on the development of the UASBR process. Reactor design and configuration play significant roles in the treatment efficiency of the process and is shown by comparing the results of the main and pilot-scale UASBRs.

Throughout the entire testing period, the pilot UASBR had reduced soluble selenium marginally better, but with considerably less retention time than that of the main unit. Both units had similar problems with sludge agglomeration and maintaining an evenly distributed flow through the reactor. Operation parameters were more easily controlled on the pilot unit due to its size and configuration, and results of some changes could be visually observed. For the main UASBR, recycle was used as a means to continuously mix and suspend the sludge bed, to prevent sludge agglomeration, and to distribute an even flow through the reactor. As a result, the main UASBR's operation was that of a completely mixed system, whereas the pilot UASBR's operation was that of a plug flow system. Upflow velocity for the main UASBR was 1.82 gpm/ft2 during Period 1 operations. During Period 3 operations, the upflow velocity range between 0.212 gpm/ft^2 and 0.433 gpm/ft^2 of which recycle was a major component except for a 7-month period from July 14, 1994 through February 13, 1995 when the main UASBR was operated without recycle. The recycle to influent flow ratio averaged 45:1 for Period 1 and ranged from 1:1 to beyond 90:1 when the main reactor was operated with recycle during period 3. From June 1, 1994 (commencement date for pilot UASBR's lab analyses), the pilot UASBR was operated without recycle and upflow velocity ranged between 0.202 gpm/ft2 and 0.442 gpm/ft2. Through trial and error, the method developed to agitate and mix the sludge bed and prevent sludge agglomeration in the pilot unit was to pulse flow through the pilot unit daily for 20 minutes using the recycle system. Twice during the test period, recycle was initiated as a means to continuously mix and agitate the sludge bed and to prevent sludge agglomeration in the pilot UASBR, but was terminated because an observed reduction in the size of the sludge

granules. Also, biomass production was observed in the pilot UASBR operations. Sludge had to be removed from the pilot unit on four occasions to improve operation.

The fluidized bed reactor process was used for both first- and second-stage treatment. Both reactors experienced problems with distribution of flow through the unit that were attributed to manifold design and attached biological growth. As a result, numerous modifications were made to both of their influent manifolds. Carryover of biomass from the main UASBR contributed to the distribution problem in FBR1. Both systems experienced biological growth on the interior of the piping and reactors and needed to be periodically cleaned. FBR2, being a first-stage process, experienced chemical precipitation in the system.

Slow sand filtration was used for both second- and third-stage treatment. The purpose for slow sand filtration was as a simple, low-cost, final polishing step to remove particulate selenium. Not only did the filters remove particulate selenium, but they also provided additional reduction of selenate and selenite and removed a portion of the biomass carryover from the upstream process. The filters required frequent backwashing. The filters also have flow distribution problems due to the biomass carryover and from salt precipitation and biological growth on both systems' interior walls. As a result, filter operations were labor intensive.

The packed bed reactor was the simplest to operate and required the least attention of all the processes tested. The PBR had problems identical to the other first-stage processes with biomass growth and precipitation in the system. The system, like the other processes, required periodic cleaning.

For the processes and treatment trains tested, selenium reduction was precedent upon the absence of nitrogen. The cost of the carbon to denitrify the drainage water is a key parameter in the economics of the processes. Methanol represented 21 percent and 31 percent of operation costs for 1- and 10-mgd plants, respectively, as reported by Owens in the 1995 operation report (ECSRI). Using IC laboratory nitrate analyses results, field dissolved oxygen measurements, and assuming the nitrite concentration to be zero, the cost for methanol (at $1.35 per gallon) required to deoxygenate and denitrify the drainage water is $95 per acre-foot. Except for the FBR2 during a 2-month period at the beginning operations, all first-stage processes were fed excess methanol. The cost for methanol ranged between $135 to $260 per acre-foot for the band of dosages tested at the Adams facility.

Molasses was tested as an alternative, low-cost carbon source using a small-scale UASBR (2.3 gallons) at the Adams facility. As reported by Owens (ECSRI 1998), molasses was less efficient than methanol in reducing nitrate and selenate due to a shift of bacteria from respiratory organisms to fermentative ones in the molasses-fed reactor as result of the high sugar content of the molasses. In anaerobic fermentation, the carbon source serves as both the electron acceptor and the electron donor, where as in anaerobic respiration, the carbon source serves only as an electron donor. For nitrate and selenate reduction to occur, anaerobic respiration must take place in which the carbon source only serves as the electron donor and the nitrate and selenate serve as the electron acceptor. This investigation showed reduction decreased as testing progressed. Coagulation and adsorption of selenium using ferric chloride also was investigated to determine the removal of particulate selenium and to investigate the adsorption of soluble selenium. This standard jar test investigation was performed on the effluents of the main UASBR, FBR1, and

the UA2. The jar tests consisted of adding ferric chloride in varying amounts to 500 ml of effluent in a 1-liter beaker. The solution was rapid mixed, flocculated and then allowed to settle for a specific period of time. A portion of the supernatant was withdrawn from the beaker and analyzed for selenium. For the test using the UASBR effluent, $FeCl_3$ dosing ranged between 0 and 500 mg/L as Fe. Highest removal for total selenium, particulate selenium, and selenate were 32 %, 80 %, and 40 % at dosages of 50, 500, and 5mg/L as Fe, respectively. No significant reduction of soluble selenium was achieved. For the tests using UA2 effluent, highest removals occurred at the $FeCl_3$ dosage of 100 mg/L as Fe and were 37 % for total selenium, 34 % for soluble selenium, 44 % for particulate selenium, and lastly, 90 % for selenite. For the tests using FBR1 effluent, the highest removal for total selenium, particulate selenium, soluble selenium, and selenite were 71 %, 59 %, 95 %, and 91 % at $FeCl_3$ dosages of 250, 250, 500, and 50 mg/L as Fe, respectively. A second set of tests using the FBR1's effluent were performed. For these tests, only two dosages were used, 50 and 100 mg/L as Fe, at three flocculation durations which were 20, 30, and 40 minutes. The results showed relatively little difference in selenium removal for the parameters selected.

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APPENDIX

DATES FOR SIGNIFICANT EVENTS

Date	Day in Test	Significant Event
09/14/92	0	Granular sludge arrived at AAADRC
10/14/92	30	Start of sampling for UASBR's lab analyses
12/07/92	84	To date, UASBR's SSe reduction above 80%
03/19/93	176	Apparent failure of UASBR's Hypalon cone
04/29/93	227	UASBR shutdown due to cone failure
07/19/93	308	UASBR restart with bakery sludge after cone repair and other
08/19/93	339	UASBR shut down due to cone failure.
09/01/93	352	UASBR restart with digester sludge
10/18/93	399	Start of sampling for both FBRs' lab analyses
11/08/93	420	Start of sampling for both SSFs' lab analyses
01/03/94	476	Start of sampling for PBR's lab analyses
02/02/94	506	Restart of UASBR after power outage on Jan. 31.
06/01/94	625	Start of sampling for UA2's lab analyses
06/23/94	647	UASBR shut down to replace Hypalon cone with baffle.
07/13/94	667	UASBR's target methanol dosage at 230 mg/L as methanol
08/01/94	686	Plant's phosphate dosage change to 0.25 mg/L from 0.5 as P and UASBR's methanol dosage increased for target between 300 and 400 mg/L as meth.
11/02/94	779	End of testing for both SSFs
01/20/95	858	FBR1's influent rate lowered from 1 gpm to 0.5 gpm.
03/10/95	907	AAADRC operations shut down due to flooding
03/27/95	924	Restart of operations after flooding
07/07/95	1026	UASBR shut down to replace baffle with polyethylene cone
07/10/95	1029	Restart of UASBR
08/29/95	1079	Plant's phosphate dosage change to 1.3 mg/L as P
11/02/95	1144	Start of UA2 testing with drainage from Firebaugh Canal Water District
11/21/95	1163	End of all testing operations

DEFINITION OF ABBREVIATIONS

Abbreviation	Definition
AAADRC	Adams Avenue Agricultural Drainage Research Center
FBR	Fluidized bed reactor
HDPE	High-density polyethylene
IC	Ion chromatography
PBR	Packed bed reactor
QC	Quality control
SSF	Slow sand filter
UA2	Pilot-scale upflow anaerobic sludge blanket reactor
UASBR	Upflow anaerobic sludge blanket reactor

Chemical Constituents:

$CaCO_3$	Calcium carbonate
CH_4O	Methanol
DO	Dissolved oxygen
EC	Electrical conductivity
PSe or Pse	Particulate selenium
SSe or Sse	Soluble selenium
Se^{+6}	Selenate
Se^{+4}	Selenite
TDS	Total dissolved solids
TSe or Tse	Total selenium
TOC	Total organic carbon
TSS	Total suspended solids
VSS	Volatile suspended solids