EVALUATION OF MIXED-OXIDANTS AGAINST SODIUM HYPOCHLORITE FOR THE DISINFECTION AND REMOVAL OF BIOFILMS FROM DISTRIBUTION SYSTEMS

by

Cynthia Lynn Crayton

A paper submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Civil Engineering

MONTANA STATE UNIVERSITY-BOZEMAN
Bozeman, Montana

December, 1997

P378
C8598

APPROVAL

of a paper submitted by

Cynthia Lynn Crayton

This paper has been read by each member of the paper committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

Dr. Anne Camper _____ (Signature) 12/4/97 Date

Approved for the Department of Civil Engineering

Dr. Donald A. Rabern _____ (Signature) 12/4/97 Date

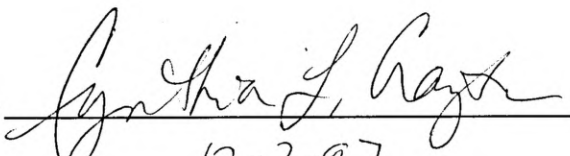
Approved for the College of Graduate Studies

Dr. Joseph J. Fedock _____ (Signature) 12/11/97 Date

STATEMENT OF PERMISSION TO USE

In presenting this paper in partial fulfillment of the requirements for a master's degree at Montana State University-Bozeman, I agree that the Library shall make it available to borrowers under rules of the Library.

If I have indicated my intention to copyright this paper by including a copyright notice page, copying is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for permission for extended quotation or reproduction of this paper in whole or in parts may be granted only by the copyright holder.

Signature 

Date 12-2-97

ACKNOWLEDGMENTS

This research was funded by a Drinking Water Assistance Program (DWAP) grant from the Montana State University System Water Resources Center and by Los Alamos Technical Associates (LATA), Albuquerque, New Mexico, and was conducted at the Center for Biofilm Engineering (CBE) at Montana State University, Bozeman, Montana, and at the KOA Campground, Great Falls, Montana.

The author wishes to thank Dr. Anne Camper, Bryan Warwood, Peg Dirckx, Calvin Abernathy, Mark Burr, Phil Butterfield, Lu Goodrum, Dr. Warren Jones, Wes Harms, and John Neuman (all at CBE); Gary Nolen, Mike Robson, and Bruce Dobbs (all at LATA); and Loren Smith and Les McCartney (both at KOA) for their invaluable assistance.

TABLE OF CONTENTS

LIST OF TABLES vii

LIST OF FIGURES viii

ABSTRACT x

INTRODUCTION 1
Problem Statement and
Significance of Research to the Drinking Water Industry 1
Overview of the Mixed-Oxidants Technology 3
Background and Chemistry 3
Advantages and Benefits 6
Considerations and Concerns 7

SCOPE OF PROJECT 9
Overview 9
Phase I 9
Phase II 12
Phase III 14
Phase IV 17
Phase V 19

EXPERIMENTAL MATERIALS AND METHODS 20
Generation of Disinfectants 20
Mixed-Oxidants Solution 20
Sodium Hypochlorite Solution 20
Sampling Procedures 20
Effluent Samples 21
Pipe Section Samples 22
Annular Reactor Coupon Samples 23
Chemical Analysis 23

RESULTS AND DISCUSSION 24
Laboratory Experiments on Biofilms (Phases I and II) 24
Coliform Monitoring (Phases II and III) 30
Corrosion Studies (Phase IV) 33
Field Studies (Phases II and III) 40
Demonstration Project 40

Initial Effects on Existing Biofilms 43
Exit Interview (Phases II and III) 44
Coliform Compliance 44
Advantages of Mixed-Oxidants Over Chlorine Disinfection 44
Effects on Distribution System 45
Effects on Contact Water Distribution System 46
Informal Cost Analysis (Phase V) 46
Results of Related Research 48

CONCLUSIONS 51
Effectiveness of Mixed-Oxidants at Destruction and Removal of Biofilms 51
Laboratory Evidence 51
Anecdotal Evidence 51
Performance of Mixed-Oxidants as a Full Scale Water Treatment Process 52
Relevance to Industry 52

APPENDICES 54

APPENDIX A-Pipe Reactor Results 55

APPENDIX B-Annular Reactor Results 65

APPENDIX C-Demonstration Site Results 71

APPENDIX D-Initial 24-Hour Sampling Results 81

APPENDIX E-Exit Interview 84

APPENDIX F-Comparative Cost Analyses 91

REFERENCES 100

LIST OF TABLES

Table 1. Mixed-oxidants demonstration study site description summary 16

Table 2. Qualitative comparative performance summary of all pipe reactor experiments 25

Table 3. Surface cell concentrations for all pipe reactor experiments 26

Table 4a. Biofilm/bulk fluid ratios: pipe reactors 28

Table 4b. Biofilm/bulk fluid ratios: pipe reactors (continued) 29

Table 5. Qualitative summary of coliform monitoring results 31

Table 6. Biofilm/bulk fluid ratios: annular reactors 36

Table C1. Results of weekly sample analyses 72

LIST OF FIGURES

Figure 1. MIOX schematic 5

Figure 2. Study design 10

Figure 3. Pipe reactor schematic 11

Figure 4. Demonstration study site map 15

Figure 5. Schematic of the laboratory annular reactor 18

Figure 6. Average surface cell concentrations: annular reactor coupons 34

Figure 7. Average bulk fluid cell concentrations: annular reactors 35

Figure 8. Average ferrous iron levels: annular reactors 37

Figure A1. Effects of 1 ppm short-term biocide on lab-grown biofilms 56

Figure A2. Effects of 1 ppm short-term biocide on active field-grown biofilms (plate counts) 57

Figure A3. Effects of 1 ppm short-term biocide on active field-grown biofilms (total cell counts) 58

Figure A4. Effects of 4 ppm short-term biocide on active field-grown biofilms (plate counts) 59

Figure A5. Effects of 4 ppm short-term biocide on active field-grown biofilms (total cell counts) 60

Figure A6. Effects of 4 ppm long-term biocide on lab-grown biofilms (plate counts) 61

Figure A7. Effects of 4 ppm long-term biocide on lab-grown biofilms (total cell counts) 62

Figure A8. Effects of 1 ppm long-term biocide on initially dormant field-grown biofilms (plate counts) 63

Figure A9. Effects of 1 ppm long-term biocide on initially dormant field-grown biofilms (total cell counts) 64

Figure B1. Reactor map showing coupon location versus sample date 66

Figure B2. Row by row results of coupon surface cell concentrations 67

Figure B3. Surface cell concentrations for all coupons sampled 68

Figure B4. Cell concentrations for bulk fluid of each reactor 69

Figure B5. Ferrous iron levels for each reactor 70

Figure C1. Weekly sample results: main building, KOA site 76

Figure C2. Weekly sample results: cottage dead-end, KOA site 77

Figure C3. Weekly sample results: irrigation line, KOA site 78

Figure C4. Comparison of sample sites for initial five months 79

Figure C5. Comparison of all sample sites for weeks 25-29 80

Figure D1. Initial effects on active biofilms (first 24 hour sampling) 82

Figure D2. Initial effects on dormant biofilms (irrigation line) and active biofilms (main building): second 24 hour sampling 83

ABSTRACT

Problem Statement:

As drinking water regulations are applied to smaller utilities, an area of emerging concern for the water industry is the installation of disinfection systems to meet the newly imposed standards. Since traditional disinfection technologies are usually beyond the safety, economic, and/or site restraint considerations for small systems, an alternative is required. The mixed-oxidants disinfection system (MIOX) appears to provide a reasonable alternative for small distribution systems as a safe, reliable, and cost effective technology that is easy to operate and is readily compatible with other treatment systems.

The goal of this five-phase study was to evaluate the potential of the MIOX disinfectant (produced on-site using feedstocks of ordinary salt, water, and twelve volt electricity) against free chlorine for biocidal efficacy, biofilm/biofouling removal, biofilm regrowth potential, relative corrosion potential, and cost effectiveness. Although mixed-oxidants have been proven effective in potable water disinfection, biofilm removal is a new application for this alternative disinfection technology.

Procedures and Results:

Phases one and two tested mixed-oxidants against free chlorine on laboratory-grown biofilms in new PVC pipe and field-grown biofilms in pipes removed from a small distribution system in rural Montana that was in repeated violation of the total coliform rule due to regrowth events in the distribution system. Results indicate that the mixed-oxidants solution was at least as effective at the removal, destruction, and regrowth prevention of biofilms as chlorine at comparable residual levels.

Phase three was a full-scale demonstration of the effectiveness of the MIOX system installed at the same small rural water distribution system in phase two. The system effectively improved water quality as demonstrated by increased water pressure, cleaner filters, less observed build-up in pipes, and no infractions of total coliform regulations.

Phase four involved experiments to determine the relative potential for corrosion of ferrous metal pipes by MIOX vs. free chlorine. Results from annular reactors indicate that MIOX corrosion levels (as measured by amounts of dissolved ferrous iron) are no greater than those of free chlorine, and are less than those of untreated water.

Phase five was an informal cost analysis of the actual operating expenses of the mixed-oxidants process which indicated that the higher capital costs could be easily recovered through the lower operational costs.

Conclusions:

The mixed-oxidants technology appears to be an economically viable disinfection technology for small water distribution systems since it is safe to operate; requires a minimum of operator training, maintenance, and process monitoring; provides biofouling removal and improved drinking water quality; exceeds EPA drinking water standards for disinfection by-products; and provides chlorine residual without imparting a chlorinous taste or odor to the treated water.

INTRODUCTION

Problem Statement and Significance of Research to the Drinking Water Industry

The occurrence of coliform bacteria in small water distribution systems when none have been detected in the source groundwater has been attributed to "regrowth" by the coliforms in biofilm on the surfaces of the distribution pipes (8, 20, 32). Since colifom bacteria are facultative (able to change their uptake mechanisms to survive under low-level oxygen conditions), the biofilm structure may provide a sheltered structure for colonization (1, 8, 21, 32). These slowly growing, environmentally derived coliforms may be more likely than those originating from a high nutrient fecal source to become re-established on distribution system pipes (8, 9). The advantages of the biofilm structure to bacteria include resistance to being washed away; protection against environmental stress, toxins, and disinfection; concentration and exchange of nutrients; and maintenance of stable conditions (1, 21, 32). It has been documented in full-scale distribution systems, as well as in laboratory experiments, that coliform bacteria can successfully compete with heterotrophic bacteria to become established on pipe surfaces, be shed into the bulk fluid, and be detected by standard monitoring techniques (8, 9, 27).

It has been shown that distribution systems with ferrous metal pipes and/or well casings are at a higher risk for regrowth events (1, 2, 8, 27, 32). Research indicates that ferrous metal surfaces may enhance the numbers of coliform bacteria found on those

surfaces (2, 8, 32). Rapid regrowth after biocide treatment may originate from areas of high corrosion (27, 32). If fed from iron-cased wells, even distribution systems with non-reactive plastic surfaces may experience coliform regrowth events due to transport and redeposition of corrosion products (8, 9, 32).

Active participation by microorganisms in adherent biofilms in distribution systems are able to initiate, facilitate, accelerate, or inhibit corrosion of metal surfaces (16, 32). Disinfection and removal of biofilms could decrease biofouling/biocorrosion, prevent regrowth events, and improve water quality and aesthetics (2, 27, 32).

As drinking water regulations are more widely applied to smaller utilities, an area of emerging concern for the water industry is the installation of treatment processes to meet the newly imposed standards. A small system in frequent violation of total coliform regulations is often required to install a disinfection system. Traditional disinfection technologies used by larger water distribution systems (gaseous chlorine, calcium hypochlorite, liquid sodium hypochlorite) are usually unrealistic for small systems due to the costs of operator training, process monitoring, and installation of new equipment; the safety considerations of handling, mixing, and/or storing highly reactive compounds that decay with time; and the constraint of site limitations. A feasible alternative is required.

There is need for a reliable, safe, and economical treatment method that provides a reasonable disinfection alternative for small and/or rural sites. In response to this need, field and laboratory studies were conducted to evaluate the potential effectiveness of mixed-oxidants as an alternative treatment process against free chlorine in the areas of biofilm/biofouling removal, water disinfection efficacy, regrowth prevention, corrosion

potential, and cost effectiveness.

Overview of the Mixed-Oxidants Technology

Background and Chemistry

The generation of the mixed-oxidants disinfectant solution was performed by a technology patented by Los Alamos Technical Associates, Inc. (LATA). The membraneless mixed-oxidant (MIOX) cell generates the oxidant solution electrolytically from a sodium chloride (NaCl) brine. Electrolysis of chloride solutions has been used since the late 1800's to generate chlorine (Cl_2) and hypochlorite ion (OCl^-) solutions (34). The MIOX system differs in that the solutions generated at the anode (oxidants at pH ~ 2.1 to 3.0) and the cathode (reductants at a pH ~ 11.5 to 12.0) are separated in a flow stream before substantial recombination of the oxidants and reductants can occur. A mixture of oxidants, rather than just hypochlorite, is produced.

The chemistry of the oxidants produced at the anode is very complex with several oxidation states of chlorine possible. The major chemical reactions are:

$$2\ Cl^- \longrightarrow Cl_2 + 2\ e^-$$

(followed by rapid hydrolysis)

$$Cl_2 + H_2O \longrightarrow HOCl + Cl^- + H^+$$

$$HOCl + H_2O \longrightarrow ClO_2 + 3\ H^+ + 3\ e^-$$

$$2\ H_2O \longrightarrow O_2 + 4\ H^+ + 4\ e^-$$

$$O_2 + H_2O \longrightarrow O_3 + 2\ H^+ + 2\ e^-$$

The major electrolytically-generated product is chlorine (Cl_2/HOCl/OCl^-). Only very small amounts of chlorate (ClO_3^-) are formed. Perchlorate (ClO_4^-) and chlorite (ClO_2^-) are not formed.

Based on electrochemical theory, other oxidant species produced at the anode include hydrochloric acid (HCl), hydrogen peroxide (H_2O_2), OH^0 , and OH^+.

The major cathodic reaction is the electrolysis of water and the generation of hydrogen gas (H_2):

$$2\ H_2O + 2\ e^- \text{---> } H_2\ (gas) + 2\ OH^-$$

Rates of generation are directly proportional to the electric current. The small amount of hydrogen gas generated is vented safely from the system presenting no safety concern (11, 13, 25). (See Figure 1 for process schematics.)

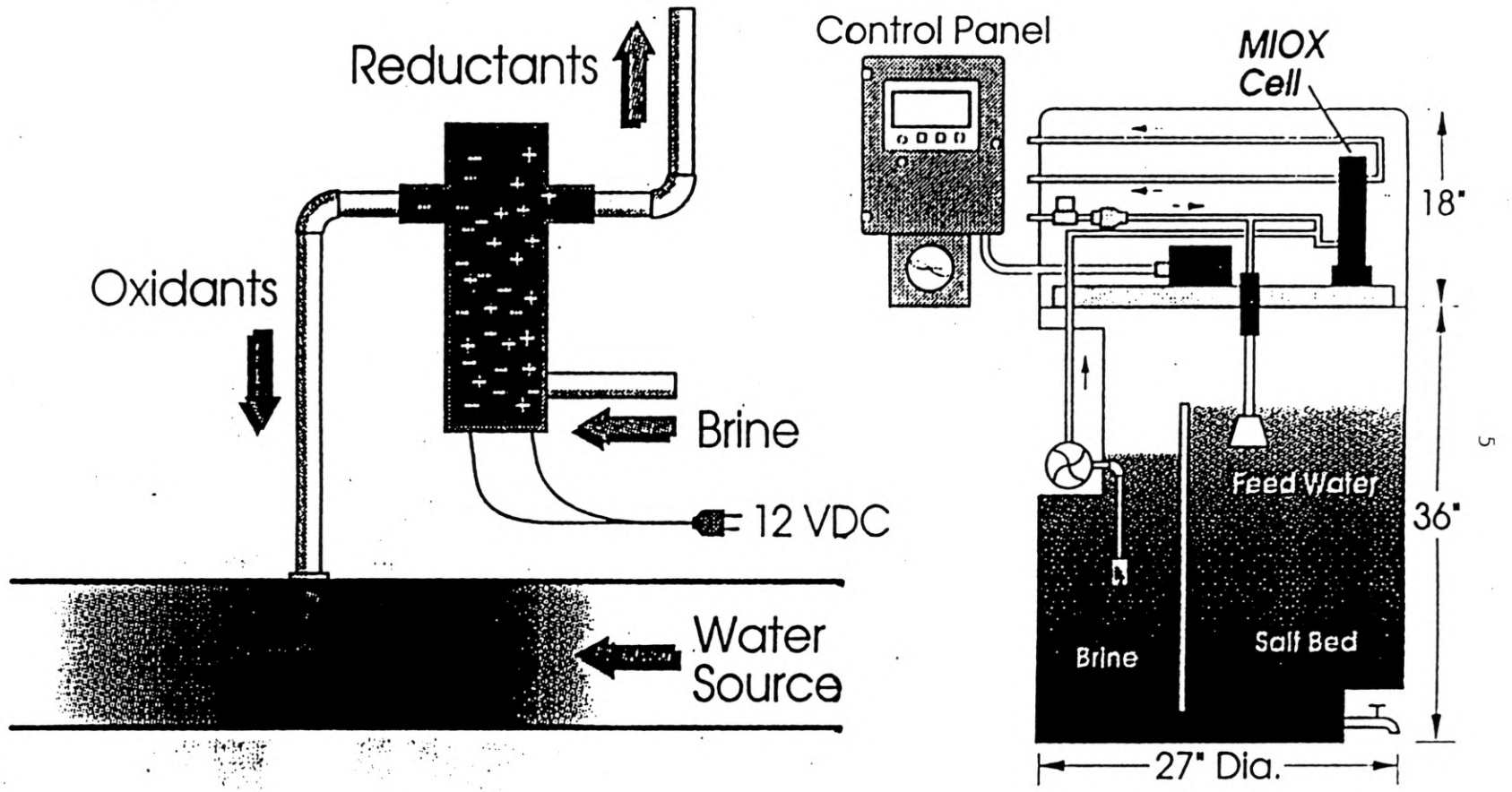


Figure 1. MIOX schematic (courtesy of Los Alamos Technical Associates, Albuquerque, NM).

Advantages and Benefits

The patented MIOX system is rugged, simple, and safe. The liquid stream of oxidants can be generated any brine solution (common water softener salt or seawater), is non-toxic/non-explosive, and can be injected immediately into raw water or stored in a tightly-sealed plastic container for up to fifteen days with minimal loss of disinfection potential (11, 23, 25).

MIOX systems have been in use for potable water, contact water (swimming pool, spas), and industrial/municipal wastewater applications for over three years. These systems have consistently met federal (Safe Drinking Water Act) and state disinfection residual and microbiological standards for treated water (11). A United States Environmental Protection Agency (EPA) evaluation of MIOX disinfection potential states that mixed-oxidants treated water meets EPA drinking water standards for disinfection by-products and chlorine residual (7). The mixed-oxidants process was designated by the EPA as a compliance technology for water disinfection (14, 29).

Because the mixed-oxidants generating equipment can be easily modified to operate on a wide variety of power sources (solar power, wind power, car batteries, generators), the disinfectant can be produced in isolated/remote locations or under disaster/emergency conditions (23, 30, 31). Pilot field study disinfection by the Pan American Health Organization (PAHO) in Latin America and the Caribbean was successful in improving water quality and decreasing the frequency of cholera outbreaks, as well as being widely accepted by local users (23, 30, 31).

Considerations and Concerns

With any disinfection process, there are potential disadvantages that must be taken into account in order to provide for optimal performance. Possible problem areas associated with the mixed-oxidants process are addressed below.

Since the mixed-oxidants solution is generated electrochemically from a brine solution, the impact of the waste stream (cathodic stream) on the salinity of treated and untreated wastewater may be significant. A 1993 study utilizing mixed-oxidants generated by a six volt cell (300 ppm as free chlorine) found that the cathodic waste stream increased the electrical conductivity of wastewater, and by inference the total dissolved solids (TDS) concentration, by as much as fifty percent. By switching to a solution generated by a twelve volt cell and a more dilute brine solution, the TDS concentration was reduced to fifty parts per million (ppm) or about one-sixth that of the six-volt solution (28). The use of larger capacity, more efficient generators (producing 2000 ppm as free chlorine) decreases the required disinfectant dosage as well as the TDS and salinity loading substantially. (26). The cathodic waste stream can be discarded, recycled, or used for other purposes such as specific industrial cleaning (33).

The location of the mixed-oxidant unit and the size of the distribution system pressure tank are crucial to providing adequate disinfection contact time before finished water is consumed (4, 5, 10, 23, 28, 30, 31, 33).

Experimentation with the concentration of the brine solution may be required to obtain maximum strength of the disinfectant solution generated and to keep scaling of the

reductant orifice to a minimum. This scaling may be a function of the water hardness as well as the concentration of the brine solution. Adjusting the application rate of water softener (if used) may help to alleviate scaling (26). Changing the orifice to a larger size will also minimize scaling (10, 26, exit interview).

The brine and/or injection pumps may require resizing to ensure proper operation (10, exit interview).

Modifications to the operating software could be required to prevent fault conditions from occurring during low current readings across the cell or during low pressure conditions from the brine feed and/or distribution system (10, exit interview). The generation unit's location is important to allow for the monitoring of these situations to avoid automatic restart failures of the system (10, exit interview). On the large capacity generators, the unit does restart automatically after power failures and transient low pressure events. This system also has alarm capabilities that allow it to notify the operator (by horn, light, or auto-dialer) of fault mode (26).

Water conditions such as temperature, alkalinity, iron levels, and manganese concentrations are all factors that potentially affect the generation of mixed-oxidants and the overall performance of the disinfection treatment process (12, exit interview).

SCOPE OF PROJECT

Overview

The goal of this five phase study is to evaluate the potential of the MIOX disinfectant (produced on-site using feedstocks of ordinary salt, water, and twelve volt electricity) against free chlorination (from sodium hypochlorite) for biocidal efficacy, removal of biofilm/biofouling, prevention of biofilm regrowth, relative potential of corrosion, and overall costs. Although mixed-oxidants have been proven effective in potable and contact water disinfection, biofilm removal is a new application for this alternative disinfection technology. The study design structure is outlined below and is detailed graphically in Figure 2.

The following timeframe (summarized by phase) was utilized for the project:

- Phase I: August-September, 1996
- Phase II: October-December, 1996 and April-August, 1997
- Phase III: October, 1996--August, 1997
- Phase IV: June-August, 1997
- Phase V: October, 1996--August, 1997

Phase I

The initial phase compared the effects of longer term versus shorter term application of two different concentrations of mixed-oxidants solution against the same

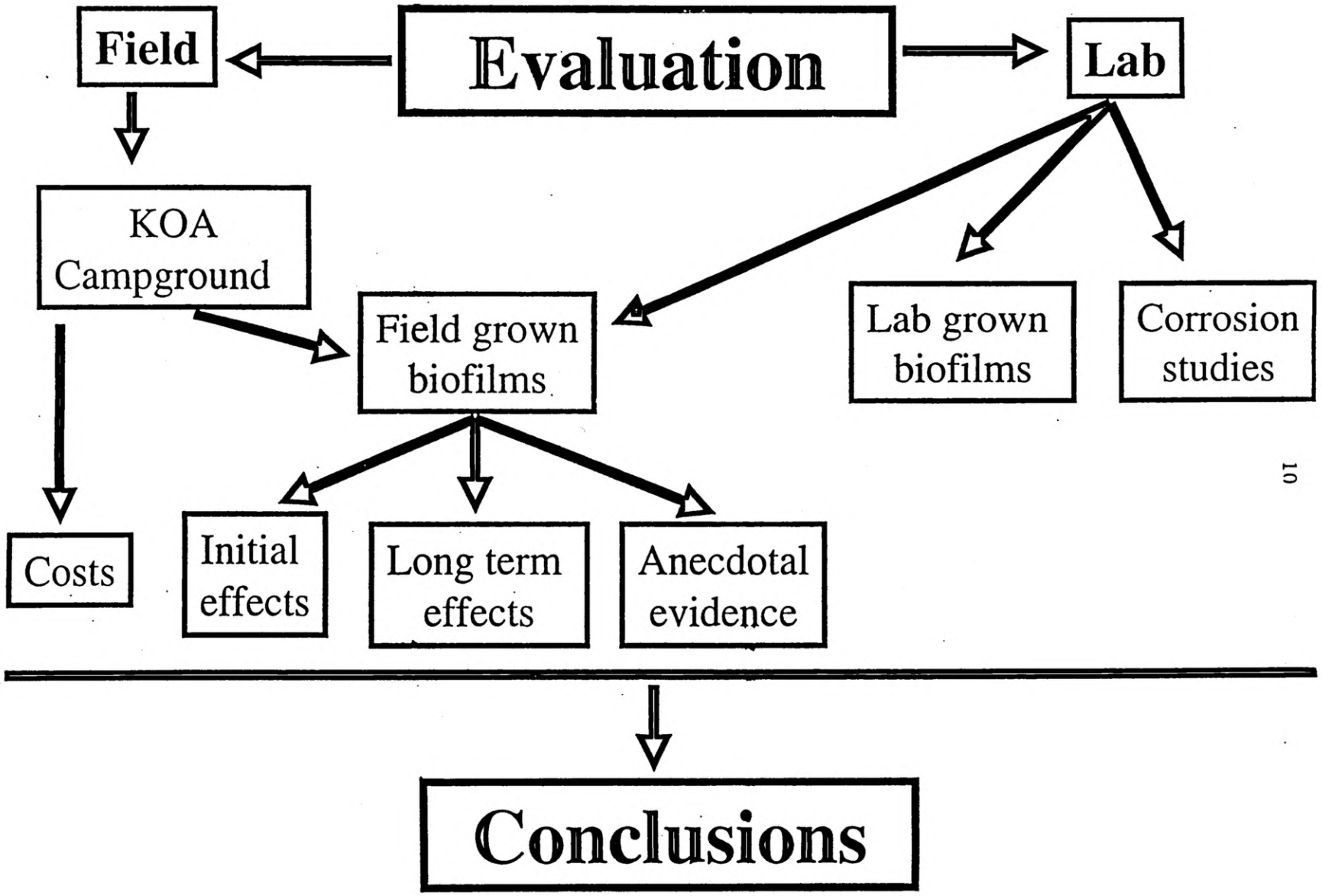


Figure 2. Study design.

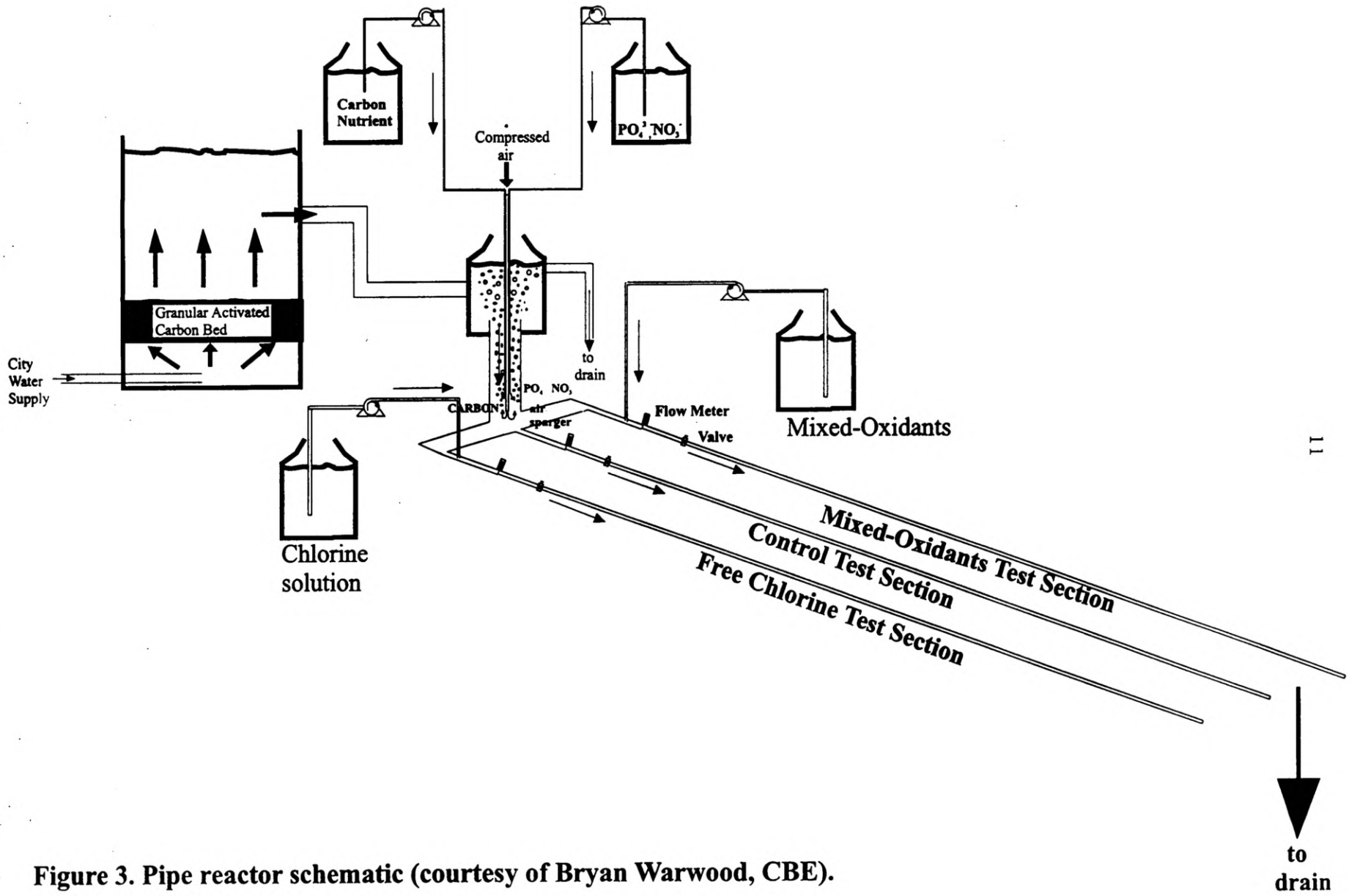


Figure 3. Pipe reactor schematic (courtesy of Bryan Warwood, CBE).

two concentrations of free chlorine on laboratory-grown bioflims in new PVC pipes. The pipe sections were installed in a small, three-component, once-through pipe reactor (Figure 3). The pipe lengths simulated actual distribution system mechanics by providing a short residence time to minimize disinfectant depletion.

In order to provide a chlorine residual-free source water (less than 0.01 mg/liter as free chlorine) and constant head pressure through the pipes, Bozeman city water was passed through a fifty gallon ripened granular activated carbon (GAC) filter and reservoir.

The pipes were colonized by laboratory-grown biofilm using indigenous bacterial populations (from the ripened GAC filter) and low concentrations of organic carbon, phosphate salts, and nitrate salts (approximately 100 µg/liter, 10 µg/liter, and 1 µg/liter respectively). The biofilms were allowed a sufficient stabilization period before experimental procedures were initiated.

Phase II

Phase two entailed experiments on pipes removed from a small distribution system in rural Montana that was in repeated violation of the total coliform rule due to regrowth events in the distribution system. The Great Falls KOA campground provided an ideal test site for the mixed-oxidants technology. The campground's water source is a deep, confined aquifer serving an average of 300 people per day in the summer. The peak summer water usage is 100,000 gallons per day providing water for drinking, showers, toilets, a water park, hot tubs, and irrigation. The average winter usage drops to an average of 10 people (the campground manager, his family, three employees, and three

campers) and 200 to 1000 gallons per day. The campground's distribution system is composed entirely of polyvinylchloride (PVC) pipe served by the iron-cased well. Experiments were conducted in the fall and spring to provide minimal impact upon the campground's operation.

A total of seven distribution pipe samples were removed to provide baseline information on existing biofilms: three in the fall (baseline data on active biofilms) and four in the spring (baseline data on dormant biofilms and resampling of active biofilms). The pipe sections were sampled immediately upon removal for numbers of active heterotrophic bacteria, numbers of total cells present, and presence/absence of coliform bacteria. In order to gain as much information as possible about the real-time effects of disinfection by the mixed-oxidants technology, the sample sections were chosen from sites with varying flow rates: full year operation with heavy use, full year operation with low and high seasonal use, and partial year operation with heavy use. As in phase one, the sampled pipe sections were placed into the pipe-loop test apparatus, provided with nutrients and chlorine-free water, and allowed a sufficient stabilization period before experimental procedures began. The effects of longer term versus shorter term application of two different concentrations of mixed-oxidants solution against the same two concentrations of free chlorine on these field-grown biofilms were compared. This information allowed for comparison against the data obtained for laboratory-grown biofilms in phase one, as well as providing a baseline for analyzing the water samples from phase three.

Sampling sites and other pertinent features of the campground are indicated on the

site map (Figure 4). Information on each site is given in Table 1.

Phase III

Phase three was a ten month long demonstration study of the effectiveness of the mixed-oxidants disinfection system installed at the same small rural water distribution system detailed in phase two. In addition to delivery of potable water to campers, employees, and permanent residents, the campground also operates a water theme park consisting a swmming pool, hot tubs, slides, and fountains.

Two intensive twenty-four hour effluent samplings were conducted to record the initial effects of biocide application on existing biofilms: the first when the mixed-oxidants generator was initially put on line in the fall (active biofilms), and the second when the seasonal irrigation system was turned on in the spring (dormant biofilms). The fall sampling sites were the first port after the addition of biocide (full year operation with heavy use) and an end-of-line port (full year operation with seasonal low and high use). The spring sampling sites were the first port and a mid-line irrigation port (partial year operation with heavy use). In addition to microbial analyses, free and total chlorine levels were monitored to ensure that biocide was being received system wide. All sampling sites are identified on Figure 4 and described in Table 1.

Samples from the same sites were then collected weekly by the campground manager, shipped on ice for delivery the following day, and analyzed immediately upon arrival to provide ongoing monitoring of the effects of biocide application on the

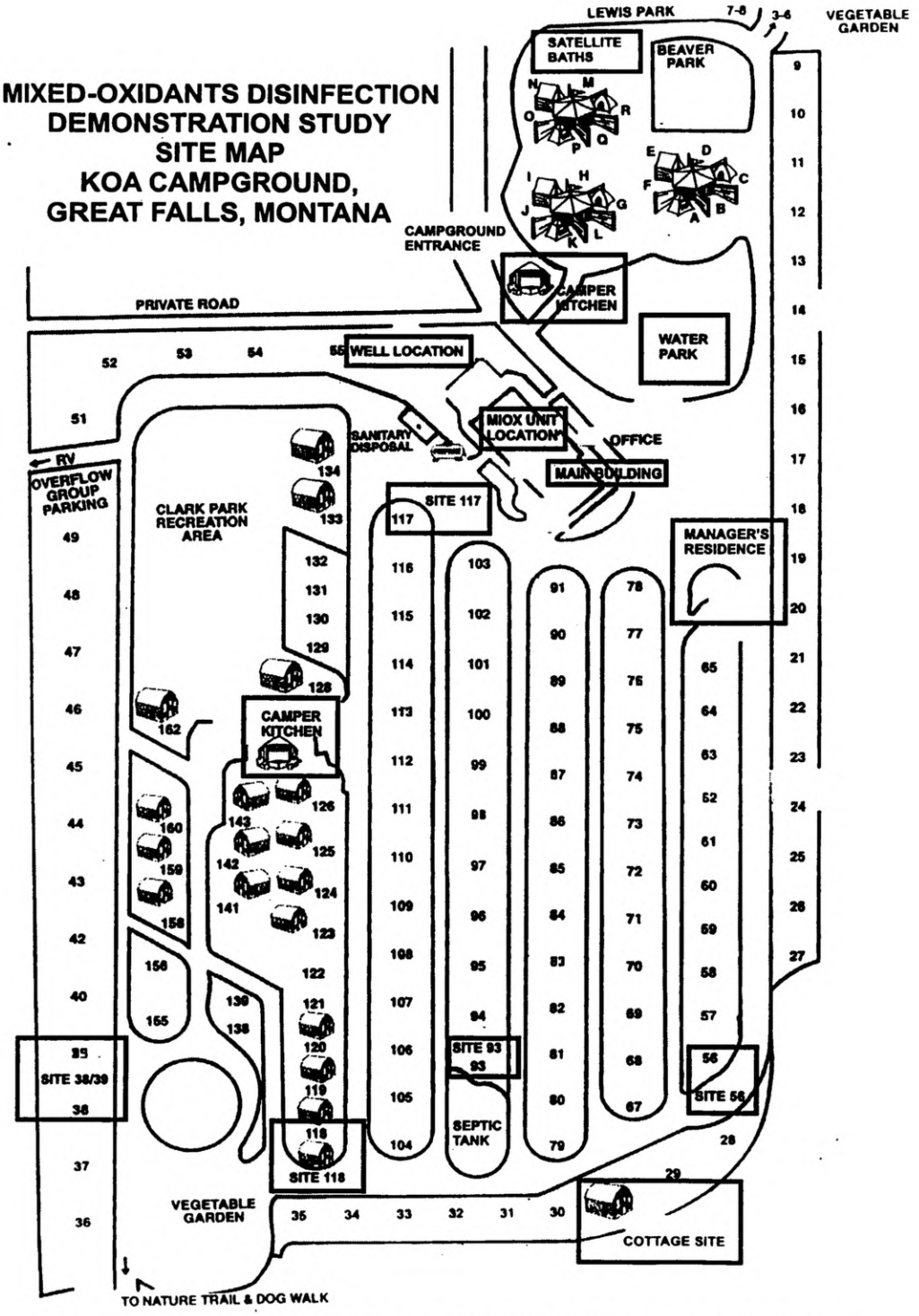


FIGURE 4. DEMONSTRATION STUDY SITE MAP (SEE TABLE 1 FOR SITE DESCRIPTION SUMMARY)

Site	Description	Experiments
MIOX unit	located in basement of main building below office	Demonstration project
56	full year, heavy use line; fall pipe removal and baseline water sample site	1 ppm, 4 ppm short-term biocide
118	full year, low use line; fall pipe removal site	1 ppm, 4 ppm short-term biocide
117	seasonal, heavy use line; fall pipe removal site	1 ppm, 4 ppm short-term biocide
93	seasonal, heavy use, dead-end line; fall baseline water sample site	1 ppm, 4 ppm short-term biocide
38/39	seasonal, heavy use, irrigation line; spring pipe removal site; weekly water sample site	1 ppm long-term biocide, initial effects on dormant biofilms
Cottage	full year, low to high use, dead-end line; fall 24 hour water sampling site; weekly water sampling site	initial effects on active biofilms, weekly samples
Main building	full year, seasonal low to high use line with showers/toilets; weekly water sample site	initial effects on active biofilms, weekly samples
Well	full year, heavy use line; spring pipe removal site	long-term effects on active biofilms
Manager's Residence	full year, heavy use line; anecdotal evidence site	Demonstration project
Camper Kitchens	partial year, heavy use lines; anecdotal evidence site	Demonstration project
Satellite baths	partial year, heavy use lines; anecdotal evidence site	Demonstration project
Water Park	partial year, heavy use lines; anecdotal evidence site; pool and hot tubs	Demonstration project

Table 1. Mixed-oxidants demonstration study site description summary.

distribution system.

Phase IV

Phase four involved the conduction of corrosion studies in annular reactors to determine the relative potential for corrosion on ferrous metal surfaces of mixed-oxidants versus chlorine. Additional analyses were performed to monitor the relation between bacteria in biofilms forming on the inner surfaces of the reactors and bacteria in the bulk fluid effluent of the reactors.

The annular reactors used for this study, constructed by BioSurface Technologies, Inc. (BST, Inc., Bozeman, MT), consisted of a stationary outer cylinder composed of mild steel with flush-mounted coupons of the same material that were removed for biofilm sampling (schematics shown in Figure 5). Mild steel simulates "worst-case" distribution systems conditions as far as corrosion product formation and support of heterotrophs and coliforms (1, 8, 9, 32). Annular reactors provide a high surface area to volume ratio; promote high reaction rates among bulk fluid, biofilm, biocides, and metal surfaces; exhibit increased disinfectant demands due to the cylinder material, microbial populations, and chemical reactions; and are simple to operate, sample, and maintain (1, 9). These reactors having been extensively used in drinking water research as a tool for simulating distribution systems (1, 9), provide operational confidence in the design of this study.

Six annular reactors were in continuous operation for the duration of the nine-

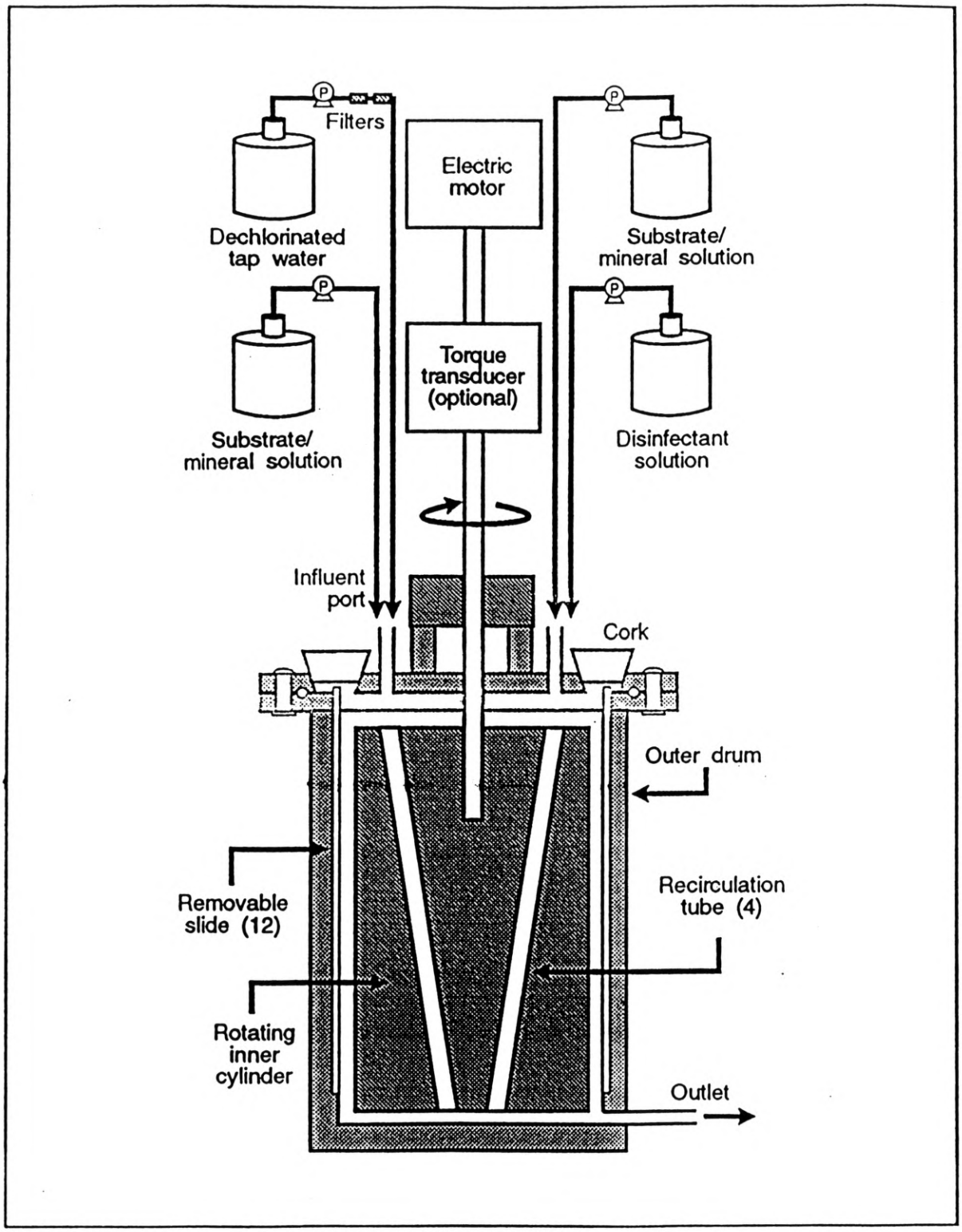


Figure 5. Schematic of the laboratory annular reactor.

week study: two dosed with mixed-oxidants solution, two dosed with free chlorine, and two acting as controls (no biocide dosing). Each reactor, providing a volume of 1.1 liters and a residence time of two hours, was operated as a continuously stirred (sixty revolutions per minute) tank reactor to simulate distribution system hydraulic conditions of one foot per second flow in a four inch pipe (1, 9).

The reactors were initially operated for one week with only nutrients (low concentrations of organic carbon, phosphate salts, and nitrate salts at 500 µg/liter, 100 µg/liter, and 10 µg/liter respectively) and ripened GAC filtered tapwater being applied to allow the reactors to become colonized with indigenous water microorganisms. Baseline sampling was conducted just prior to the application of 3.25 mg/l (as free chlorine) of mixed-oxidants solution and of sodium hypochlorite to the reactors. Eight subsequent samplings were conducted on a weekly basis and included the monitoring of residual free and total chlorine levels, dissolved (ferrous) iron levels, and numbers of heterotrophic microorganisms.

Phase V

' Phase five is an informal cost analysis of the actual operating expenses (obtained from the exit interview with the campground manager) of the mixed-oxidants disinfection treatment process, with comparative reference to more traditional chlorine disinfection processes.

EXPERIMENTAL MATERIALS AND METHODS

Generation of Disinfectants

Mixed-Oxidants Solution

The concentrated solution of mixed-oxidants was generated by a proprietary membraneless electrolytic cell. The required strength of the disinfectant was obtained by dilution of the mixed-oxidants solution with chlorine-free water (reverse osmosis process).

Sodium Hypochlorite Solution

The sodium hypochlorite disinfectant solution was generated from common household bleach. The required strength of the disinfectant was obtained by dilution of the bleach with chlorine-free water (reverse osmosis process).

Sampling Procedures

Consistent sampling procedures were used for each collection. Samples were analyzed immediately after collection for all laboratory and field experiments. The weekly water samples were collected, shipped on ice for arrival the next day, and analyzed immediately upon arrival.

Effluent Samples

Effluent water samples were collected from the bulk outflows of the pipe loop reactor, the annular reactors, and the demonstration site distribution system into sterile containers. All samples were tissuemized (Staufer tissuemzer, Germany) and analyzed for heterotrophic bacterial growth [samples diluted in a standard phosphate buffered saline, (PBS) dilution series and spread plated for culturable cells in triplicate on R2A medium (DIFCO, Detroit, MI) for optimal growth of recoverable bacteria] and AODC (Acridine Orange Direct Counts) total cell counts [samples preserved with formalin, stained with fluorescent acridine orange stain (DIFCO, Detroit, MI), and enumerated under epifluorescence microscopy] (15). Effluent from each annular reactor was additionally analyzed for dissolved iron content (ferrozine iron) and for residual biocide concentration (free and total chlorine). Coliform monitoring [effluent samples filtered and plated on mT7 medium (17) for optimal recovery of injured coliforms exposed to sublethal disinfectant doses] was performed on all water samples from phases two and three.

Plate counts, taken after a standardized time period, are reported as the number of colony-forming units per milliliter of sample. Total cell counts are reported as the number of cells per milliliter of sample. Due to the very small numbers of coliforms cultured, only the presence or absence of these bacteria is reported for each sample.

Pipe Section Samples

For phases one and two, biofilm samples were collected from each pipe by aseptically removing a one foot length (pipe cutter soaked in ethanol and flamed, exterior of pipe wiped with ethanol, section cut from pipe). Three samples (approximately one inch in length) were collected from each removed pipe section. The biofilm was aseptically removed from each one inch sample section by scraping the inner surface of the pipe with a sterile polycarbonate slide into twenty-five milliliters of sterile phosphate buffered saline (PBS) and rinsing the slide and pipe section with additional 25 ml of PBS. The 50 ml (total) of each biofilm solution was then tissuemized, diluted in a standard PBS dilution series, spread plated in triplicate on R2A medium, and incubated for a standard period before being counted. A portion of each sample was preserved for AODC total cell counts. Phase two and three samples were also analyzed for the presence/absence of coliform bacteria by filtering a standard volume and plating on mT7 medium (17).

Microbial and total cell counts for scraped samples are reported as colony-forming units per square centimeter of inner pipe surface. Inner surface areas are calculated by averaging 10 pipe length measurements (taken at equally spaced intervals around the pipe sample section) and multiplying by the known inner diameter of the pipe: Area = Π * diameter * average pipe section length. One inch diameter pipe was used for phase one experiments. The pipes removed and sampled at the KOA site and used in phase three experiments were one and one-half inches in diameter. Due to the very small numbers of coliforms cultured, only the presence or absence of these bacteria is reported for each

sample.

The pipes in phase one were sampled three times: at the end of stabilization period immediately before biocide was applied, at the end of the biocide application period, and at the end of a recovery from biocide period. Due to the longer experimental time frame in phase two, three additional interim samples were taken.

Annular Reactor Coupon Samples

Two flush-mounted coupons from each annular reactor were sampled weekly. Each coupon was removed and the biofilm/corrosion products aseptically scraped using a sterile (ethanol-soaked and flamed) stainless steel slide into 10 ml of sterile nano-pure water. After tissuemizing each sample, a standard nano-pure water dilution series was made and the solutions were spread plated in triplicate on R2A medium.

After a seven day incubation period, the numbers of heterotrophic bacteria were counted and reported as colony-forming units per milliliter for effluent samples and as colony-forming units per square centimeter for coupon scrapings.

Chemical Analysis

Disinfectant residual concentrations for all effluent samples were determined using a standard Hach colorimetric unit (HACH Co., Loveland, CO). Dissolved iron levels were measured in the effluent streams of the annular reactors using standardized Hach spectrophotometric procedures for Ferrozine iron (HACH Co., Loveland, CO).

RESULTS AND DISCUSSION

Laboratory Experiments on Biofilms (Phases I and II)

Comparative pipe section studies were conducted (as described in Scope of Project section, phases one and two) to determine the effectiveness of mixed-oxidants in relation to equivalent concentrations of free chlorine. The effects of different biocide dosages applied for varying time periods on both lab-grown and field-grown biofilms were evaluated. Due to the short residence time in each pipe section, the residual disinfectant level were approximately the same as the dosage level.

A qualitative comparative summary of the performance of mixed-oxidants versus chlorine is given in Table 2. Graphical results for each experiment as noted in Table 2 are available in Appendix A. Numerical results for all experiments are presented in Table 3.

In all experiments (as indicated in Table 2), the performance of mixed-oxidants was comparable or at least as effective as sodium hypochlorite (at equivalent concentrations of free chlorine) at the disinfection and removal of both laboratory and field grown biofilms. For example, 1 ppm long-term biocide application on field-grown biofilms produced a six-log reduction of cultured heterotrophic bacteria by mixed-oxidants, while sodium hypochlorite provided a five-log reduction. Similar rates of regrowth for both biocides were observed after a recovery period (one-log increase).

An inspection of Table 3 reveals that biocide application tended to yield slightly

Performance of Mixed-Oxidants and Chlorination: Destruction and Removal of Biofilms

	1 ppm	4 ppm
Short Term Biocide Application:		
Laboratory-Grown Biofilms	In two separate experiments, mixed-oxidants were shown to be at least as effective as sodium hypochlorite at disinfecting and removing biofilm from 1" PVC pipe. (See figure A1.)	No experiment conducted.
Field-Grown Biofilms	Mixed-oxidants disinfection proved similar to chlorine at destruction of biofilm in 1.5" PVC pipe and allowed only very low levels of biofilm regrowth to occur. (See figures A2-A3.)	Mixed-oxidants demonstrated biofilm removal and regrowth prevention potential at least as effective as sodium hypochlorite. (See figures A4-A5.)
Long Term Biocide Application:		
Laboratory-Grown Biofilms	No experiment conducted.	Disinfection by mixed-oxidants proved to be at least as effective as sodium hypochlorite at biofilm removal from 1" PVC pipe. Similar amounts of regrowth occurred. (See figures A6-A7.)
Field-Grown Biofilms	After disinfection of 1.5" PVC seasonal irrigation pipe (low, patchy, recently dormant biofilms), complete regrowth prevention was demonstrated by both biocides. (See figures A8-A9.)	No experiment conducted.

Table 2. Qualitative comparative performance summary of all pipe reactor experiments.

Summary of Results: Colony-Forming Units Per Square Centimeter of Pipe Surface

(Mixed-oxidants values are indicated by M.O.; Sodium hypochlorite values are indicated by Cl_2)
(All values are given in units of CFU/cm^2)

	1 ppm			4 ppm		
	Baseline	**End of Biocide Dosing**	**End of Recovery Period**	**Baseline**	**End of Biocide Dosing**	**End of Recovery Period**
Short Term Biocide Application:						
	M.O. / Cl_2	M.O. / Cl_2	M.O. / Cl_2	M.O. / Cl_2	M.O. / Cl_2	M.O. / Cl_2
Lab-Grown Biofilms (2 experiments)	3.0E8 / 7.0E4 5.9E5 / 5.2E5	2.1E5 / 2.7E5 7.6E3 / 2.5E4	2.9E7 / 7.6E7 2.5E4 / 2.2E4			
Field-Grown Biofilms	1.3E5 / 1.1E12	2.2E6 / 6.3E6	1.8E6 / 4.7E4	2.5E10 / 2.8E7	3.6E4 / 6.1E2	9.6E5 / 1.8E3
Long Term Biocide Application:						
	M.O. / Cl_2	M.O. / Cl_2	M.O. / Cl_2	M.O. / Cl_2	M.O. / Cl_2	M.O. / Cl_2
Lab-Grown Biofilms				8.7E3. / 5.3E3	2.1E2 / 1.3E2	6.3E3 / 1.8E3
Field-Grown Biofilms	2.4E3 / 6.1E2	8.9E1 / 1.1E3	9.3E5 / 6.5E5			

Table 3. Surface cell concentrations for all pipe reactor experiments.

more consistent results on lab-grown biofilms. These discrepancies support the concept of patchy biofilm formation on pipe surfaces due to variable nutrient or electrochemical conditions (2, 9, 21, 32). Laboratory conditions may have provided a more consistent set of conditions for biofilm formation, while the variability of conditions in the field pipes may have caused less homogeneous biofilm formation. Since uniform formation of biofilms is not guaranteed, spatial variations in biofilm density along the pipe section length rather than biocide performance may be responsible for these variable results. The conclusion of comparable biocidal performance remains valid, since the variations are not dramatic.

Comparisons were made between numbers of attached heterotrophic bacteria (in the biofilm) and numbers of suspended bacteria (in the bulk fluid) in order to evaluate the biofilm removal efficiencies of each biocide. These are reported as bacterial biofilm/bulk fluid ratios. (Biofilm/bulk fluid ratios can be viewed for pipe reactor experiments in Tables 4a and 4b.) Since the number of bacteria in the bulk fluid should be the result of organisms detached from the biofilm, the ratio of biofilm to bulk fluid bacteria should be expected to decrease with effective disinfection. Inspection of Table 4a reveals that this is the case only for heterotrophic organisms (R2A ratio) for 4 ppm short-term biocide application on field-grown biofilms. This is an unexpected result and may be attributed to the patchiness of biofilm formation. The results viewed in Table 4b are more in line with theoretical expectations. Mixed-oxidants consistently provided removal of bacteria in both biocide regimes (Table 4b).

These experiments, although designed to simulate a full-scale distribution system,

1 ppm short-term biocide: field-grown biofilms.

		R2A (1) Ratio	AODC (2) Ratio
CHLORINE			
10-7	Pipe rem.	0.66	2659.11
11-4	Baseline	280800493.22	116.85
11-5	Biocide	119.06	214.60
11-6	Recovery	16.37	811.11
CONTROL			
10-7	Pipe rem.		
11-4	Baseline	16.73	251.33
11-5	Biocide	4261.05	576.99
11-6	Recovery	4452.58	875.78
MIOX			
10-7	Pipe rem.		
11-4	Baseline	267.96	276.10
11-5	Biocide	39013.10	462.08
11-6	Recovery	2087.80	829.12

4 ppm short-term biocide: field-grown biofilms.

		R2A (1) Ratio	AODC (2) Ratio
CHLORINE			
11-6	Prev. Exp.	16.37	811.11
12-10	Baseline	6865.63	387.97
12-11	Biocide	1.89	847.08
12-12	Recovery	3.03	1256.34
CONTROL			
11-6	Prev. Exp.	4452.58	875.78
12-10	Baseline	24690.43	710.54
12-11	Biocide	4330.43	1125.74
12-12	Recovery	3092.97	1430.77
MIOX			
11-6	Prev. Exp.	2087.80	829.12
12-10	Baseline	29538624.63	726.78
12-11	Biocide	15.48	843.03
12-12	Recovery	423.71	223.14

(1) Biofilm/bulk fluid ratio of culturable heterotrophic bacteria.
(2) Biofilm/bulk fluid ratio of total bacterial cell counts.

Table 4a. Biofilm/bulk fluid ratios: pipe reactors.

4 ppm long-term biocide: lab-grown biofilms.

		R2A (1) Ratio	AODC (2) Ratio
CHLORINE			
3-31	Baseline	100.16	28.86
4-4	Biocide	0.14	89.47
4-9	Recovery	2.80	197.84
CONTROL			
3-31	Baseline	83.72	23.04
4-4	Biocide	0.72	109.87
4-9	Recovery	1.62	92.62
MIOX			
3-31	Baseline	96.30	40.79
4-4	Biocide	1.77	36.76
4-9	Recovery	8.66	225.54

1 ppm long-term biocide: field-grown biofilms.

		R2A (1) Ratio	AODC (2) Ratio
CHLORINE			
4-16	Pipe rem.	0.01	1.50
5-21	Baseline	60.74	44.91
7-3	Biocide	11.04	14.87
7-31	Recovery	41.53	30.24
CONTROL			
4-16	Pipe rem.	0.02	10.19
5-21	Baseline	203.51	10.74
7-3	Biocide	188.82	4.57
7-31	Recovery	135.79	55.58
MIOX			
4-16	Pipe rem.	0.00	8.29
5-21	Baseline	118.12	13.02
7-3	Biocide	1.41	3.76
7-31	Recovery	108.16	6.49

(1) Biofilm/bulk fluid ratio of culturable heterotrophic bacteria.
(2) Biofilm/bulk fluid ratio of total bacterial cell counts.

Table 4b. Biofilm/bulk fluid ratios: pipe reactors (continued).

were in no way a complete representation of the widely varied, unique, and interactive conditions present in the field. Regrowth events within distribution systems are dependent upon the very complex interaction of these conditions and can occur in only hours (9, 19, 27). Reliance on disinfection alone may be ineffective at the control/prevention of regrowth events. Improved maintenance of distribution system components, reduction of organics entering the system, increased or more rigorous monitoring/sampling for prediction purposes, and/or implementation of active corrosion control strategies may need to considered.

Coliform Monitoring (Phases II and III)

In order to assess the relative effectiveness of mixed-oxidants versus chlorine for coliform removal, coliform detection monitoring was conducted on all field samples. The use of mT7 culture medium, recommended for systems experiencing regrowth problems, ensured a more accurate indication of coliform presence than the use of federally allowed standard m-Endo media since mT7 is more sensitive and recovers injured as well as healthy coliform bacteria (1, 9, 17).

In all field studies and field-related experiments, the numbers of coliform colony-forming units detected were quite low. Due to these small numbers, only the presence or absence of the bacteria was recorded. A qualitative summary of coliform monitoring results is presented in Table 5.

As indicated in the table, the 1 ppm short-term biocide application yielded the best removal and regrowth prevention results. However, the control pipe section (no biocide

Summary of Coliform Monitoring Results

Experiment	Results	Comments
Pipe removal (10-7-96)	No coliforms detected in any samples.	Used for baseline detection in Nov 4-6 experiment.
24 hour water sampling (Oct 21-22, 1996)	Coliforms detected in only one sample: baseline sample at the full-year, low to high seasonal use, dead-end sampling point (cottage). Prior water usage was very low.	Initial bulk fluid conditions at dead-end possibly more favorable to coliform growth.
1 ppm short term biocide application (Nov 4-6, 1996)	Initial detection: all bulk fluid samples; biofilm sample of full-year, low use pipe. No detection at end of biocide application. After recovery: Coliforms detected in biofilm of full-year, low use pipe (no biocide).	Initial detection: Higher nutrient levels, temperature, entered pipes attached to carbon fines from GAC.
4 ppm short term biocide application (Dec 10-12, 1996)	Initial detection: all bulk fluid and all biofilm samples. Detection at end of biocide application: all bulk fluid samples; biofilm samples (2/3 chlorine, 3/3 control, 1/3 MIOX). After recovery: all bulk fluid samples; biofilm samples (2/3 chlorine, 1/3 control, 3/3 MIOX).	Same pipes as Nov 4-6 experiment. Good establishment (regrowth) indicated by coliform persistence after 4 ppm biocide application,
Pipe removal (4-16-97)	Coliforms detected in 4/6 scrapings of dormant biofilms (seasonal pipes) and 0/2 scrapings of active biofilms (year-round pipes).	Suggests that coliforms have survived in dormant/dry biofilms.
24 hour water sampling (April 16-17, 1997)	Coliforms initially detected at year-round and seasonal sample sites. Intermittent detection was observed at both sites until the seventh hour for the seasonal line and the sixteenth hour for the year-round line.	Suggests that coliforms shed more easily from dormant biofilms than from active (never dried out) ones.
1 ppm long term biocide application (5-21 to 7-31, 1997)	Initial detection: no positive results for any sample. Detection at end of biocide application: bulk fluid of both disinfected pipes. After recovery: all bulk fluid samples; biofilm samples of control, MIOX.	Suggests shedding from biofilm due to biocide. Re-establishment occurring after recovery period.

Table 5. Qualitative summary of coliform monitoring results.

applied) also exhibited comparable results. This incident points out a general weakness in all coliform monitoring methods--the occurrence of false positives and false negatives. Frequent and repeated monitoring is essential to provide more valid assessment of coliform presence in distribution systems. Coliform detections are indicated on field study graphs and tables as applicable (See Appendices A, C, and D.)

No significant patterns in coliform reduction were observed. The effectiveness of mixed-oxidants over sodium hypochlorite at the disinfection and removal of coliforms from field-grown biofilms or from the bulk fluid of the demonstration site was not clearly evident. However, it appears that mixed-oxidants disinfection has been more successful than the chlorination method previously used at the campground at the prevention of coliform regrowth events since the campground has not been in violation of the total coliform rule since implementing the use of mixed-oxidants.

Corrosion Studies (Phase IV)

Annular reactors were run continuously for nine weeks to gain information about the relative potential for corrosion of mixed-oxidants versus sodium hypochlorite, as well as monitor the numbers of heterotrophic bacteria in surface biofilms and bulk fluid effluents.

Average results of corrosion study comparisons for mixed-oxidants versus sodium hypochlorite are presented graphically for biofilm bacterial counts from scraped coupons in Figure 6, for reactor bulk fluid bacterial counts in Figure 7, for biofilm/bulk fluid ratios in Table 6, and for dissolved iron levels in Figure 8. Appendix B contains unaveraged, detailed graphic results for all corrosion-related studies.

Since annular reactors are designed to provide a reasonable simulation of a distribution pipe's hydraulic conditions, efforts were made to relate the differences (if any) between flow condition, biofilm formation, and corrosion product deposition to the coupon position among the four rows (top to bottom) of each reactor. A power failure during the experiment (indicated on each graph) provided information on the effects of stagnant conditions in the reactors. Although an overall change in all variables studied was observed in each reactor, the behaviors of the biocides remained consistent. A row by row comparison of coupon location versus sampling date provided no additional information on biocide performance. Figure B1 is a map of coupon locations and sampling dates. Figure B2 presents row by row sampling results.

As was expected, significant chlorine demand was exhibited by each reactor being dosed with disinfectant solution. Equivalent concentrations (3.25 ppm as free chlorine)

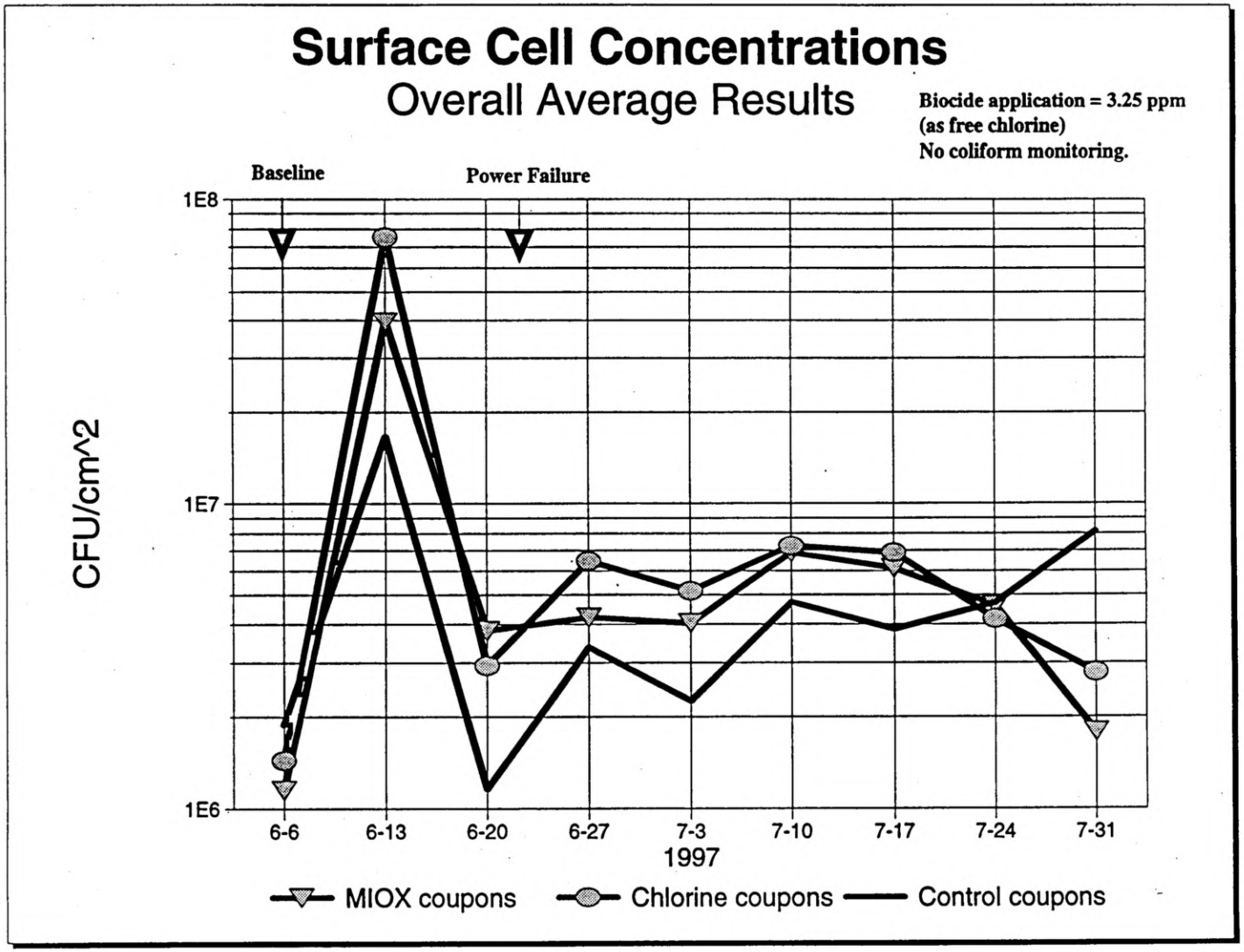


Figure 6. Average surface cell concentrations: annular reactor coupons.

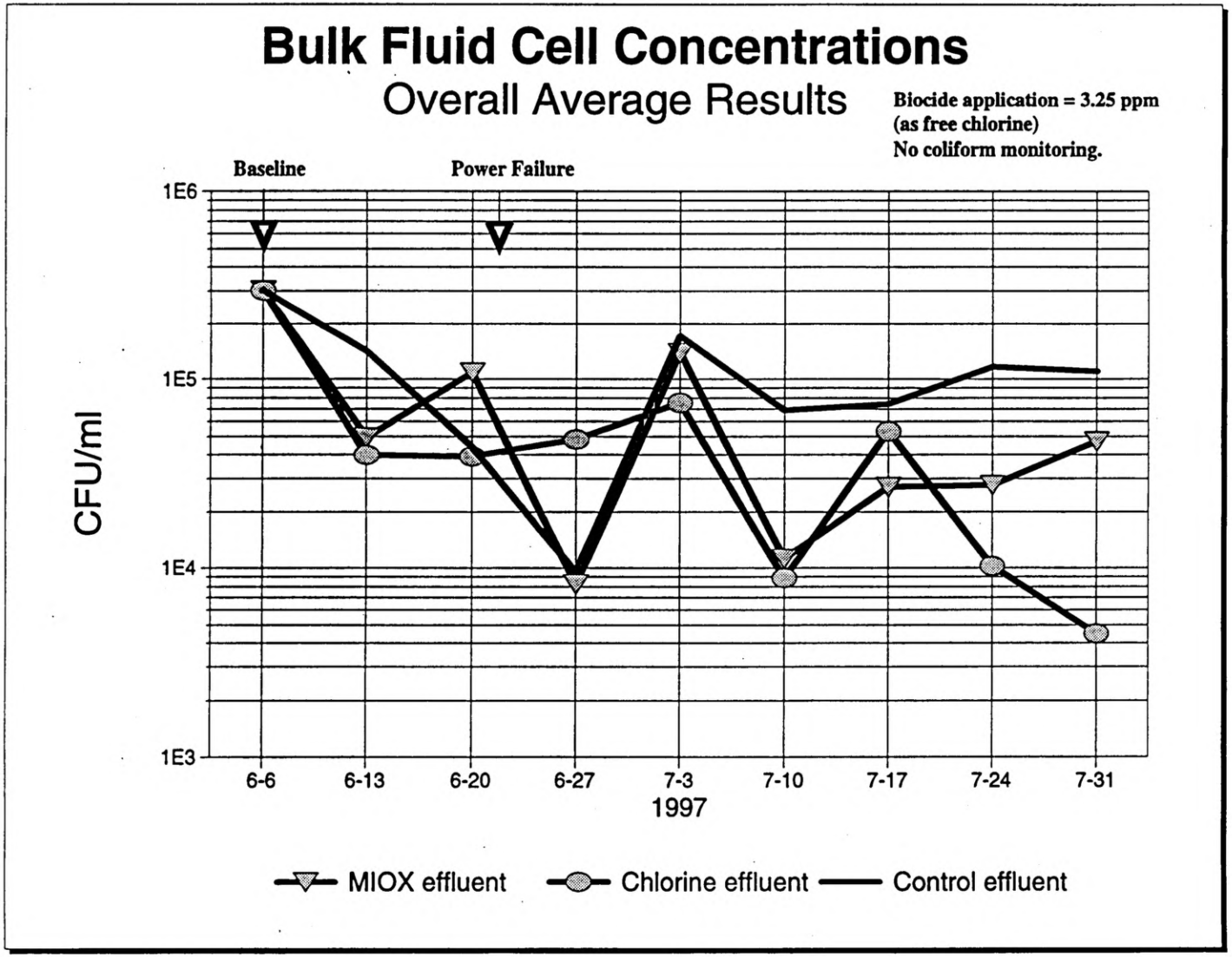


Figure 7. Average bulk fluid cell concentrations: annular reactors.

REACTORS	R2A Ratio (1) MIOX	R2A Ratio (1) CHLORINE	R2A Ratio (1) CONTROL
Baseline 6-6	3.83	4.77	6.26
6-13	804.67	1892.11	117.76
6-20	34.95	74.81	26.51
6-27	513.25	134.02	353.22
7-3	29.04	68.32	13.20
7-10	608.85	817.71	68.65
7-17	226.12	129.50	52.13
7-24	166.99	404.60	40.11
7-31	38.01	623.95	73.42

(1) Biofilm/bulk fluid ratio of culturable heterotrophic bacteria.

Table 6. Biofilm/bulk fluid ratios: annular reactors.

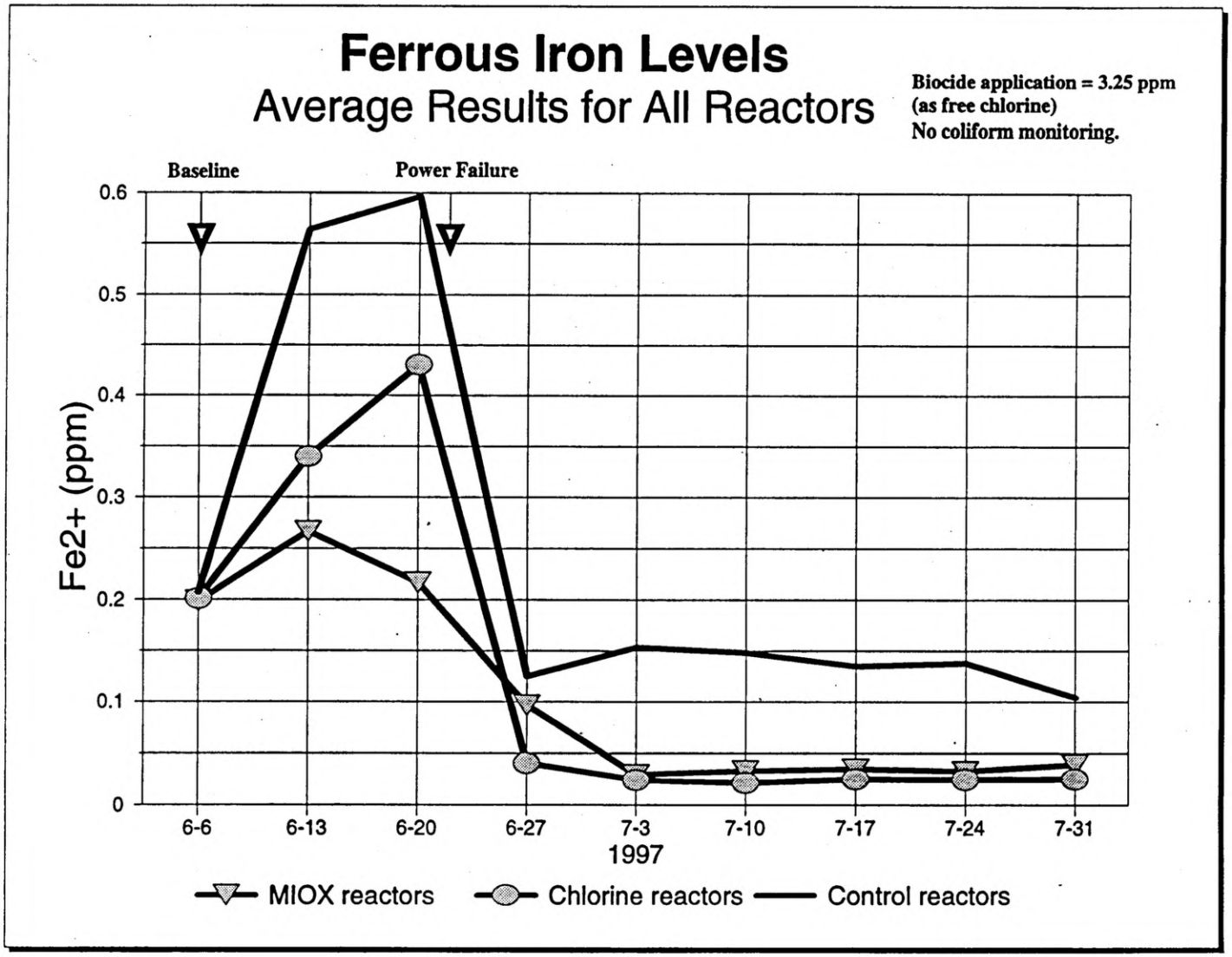


Figure 8. Average ferrous iron levels: annular reactors.

of each biocide applied yielded a residual disinfectant concentration of less than 0.07 ppm in the reactor effluents for the duration of the experiment. The chlorine concentration present in the effluents of the control reactors was effectively zero ($\leq$ 0.01 ppm) for each sampling.

Two coupon samples were taken weekly from each reactor for a total of four coupons for each biocide type (mixed-oxidants, free chlorine, and no biocide). A bulk fluid sample was also taken each week, providing two samples for each biocide type. At comparable levels, mixed-oxidants were shown to be at least as effective at the disinfection and control of biofilms as measured by numbers of heterotrophic bacteria on mild steel coupon surfaces and in the reactor bulk effluent as free chlorine. Figure 6 presents the averaged biofilm results for each biocide and the control (no biocide). Figure 7 presents the averaged bulk fluid results. Similar average trends for all biocide types were observed in both biofilm and bulk fluid samples. The potential for removal of biofilms was evaluated by the comparison of biofilm to bulk fluid ratios. Table 6 reveals no apparent trends for any biocide type.

The relative potential of each biocide for the corrosion and dissolution of mild steel was measured by comparing levels of dissolved ferrous iron in each reactor. Graphic results (averaged by biocide type) are presented in Figure 8. Results indicated that the corrosion levels exhibited by mixed-oxidants are no greater that those of free chlorine. Dissolved iron levels for both biocides were generally lower than those of disinfectant-free water.

Results of a recent survey reported that over one quarter of responding utilities

had problems with the presence and regrowth of iron bacteria (32). Iron bacteria convert soluble iron to an insoluble form which is deposited on or outside the bacterial cells leading to biofouling and biocorrosion. Iron bacteria can rapidly become established in biofilms on distribution piping accelerating corrosion, deteriorating distribution components, reducing water distribution capacities, increasing operating/maintenance costs, masking the presence of pathogens, reducing disinfection efficacy, and increasing disinfection demand (1, 2, 32). Corrosion may play a role in coliform regrowth events since a variety of coliforms is included in this group of heterotrophic iron-precipitators (32).

Following the completion of the corrosion studies, the reactors were disassembled so that inner surfaces could be observed. As observed in previous related studies (9, 32) all reactors exhibited patchy biofilm/corrosion product formation. This has significant implications for water treatment strategies. Biofilms are able to influence corrosion rates by this introduction of gradients and patchiness, leading to electro-potential differences and subsequent corrosion currents (32). The resultant corrosion increases surface area, provides niches for microbial diversity, adsorbs nutrients, and reduces disinfection penetration to biofilms (1, 16). Potential for the regrowth of iron bacteria, including several varieties of coliforms, also requires consistent monitoring, maintenance, and specific disinfection of the distribution system (2).

Field Studies (Phases II and III)

Monitoring and analysis of the actual performance of the mixed-oxidants technology under field conditions provided valuable information on its feasibility as an alternative disinfection process. See Appendix C for complete tabular and graphic information on sloughing (the release of biofilms, corrosion products, biofouling, etc. from pipe surfaces), residual disinfectant levels, coliform monitoring, plate counts, and AODC for the ten month study.

Demonstration Project

The study of the full-scale mixed-oxidants treatment process progressed sequentially to provide useful information various components of the KOA's distribution system. The field study timeframe is summarized below.

- July 15, 1996: MIOX unit put on line for treatment of contact water in pool/water park.
- October 21, 1996: Treatment of full-year potable water by MIOX unit begun.
- April 16, 1997: Treatment of seasonal potable and irrigation section of distribution system begun.
- August 19, 1997: Last sampling conducted.

Application of the mixed-oxidants disinfection solution appeared to have successfully removed biofilms and biofouling from the distribution system of the KOA

campground as observed by the release of orange deposits and the initial fouling of filters. Although previously in repeated non-compliance of the total coliform rule when using powdered sodium hypochlorite, the campground hasn't had a single infraction since using mixed-oxidants for disinfection of its water supply.

The sloughing of biofilms and biofouling from redeposition of corrosion products on the full year distribution system lines was observed periodically throughout the first seven months of the ten month study as a reddish residue on filter membranes as the weekly water samples were processed for analysis. The sloughing began four weeks after the mixed-oxidants unit was put on line, continued into the seventh month of biocide application, and varied substantially in color intensity and numbers of heterotrophic bacteria observed in cultured plates and direct cell counts. Previous anecdotal results were consistent with this phenomena (12). Low or non-existent residual disinfectant concentrations (as measured by total chlorine concentrations), accompanied by elevated numbers of cultured heterotrophs, indicated that the mixed-oxidants were not always reaching the distribution line dead-ends. Periods of low and/or intermittent water use during the fall and winter most likely led to these fluctuating results. Disinfection may have detached and inactivated the organisms upstream, but did not prevent their growth later on in the distribution system (8, 20, 27). Higher temperatures, longer residence times, dead-end or low use points, and larger ratio of pipe surface to water volume of the relatively small distribution pipes are other conditions in the in the campground's distribution system that may tend to favor bacterial proliferation and increased chlorine decay (22). Regular flushing of water lines during low water use periods was begun,

ensuring that disinfectant would reach all points of the distribution system (1, 2, 22). When adequate disinfectant residual (greater than 0.2 ppm as total chlorine) was present in distribution sampling points, cultured cell numbers were generally lower and total cell counts generally higher indicating that disinfection was occuring.

When the irrigation system was put on line in the spring, flow through the seasonal systems was much higher and more continuous than that for the full year system. Biofilm/corrosion product sloughing began almost immediately (after the first week of mixed-oxidants application), was more continuous in color intensity, and was significantly shorter in duration (no reddish tint observed after only two weeks). Possible conclusions are that dormant biofilms are more easily removed by mixed-oxidants and/or that more continuous flow conditions are required for effective biofilm removal.

Coliforms were more likely to be detected in the weekly water samples at the low-use or dead-end sampling points during the campground's off-season months. However, from the time consistently higher water use began in mid-April (irrigation system turned on and campsite use increased) until mid-May, there were only two positive coliform cultures in the weekly samples processed. From mid-May until the termination of the demonstration study, no coliforms were detected.

In contrast, previous dosing of the distribution system with high concentrations (up to 1000 ppm) of sodium hypochlorite produced no observable periodic sloughing or filter fouling and repeatedly was followed by positive coliform samples.

Initial Effects on Existing Biofilms

Except when replication of bacteria in the bulk fluid is made possible by long residence times, the numbers of bacteria enumerated in the bulk fluid of a distribution system should be the result of organisms detached from the biofilm (9). In order to evaluate the initial effects of mixed-oxidants on existing biofilms, two intensive twenty-four hour water sampling experiments were conducted. In each instance, a baseline bulk fluid measurement of heterotrophs and total coliforms (media plate cultures and direct cell counts) was made just prior to initiating the application of mixed-oxidants. Fifteen subsequent samples were taken during the following twenty-four hours.

Results from both experiments indicate that there was no significant biofilm removal during the first full day of operation. The initial application of mixed-oxidants appeared to have little effect on the active or dormant biofilms present in the distribution system. As expected, residual disinfectant levels (as measured by free and total chlorine concentrations) fluctuated in response to chlorine demand within the system. Previous anecdotal results were consistent with these phenomena (12).

The initial effects of mixed-oxidants on active biofilms in the year-round distribution system and on dormant biofilms in the seasonal distribution system are presented in Appendix D.

Exit Interview (Phases II and III)

In recognition of the uniqueness and complexity of field operating conditions and to gain as much information and insight as possible concerning the actual performance of

the mixed-oxidants treatment process, an exit interview with the campground manager (person directly responsible for water treatment at the test site) was conducted at the close of the study period. The resulting information may assist in the installation, operation, and effectiveness of future mixed-oxidants water treatment systems. This interview in its entirety is presented in Appendix E. Major points are summarized in the remainder of this section.

Coliform Compliance

The KOA system has not had a single non-compliance since the mixed-oxidants generation unit was put on line. Previously, even with free chlorine slug dosage levels (from powdered sodium hypochlorite) as high as 1000 parts per million, positive coliform samples were repeatedly obtained.

Advantages of Mixed-Oxidants Over Chlorine Disinfection

The mixed-oxidants disinfection process is far less labor intensive than dosing with powdered sodium hypochlorite. The MIOX disinfectant solution is safer, cleaner, less expensive, and easier to use. There is no detectable off-gassing which can be highly corrosive to electrical equipment in the disinfection area. The mixed-oxidants solution contains no granules of undissolved disinfectant which can lead to clogging of the injectors. The mixed-oxidants process can be sited at any convenient location and does not require special containment conditions. The mixed-oxidants generator is easily integrated into existing chlorine injection systems.

Effects on Distribution System

Mixed-oxidants led to the sloughing off of previously accumulated biofilm/biofouling in the KOA's water distribution system. This resulted in an obvious increase in the water pressure and water quality at the manger's residence. Prevention of biofilm formation was observed through absence of "black slime", a common biofilm (27), in the showers.

After the initial sloughing of corrosion products and biofilm, the filters throughout the distribution system required far less maintenance than before the installation of the mixed-oxidants system: the filters are cleaned every three to four weeks now as compared to every two to three days previously.

Prior to the use of mixed-oxidants, loss of pressure in the water distribution system during periods of electrical problems (frequent power outages) caused the release of biofouling in the pipelines. These sloughing events always required flushing of the system when pressure was regained. In contrast, upon restart of the system after a loss of pressure this summer due to a well malfunction, no discoloration was present and no flushing was required.

Effects on Contact Water Distribution System

The water theme park is well into its second season of disinfection by mixed-oxidants. At a dosage of two to three parts per million of free chlorine from the mixed-oxidants solution, there have been no consumer complaints of chlorine taste/odor. The

growth of algae on pool area surfaces is typically a problem for the majority of outdoor swimming pools. However, there has been no algal growth, even on the unpainted concrete areas, eliminating the need for algacide application.

The only disinfection process used for the pool area has been that of mixed-oxidants, since the opening of the water park coincided with the installation of the mixed-oxidants treatment process. Visual inspection of pool pipe, connections, and filters has revealed that all components remain in essentially new condition. There is no visual or tactile accumulation of biofilms or corrosion products. In contrast, when sodium hypochlorite was used for potable water disinfection, corrosion products and "slime" were developed in a very short time on all new (from repairs, replacements, or extensions) distribution system components.

The only problem with the treatment process was that on days of very high pool usage (typically eighty to ninety percent of campground chlorine demand), it was necessary to provide supplemental disinfection through the addition of sodium hypochlorite. This problem will be taken care of with the installation of a larger disinfectant solution storage reservoir.

Informal Cost Analysis (Phase V)

The actual operational costs of the mixed-oxidants disinfection system for the demonstration site were attributed almost totally to the salt requirements. During KOA water system peak usage (100,000 gallons per day), only one fifty pound bag of salt per day at a total cost of $2.79 was required, as compared to the $35.00 average daily cost of

powdered sodium hypochlorite for dosing with free chlorine. Eighty to ninety percent of this biocide demand was attributed to the water park area. During the off-season, a fifty pound bag of salt was sufficient for up to two months of solution generation.

The generation of the mixed-oxidants solution required to meet chlorine demands in the peak season required a daily operational time of eighteen to twenty hours, dropping to less than one half hour per day during the off-season. Due to the large electrical requirements of the campground (average summer monthly electrical bill of $3000.00), there was no detectable increase in power costs associated with the use of the mixed-oxidants system.

Monitoring, maintenance, and operator training costs were negligible. During the limited down-time of the mixed-oxidants unit, the reversion to application of sodium hypochlorite was easily accomplished at no additional cost or modification to the existing system.

Alternate possibilities for disinfection processes at the campground are quite limited. The continuation of sodium hypochlorite is an option, but requires too much of the manager's time for mixing and monitoring. He feels his time commitment for disinfection is substantially reduced by the use of mixed-oxidants. Gaseous chlorine or ozone generation systems are completely unfeasible as options for disinfection treatment processes at the campground due to the high equipment costs, the rigorous operator training requirements, the highly variable (seasonal) disinfectant demands, and the operational site restrictions.

The only limiting factor in the campground manager's consideration of future

installations of mixed-oxidants disinfection systems is the high capital cost of the generation unit itself. The retail price, installation not included, for the unit in operation at the campground is $12,000. Although considerably more expensive than a sodium or calcium hypochlorite injection system, this capital cost is actually substantially less than that of gaseous chlorine systems. When total costs are amortized over ten years, the cost per thousand gallons of water treated is less than half that of gaseous chlorine (18).

Detailed comparative cost analyses of four sizes of mixed-oxidants systems versus gaseous chlorine, sodium hypochlorite, and calcium hypochlorite systems are presented in Appendix F (18).

Results of Related Research

Additional supporting evidence for the success of mixed-oxidants as a viable alternative water treatment option is provided by related research. A 1996 study on a 0.5 MGD drinking water treatment facility demonstrated that mixed-oxidants could reduce manganese levels to below the secondary standard contaminant levels (SMCLs) with a smaller dose and a shorter reaction time than potassium permanganate at an operational cost of about $1.50 per day (3).

A 1.2 MGD drinking water treatment plant was able to reduce total THM content of finished water by 20% and realize a 50% savings in disinfectant generation costs using mixed-oxidants instead of gaseous chlorine (10).

Laboratory tests have indicated that the mixed-oxidants solution may produce from 10-40 percent of the total trihalomethanes (TTHMs) of hypochlorite on an equal

chlorine basis (6, 11). The non-chlorine oxidant species present in the mixed-oxidants solution have consistently had the effect of reducing the free chlorine demand of both model and real waters when compared to equivalent amounts of sodium hypochlorite, without enhancing the formation of trihalomethanes (THMs) (13).

Mixed-oxidant generators have been used successfully at less than half the price of hydrogen peroxide (H_2O_2) to treat sewage odor problems by removing dissolved and atmospheric hydrogen sulfide (H_2S) without the formation of sulfites (SO_3^{2-}) or sulfates (SO_3^{2-}). Lower H_2S levels resulted in decreased corrosion of concrete pipes (24).

Data from evaluation on wastewater clearly show that the mixed-oxidants solution is an effective biocide with strong oxidizing power which produces finished water quality parameters typical of those expected for a well operated municipal wastewater treatment plant (28).

Mixed-oxidants have been shown to inactivate both *Cryptosporidium parvum* oocysts and *Clostridium perfringens* spores more effectively than free chlorine at the same dosage and exposure (30, 31). Effective removal has also been demonstrated against *E. coli*, *Serratia marcescens* ,coliforms, total aerobes, and some viruses (4, 5).

Industrial studies indicate that the use of mixed-oxidants consistently results in poultry processing chill water samples that are less contaminated by *E. coli* and coliforms than chill water samples treated with the same levels of free available chlorine from sodium hypochlorite (33).

Anecdotal evidence supports the removal of biofilm/biofouling by the application of mixed-oxidants disinfection. Following the replacement of a gaseous chlorine system

with a mixed-oxidants system at the Sandia Ranger Station in Tijeras, New Mexico, operation staff observed the sloughing of "orange deposit" (presumed corrosion products and biomass). Another installation site in West Richland, Washington, reported sloughing of manganese build-up and removal of "green slime" from distribution pipes after a few weeks of operation (12).

CONCLUSIONS

Effectiveness of Mixed-Oxidants at Destruction and Removal of Biofilms

Laboratory Evidence

All results indicate that the application of mixed-oxidants is at least as effective as free chlorine (at similar concentrations) at the disinfection and removal of biofilms on PVC pipe. Additionally, no significant difference in the recovery rates of biofilms exists between the two biocides. The reduction and recovery rates of the naturally occurring biofilms were analogous to those of the laboratory grown biofilms. The mixed-oxidants solution demonstrated a reduction in heterotrophic plate counts in both the biofilm and the bulk fluid that was at least as great as chlorine.

The efficacy of mixed-oxidants at disinfection of biofilms on mild steel is at least that of free chlorine. The corrosion potential of mixed-oxidants (as measured by amounts of ferrous iron) is no higher than that of free chlorine at comparable levels and is lower than that of disinfectant-free water.

Anecdotal Evidence

Observations from the manager of a rural distribution system suggest that the use of mixed-oxidants is effectively improving water quality as demonstrated by increased water pressure, cleaner filters, and less observed build-up in pipes.

The distribution system has not been in violation of the total coliform rule since

beginning the application of mixed-oxidants, indicating that coliform regrowth events have been effectively controlled.

Performance of Mixed-Oxidants as a Full Scale Water Treatment Process

The mixed-oxidants disinfection system has the potential to provide a reasonable alternative for small distribution systems as a safe, reliable, and operationally cost effective technology that is easy to operate and is readily compatible with other operational systems.

Actual operating costs during peak operation (ninety days in the summer) were approximately $196 for salt. When compared to the potential cost of sodium hypochlorite for the same time period (approximately $3150 for ninety days), the net savings in chemicals alone could offset the extra capital costs of mixed-oxidants in just a few seasons. This operational cost consideration, as well as increased performance and reduced maintenance, supports the choice of mixed-oxidants over chlorine for disinfection of small distribution systems.

Relevance to Industry

The mixed-oxidants technology appears to be an economically viable disinfection technology for small water distribution systems since it is safe to operate; is readily compatible with other operational systems; appears to prevent coliform regrowth events; requires a minimum of operator training, maintenance, and process monitoring; provides biofilm/biofouling removal and improved drinking water quality; exceeds EPA

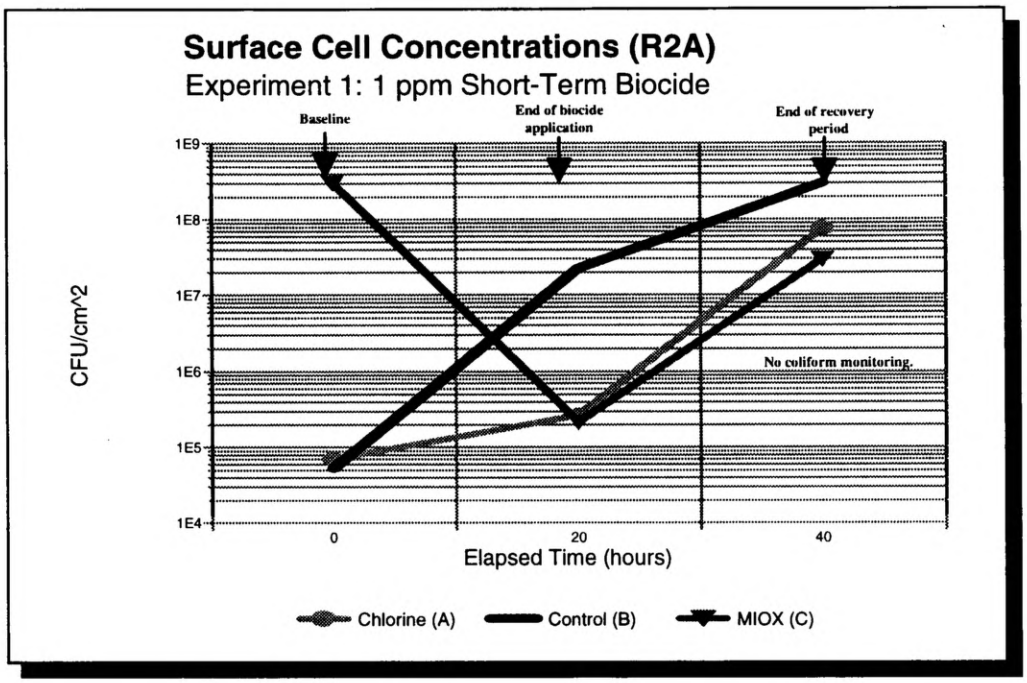
drinking water standards for disinfection by-products; and provides chlorine residual without imparting a chlorinous taste or odor to the treated water.

APPENDICES

APPENDIX A

Pipe Reactor Results

Figure A1. Effects of 1 ppm short-term biocide on lab-grown biofilms.



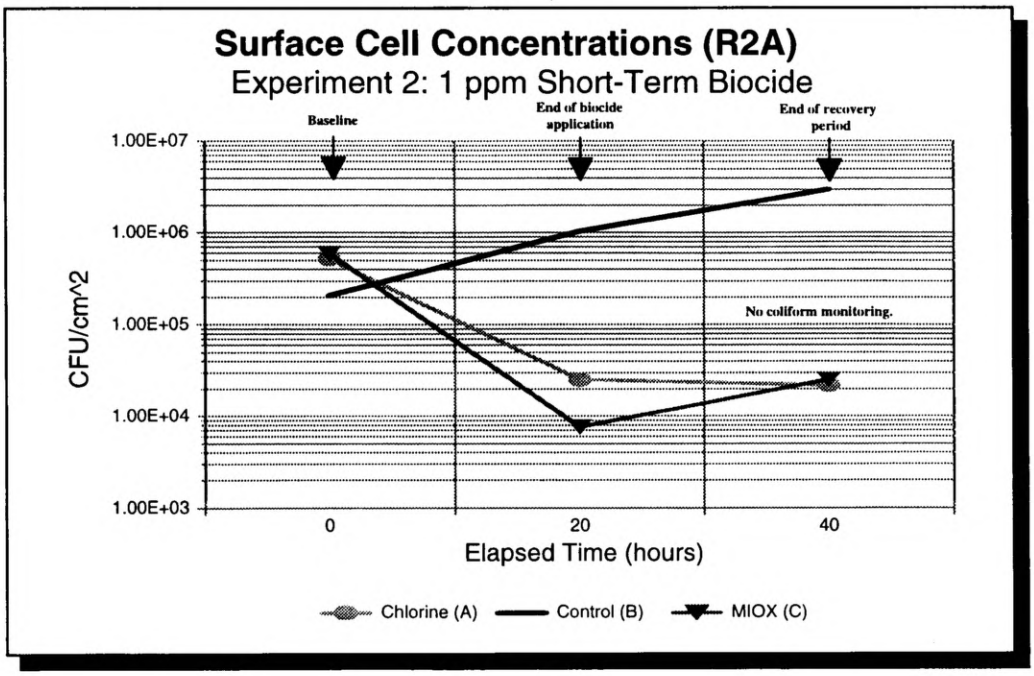
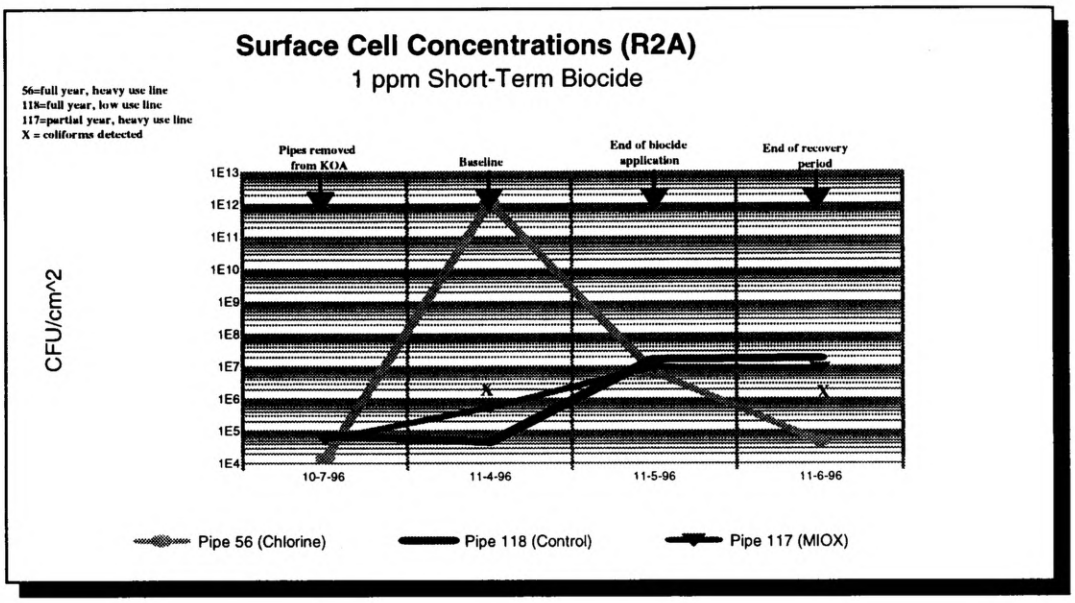


Figure A2. Effects of 1 ppm short-term biocide on active field-grown biofilms (plate counts).



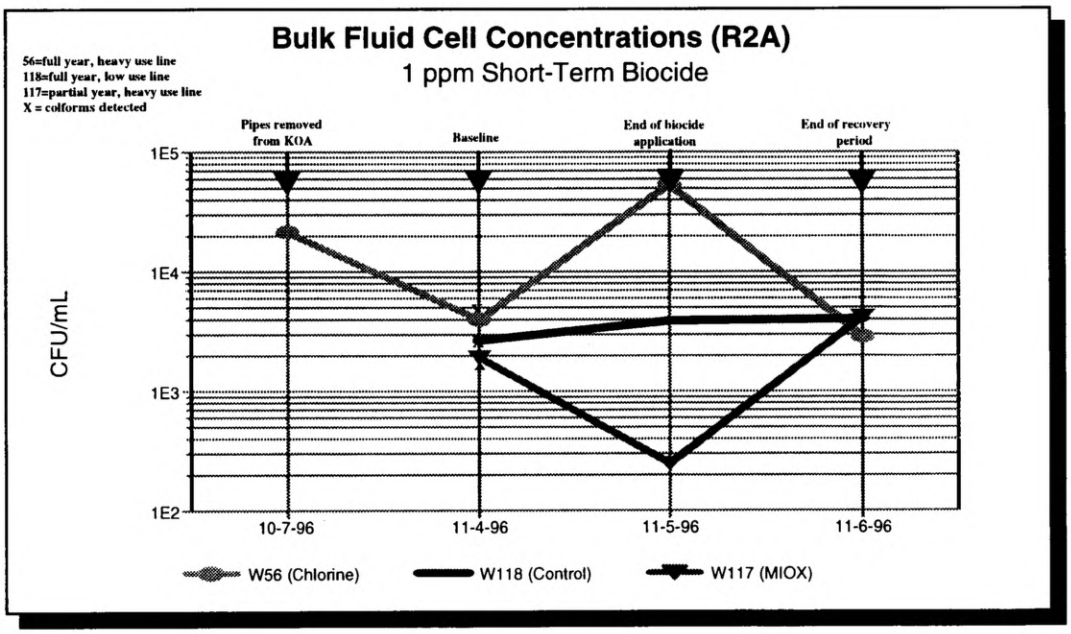
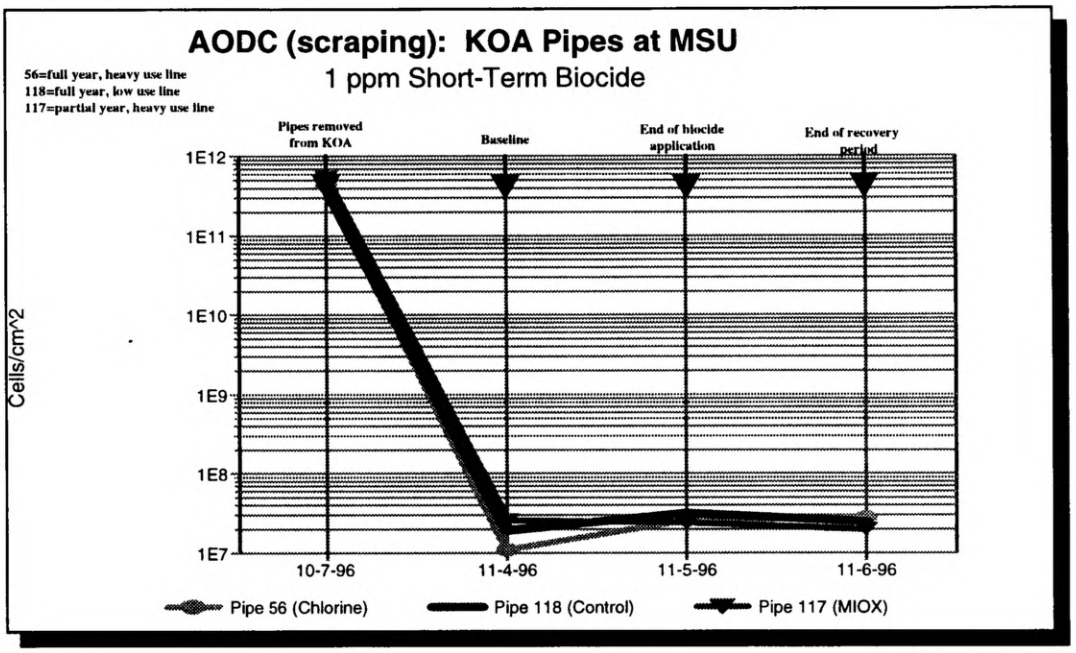


Figure A3. Effects of 1 ppm short-term biocide on active field-grown biofilms (total cell counts).



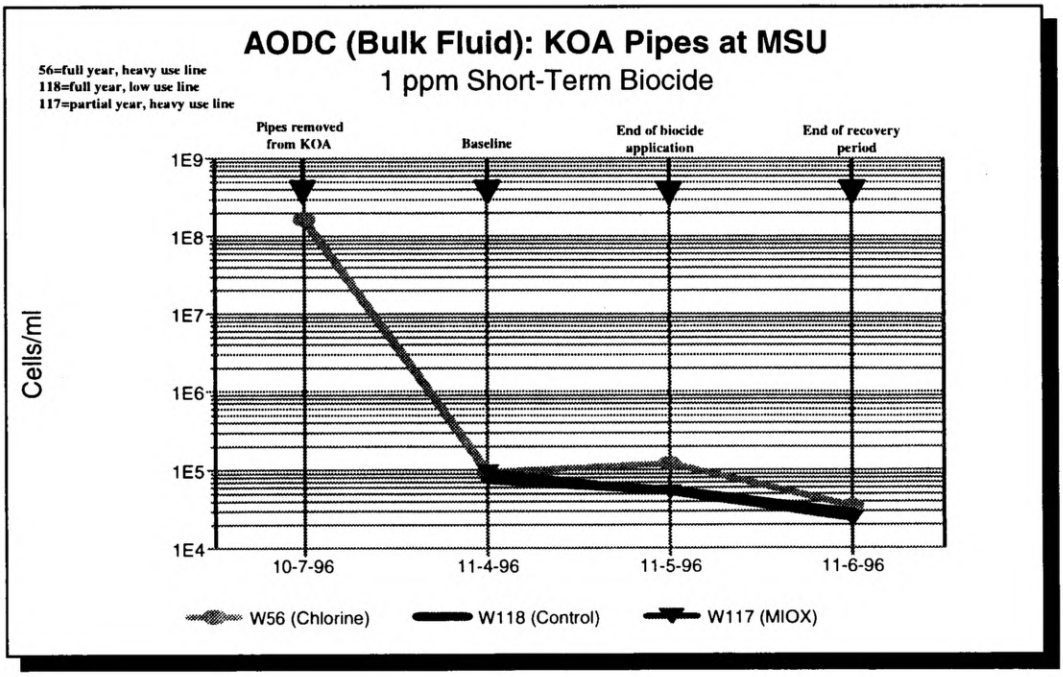
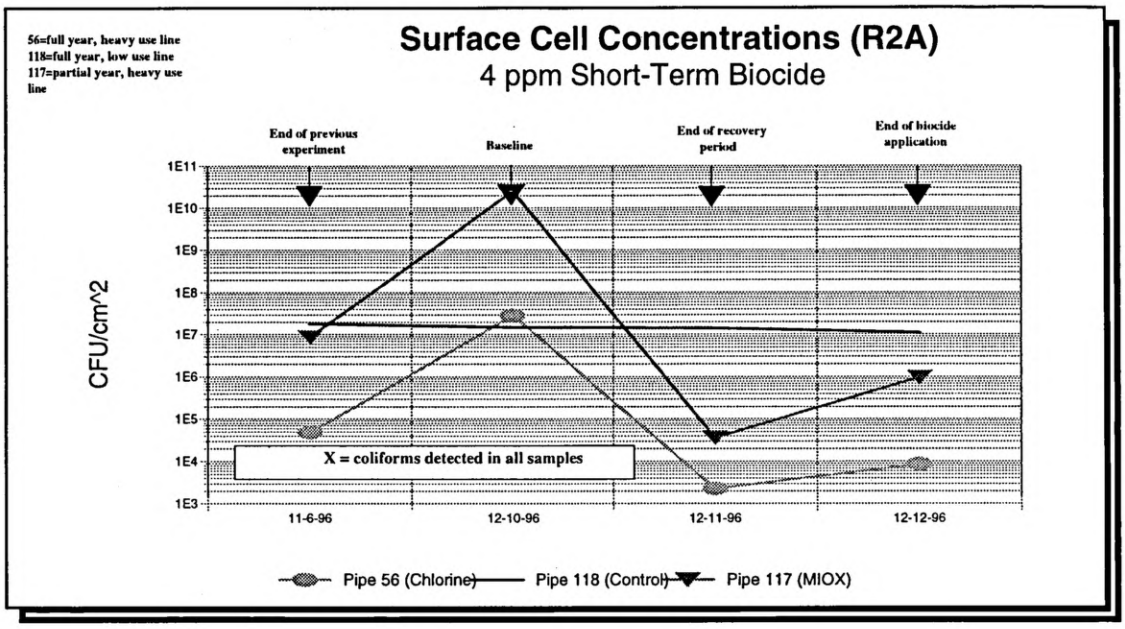


Figure A4. Effects of 4 ppm short-term biocide on active field-grown biofilms (plate counts).



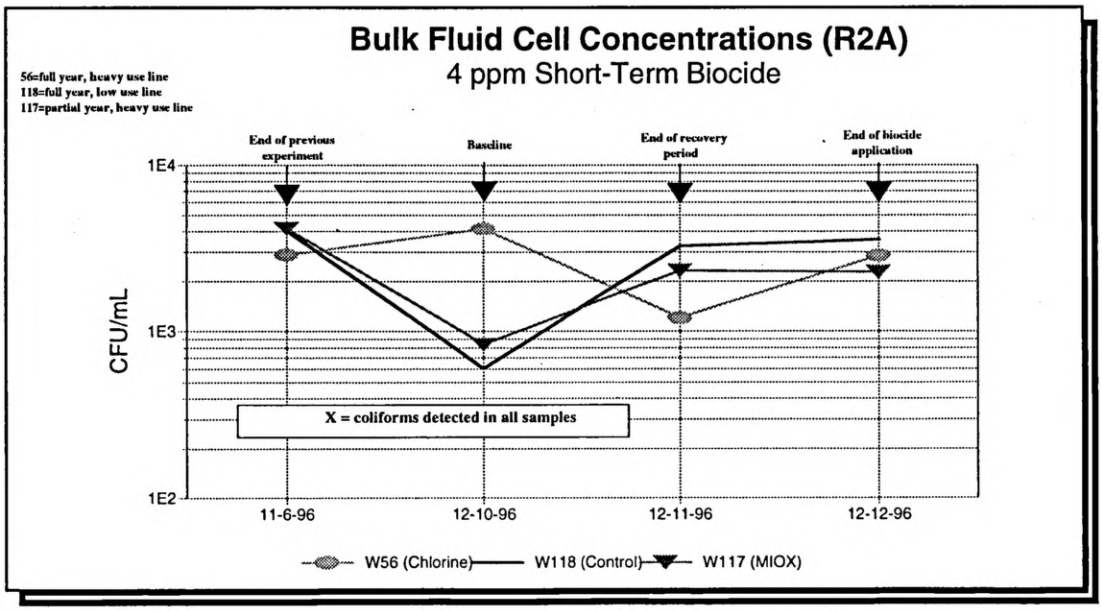
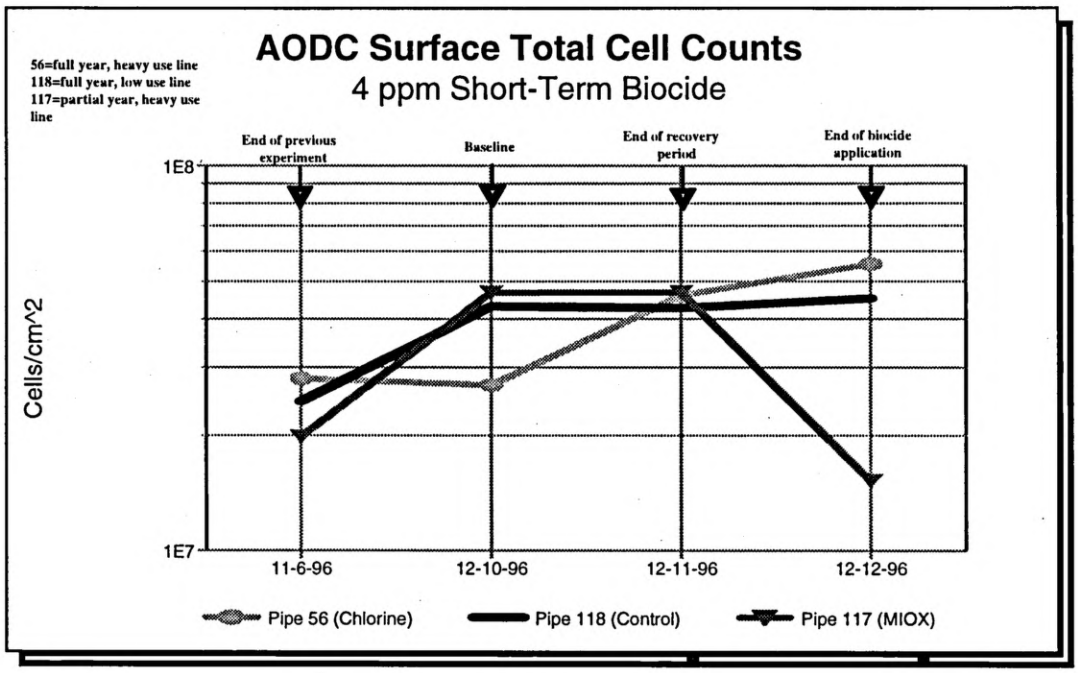


Figure A5. Effects of 4 ppm short-term biocide on active field-grown biofilms (total cell counts).



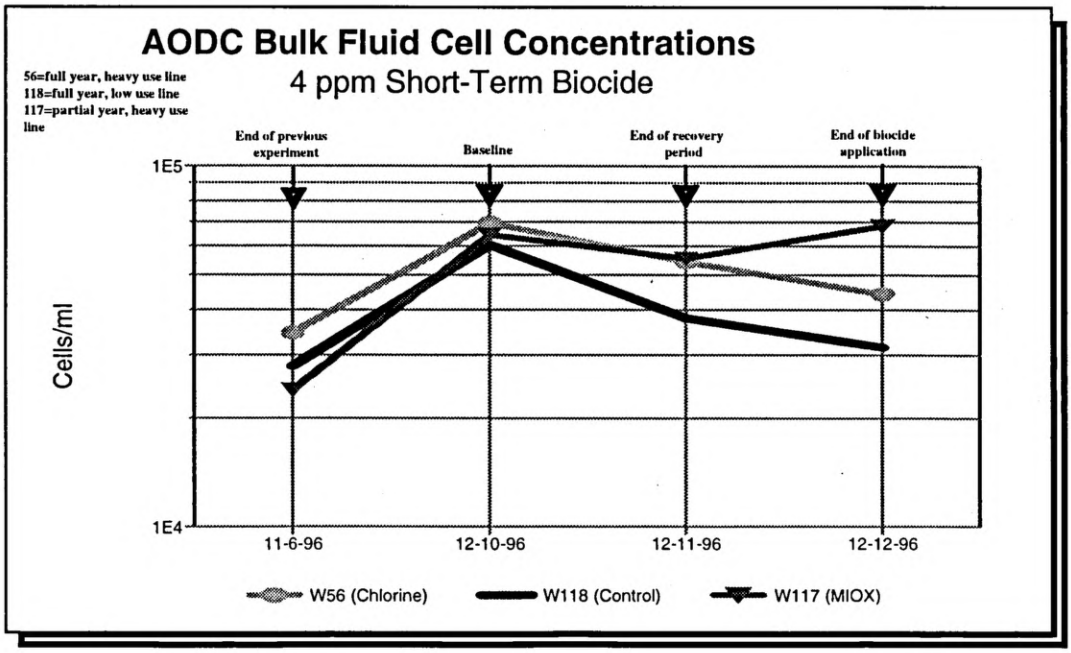
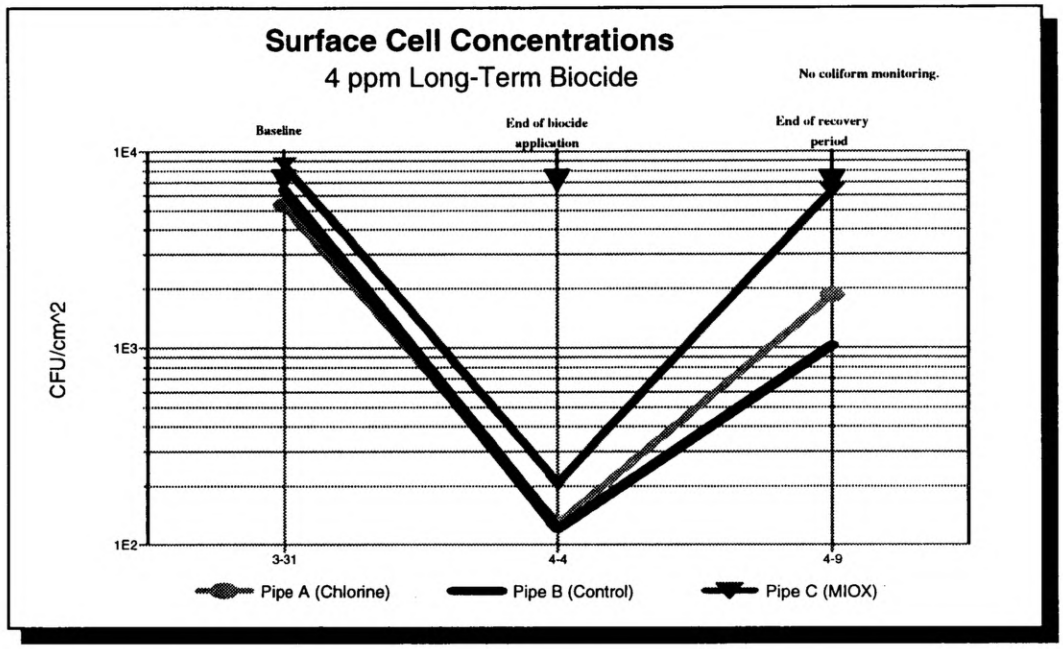


Figure A6. Effects of 4 ppm long-term biocide on lab-grown biofilms (plate counts).



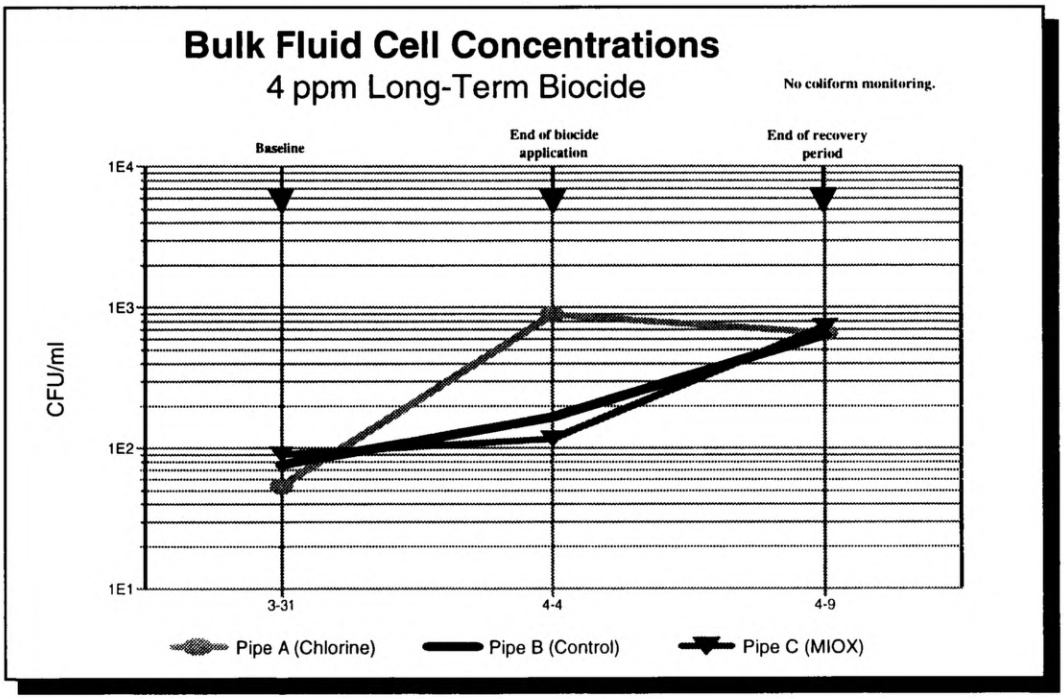
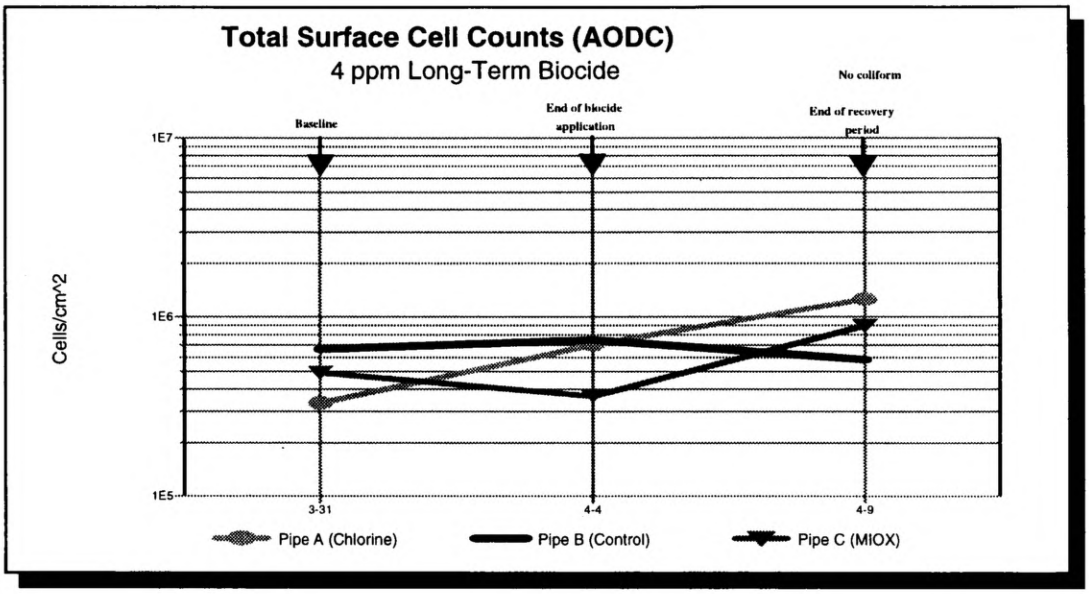


Figure A7. Effects of 4 ppm long-term biocide on lab-grown biofilms (total cell counts).



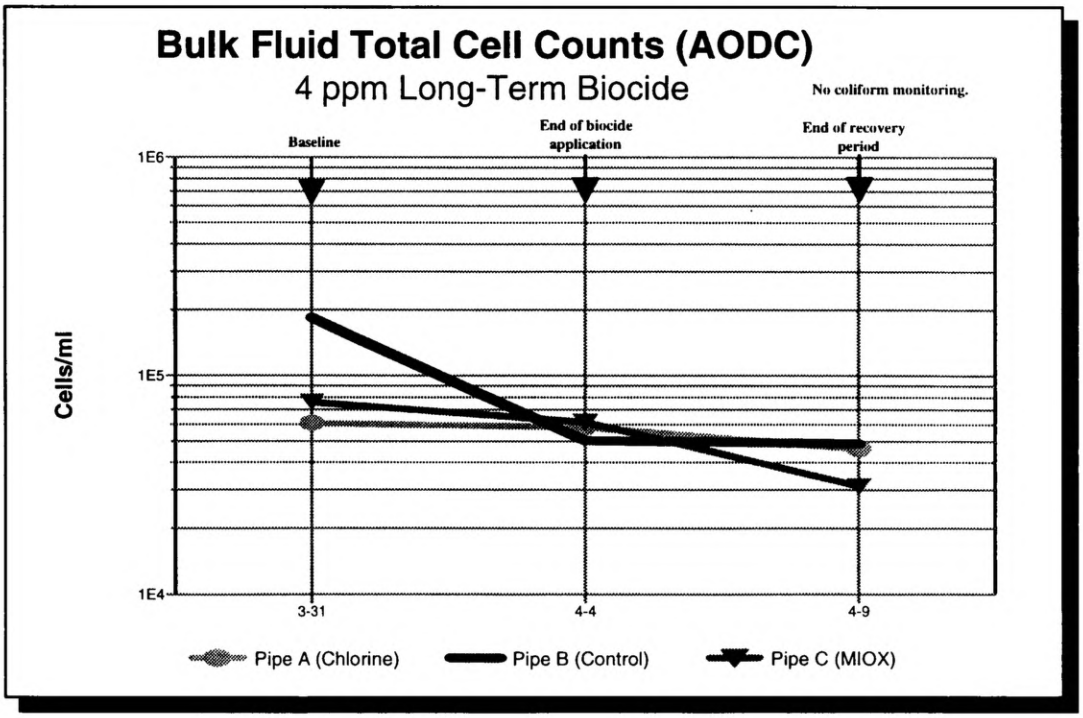
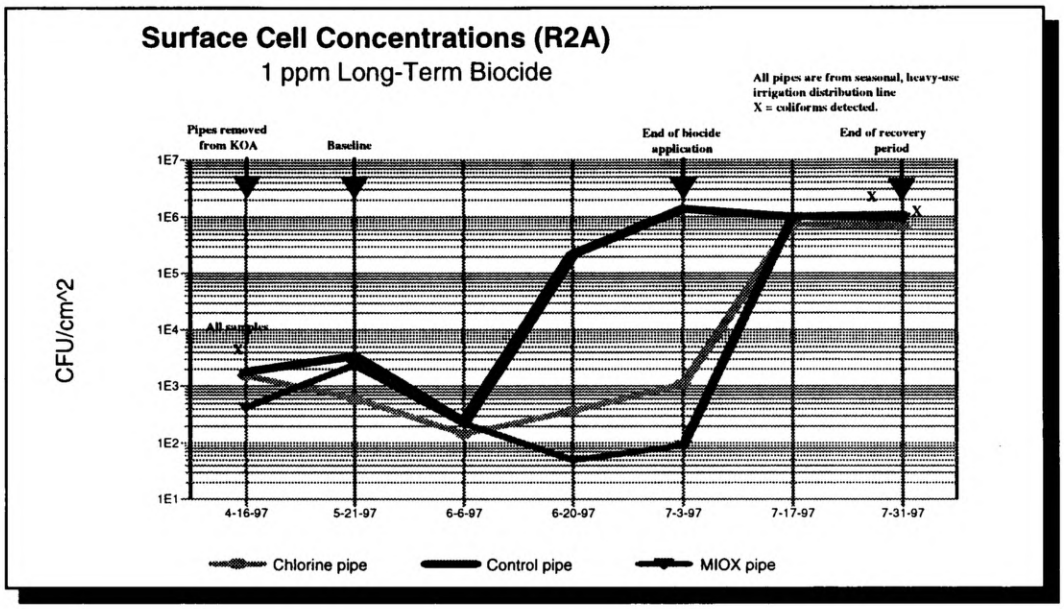


Figure A8. Effects of 1 ppm long-term biocide on initially dormant field-grown biofilms (plate counts).



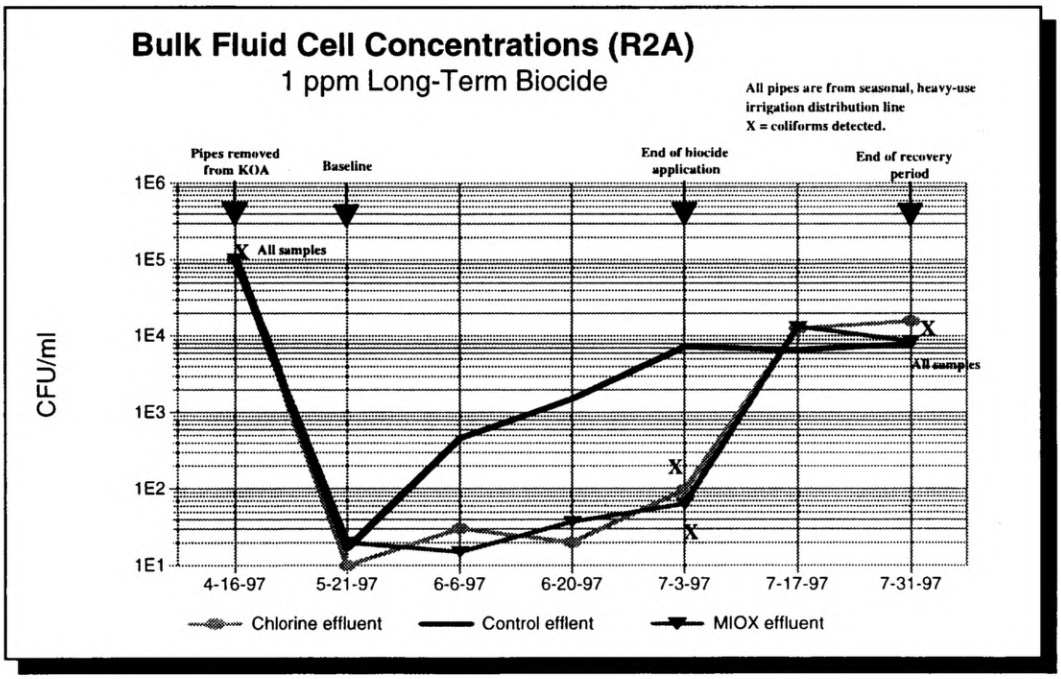
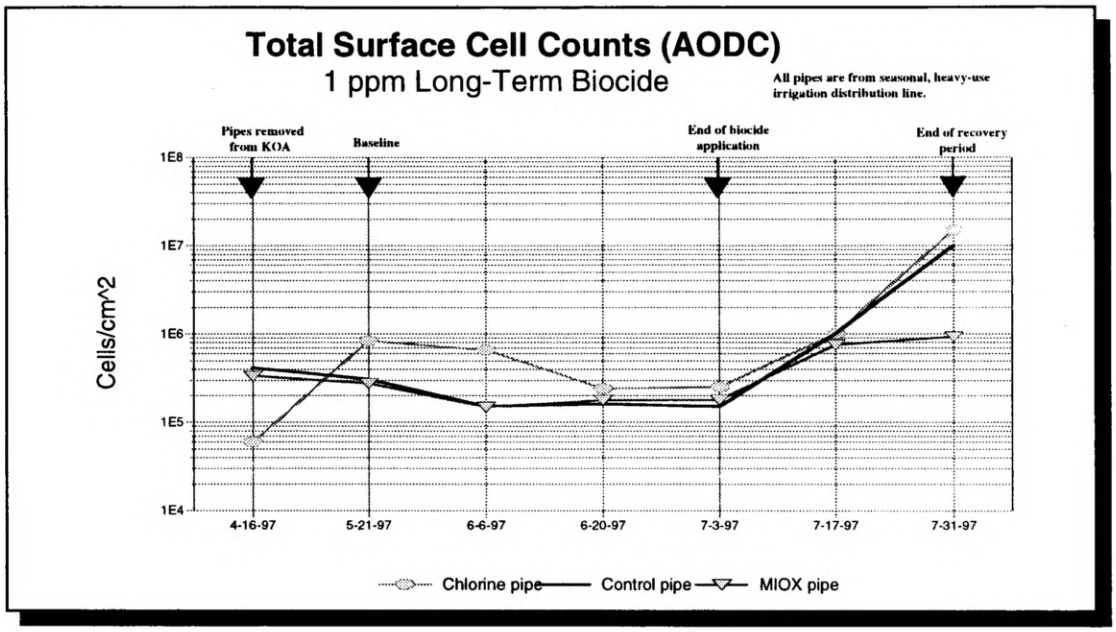
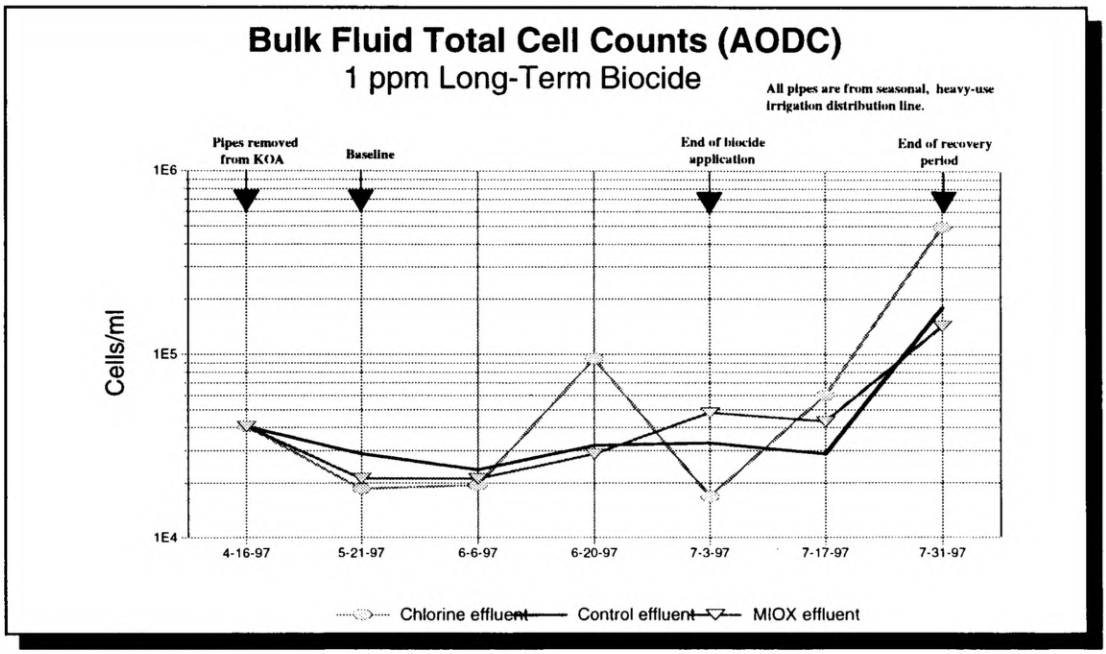


Figure A9. Effects of 1 ppm long-term biocide on initially dormant field-grown biofilms (total cell counts).





APPENDIX B

Annular Reactor Results

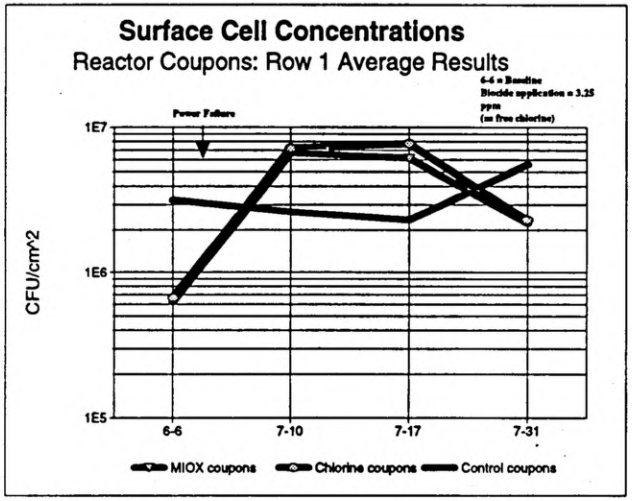
Reactor Map

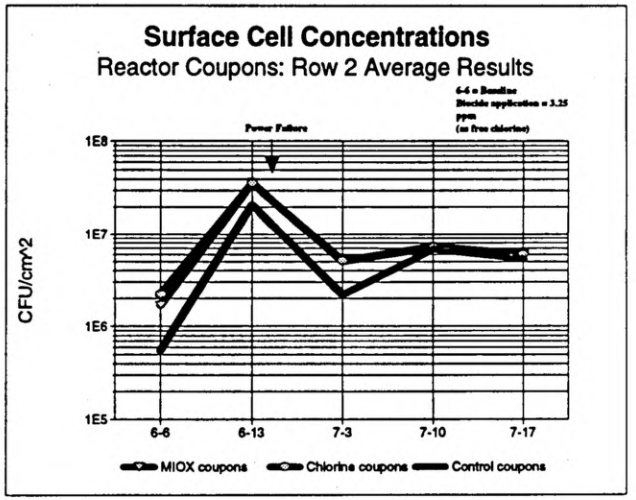
Dates indicate coupon samplings.
Two coupons were sampled on each date.

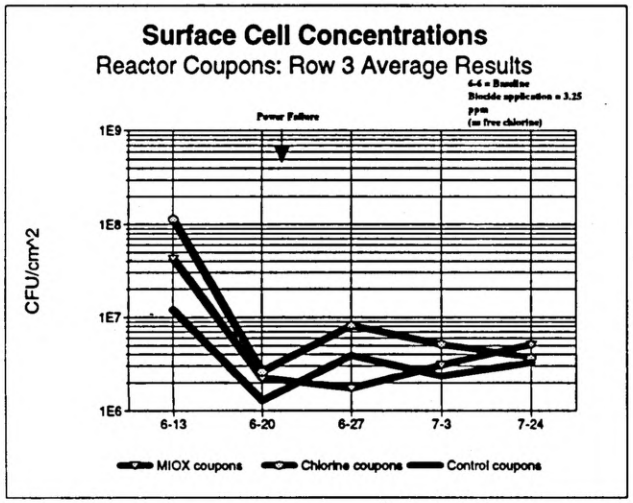
6-6-97	7-17-97	7-10-97	7-31-97	(not sampled)
7-3-97'	6-6-97'	6-13-97	7-10-97'	7-17-97'
7-24-97	7-3-97	6-20-97	6-13-97'	6-27-97'
(not sampled)	6-20-97'	7-24-97'	6-27-97	7-31-97'

Figure B1. Reactor map showing coupon location versus sample date.

Figure B2. Row by row results of coupon surface cell concentrations.







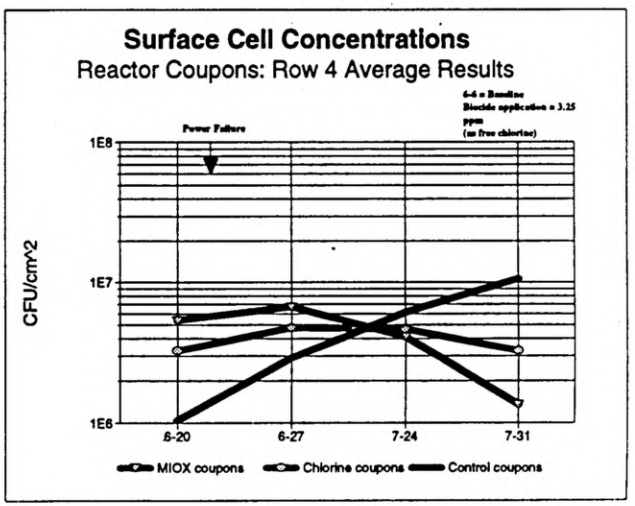


Figure B3. Surface cell concentrations for all coupons sampled.

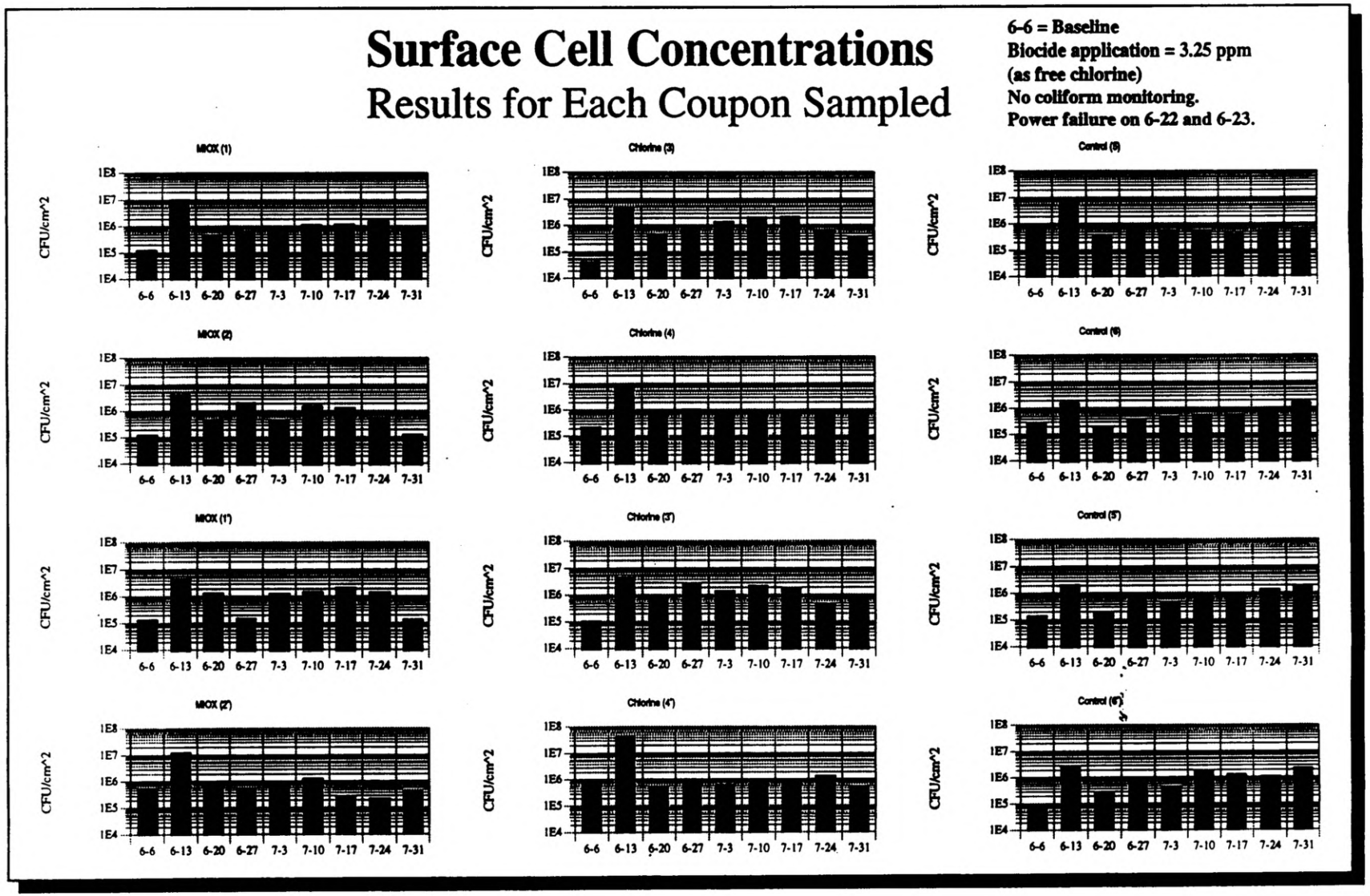


Figure B4. Cell concentrations for bulk fluid of each reactor.

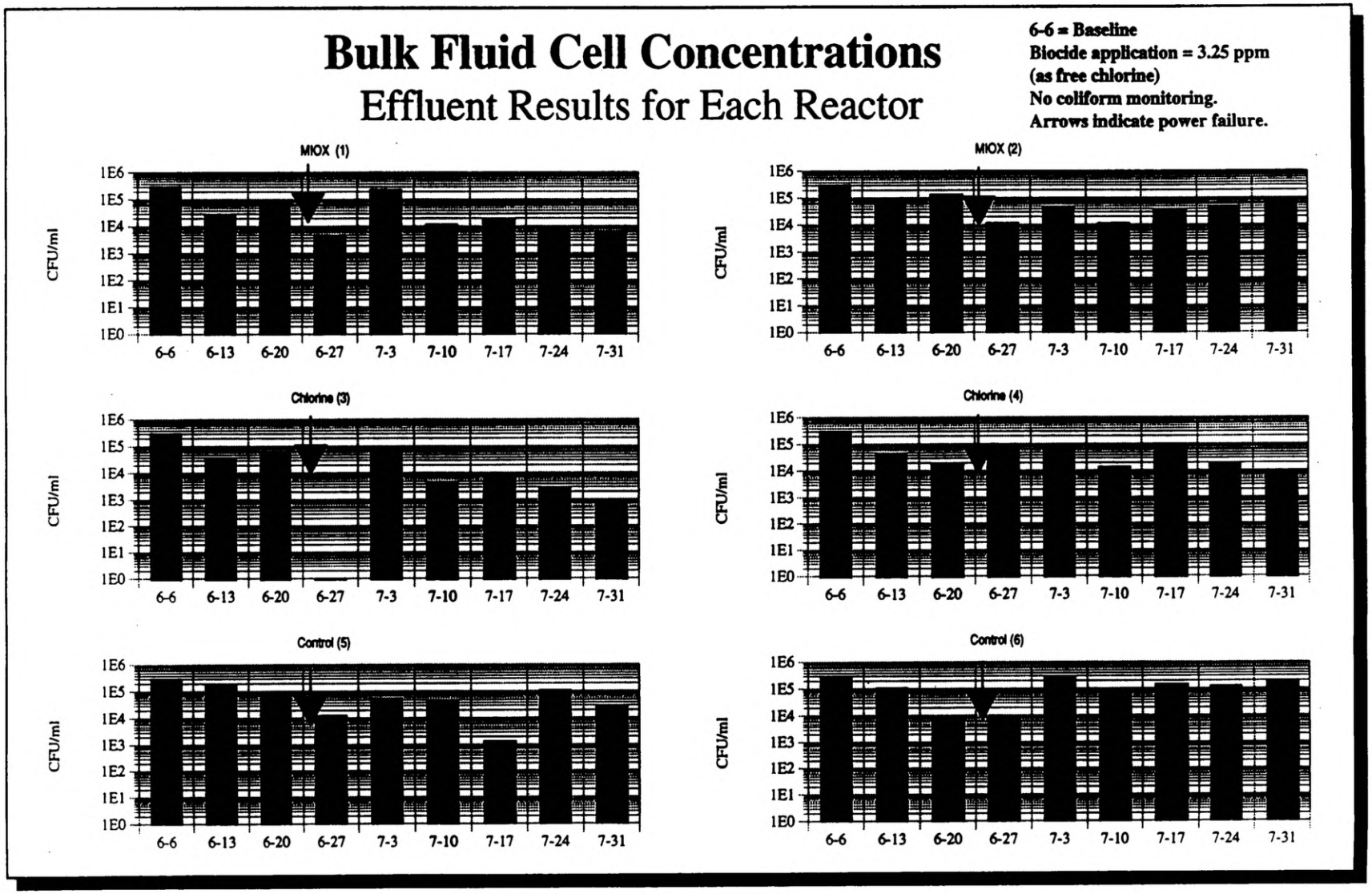
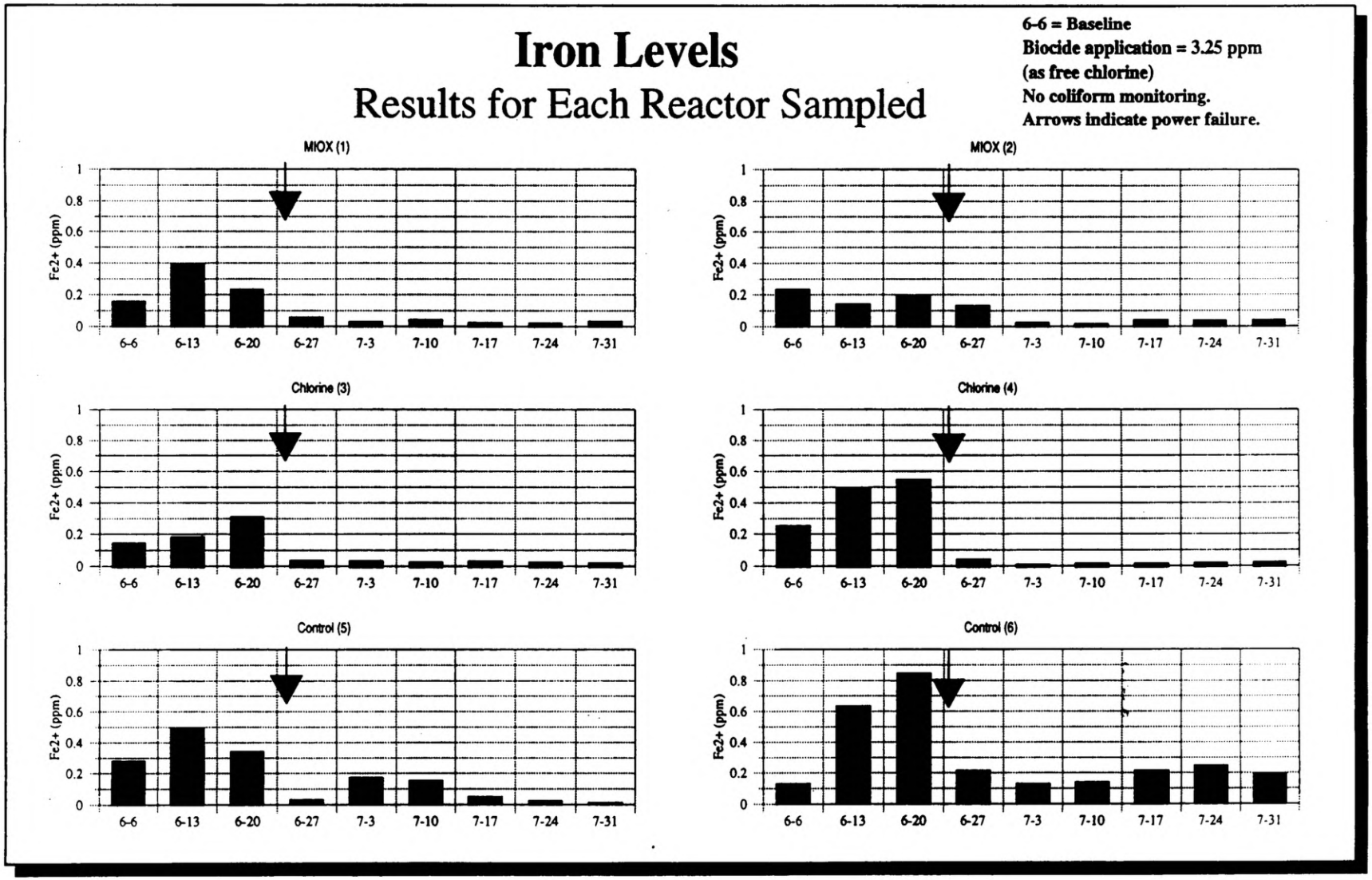


Figure B5. Ferrous iron levels for each reactor.



APPENDIX C

Demonstration Site Results

Weekly Samples from Les at KOA							
200 mL filtered and placed on mT7							
Approximately 100 mL placed in small autoclaved container and tissuemized for 60 seconds							
Plates on indicated dilution tubes				A=main building			
13.5 mL sample and 1.5 mL formalin for direct counts				B=cottage (end)			
AODC counts done on 15 ml (full tube) filtration				C=irrigation line			
		Date		free chlorine in mg/l			
Sample	Date sent	analyzed	Comments	A	B	C	mT7 results
1	10-28-96	10-29-96	no tint				negative
2	11-4-96	11-6-96	no tint				negative
3	11-11-96	11-12-96	no tint				negative
4	11-18-96	11-19-96	ab=slight reddish tint				negative
5	11-25-96	11-26-96	very tiny colonies on B	0.15	0		negative
6	12-2-96	12-4-96	a=reddish; b=not	1.5	0.5		negative
7	12-9-96	12-10-96	a=reddish; b=not	0.5	0		negative
8	12-16-96	12-19-96	a=reddish; b=not	0.5	0		A-neg;B-pos
9	12-23-96	12-26-96	abc=all reddish	0.4	0.25		A-neg;B,C-pos
10	12-30-96	not received	no samples taken				NA
11	1-6-97	1-8-97	ab=both reddish	0.1	0		A-neg;B-pos
12	1-13-97	1-14-97	a=reddish;b=lt.reddish	1	0.5		A-neg;B-pos
13	1-20-97	1-21-97	ab=both reddish	1	0.75		A-neg;B-pos
14	1-27-97	1-28-97	a=reddish;b=lt.reddish				A-neg;B-pos
15	2-4-97	2-5-97	a=reddish;b=very reddish	1	0.1		A-pos;B-pos
16	2-10-97	2-11-97	ab=slight reddish tint	0.85	0.8		A-pos;B-pos
17	2-17-97	2-18-97	ab=very light reddish tint	0.85	0.2		A-pos;B-pos
18	2-24-97	2-25-97	a=reddish;b=very reddish	0.7	0.7		negative
19	3-3-97	3-4-97	a=reddish; b=not	0.8	0.6		A-pos;B-pos
20	3-10-97	3-11-97	a=reddish;b=lt.reddish	0.7	0		negative
21	3-17-97	not received	no samples taken				NA
22	3-24-97	3-25-97	a=lt reddish;b=not	0.8	0.3		A-pos;B-neg
23	3-31-97	4-1-97	ab=slight reddish tint	0.8	0.7		negative

Table C1. Results of weekly sample analyses.

Weekly Samples from Les at KOA							
200 mL filtered and placed on mT7							
Approximately 100 mL placed in small autoclaved container and tissuemized for 60 seconds							
Plates on indicated dilution tubes				A=main building			
13.5 mL sample and 1.5 mL formalin for direct counts				B=cottage (end)			
AODC counts done on 15 ml (full tube) filtration				C=irrigation line			
		Date		free chlorine in mg/l			
Sample	Date sent	analyzed	Comments	A	B	C	mT7 results
24	4-7-97	not received	no samples taken				NA
25	4-14-97	4-15-97	a=lt red;b=very red;c=not				A,B-neg;C-pos
26	4-21-97	4-22-97	a,b,c=slight reddish tint	1	1	0.8	A,B,C-neg
27	4-28-97	4-29-97	a,c=not;b=slight				A,B,C-neg
28	5-5-97	5-6-97	a,c=not;b=slight				A,B,C-neg
29	5-12-97	5-13-97	a,c=not;b=slight	1.1	0.5	0.9	A-neg;B,C-pos
30	5-19-97	not received	pump down				NA
31	5-26-97	5-27-97	a,b,c=not	1.25	0	1.25	A-pos;B,C-neg
32	6-1-97	not received	no samples taken				NA
33	6-8-97	not received	MIOX unit down				NA
34	6-15-97	not received	no samples taken				NA
35	6-22-97	not received	needed label replaced				NA
36	6-29-97	not received	no samples taken				NA
37	7-6-97	not received	no samples taken				NA
38	7-13-97*	7-14-97	abc=all not reddish	0.8	0.1	0.6	A,B,C-neg
39	7-20-97	not received	no samples taken				NA
40	7-27-97*	7-28-97	abc=all not reddish	0.5	0.2	0.5	A,B,C-neg
41							
42							
43	8-19-97**	8-20-97	abc=all not reddish	0.5	0.2	0.5	A,B,C-neg
	*This sample not included in data analysis: not collected acc. to standards						
	**FINAL SAMPLE TAKEN BY C. CRAYTON AT KOA						

Table C1. Results of weekly sample analyses (continued).

	Plate counts			AODC			
	A	B	C	A	B	C	
	graph	graph	graph	graph	graph	graph	dilution used
Sample	values	values	values	values	values	values	for plate counts
1	7933.333	12833.33		21239.77	12176.25		10^-2/10^-2
2	106.6667	156.6667		9292.398	90452.11		10^-1/10^-1
3	1	133.3333		20003.83	30440.61		10^-1/10^-1
4	43.33333	76.66667		60533.33	76507.41		10^-1/10^-1
5	160	2433.333		53807.41	40355.56		10^-1/10^-1
6	90	10133.33		76507.41	263992.6		10^-1/10^-1
7	46.66667	11200		73985.19	62214.81		10^-1/10^-2
8	46.66667	1170		77348.15	362359.3		10^-1/10^-2
9	13.33333	223.3333		31107.41	63896.3		10^-1/10^-1/10^-2
10							
11	993.3333	2420		129474.1	137040.7		10^-1/10^-1
12	220	410		109296.3	40355.56		10^-1/10^-1
13	1450	1443.333		41196.3	56329.63		10^-1/10^-1
14	1333.333	1416.667		86596.3	138722.2		10^-1/10^-1
15	4966.667	2233.333		67259.26	125270.4		10^-2/10^-2
16	6900	12466.67		72303.7	153855.6		10^-2/10^-2
17	8600	16400		165625.9	145448.1		10^-2/10^-2
18	68666.67	2366.667		62214.81	33629.63		10^-3/10^-2
19	52000	8800		35311.11	68100		10^-3/10^-2
20	11133.33	13233.33		67259.26	60533.33		10^-2/10^-2
21							
22	12233.33	28800		84914.81	624670.4		10^-2/10^-2
23	9433.333	10133.33		50444.44	47922.22		10^-2/10^-2

Table C1. Results of weekly sample analyses (continued).

	Plate counts			AODC			
	A	B	C	A	B	C	
	graph	graph	graph	graph	graph	graph	dilution used
Sample	values	values	values	values	values	values	for plate counts
24							
25	200	1166.667	200	72303.7	15133.33	15974.07	10^-1/10^-2/10^-2
26	7300	27266.67	15866.67	54648.15	168148.1	53807.41	10^-2/10^-2/10^-2
27	3433.333	12500	9133.333	30266.67	21018.52	17655.56	10^-2/10^-2/10^-2
28	5433.333	10533.33	6100	628874.1	84074.07	16814.81	10^-2/10^-2/10^-2
29	1533.333	45600	1966.667	23540.74	27744.44	428777.8	10^-2/10^-2/10^-2
30							
31	3033.333	6733.333	5633.333	43718.52	39514.81	76507.41	10^-2/10^-2/10^-2
32							
33							
34							
35							
36							
37							
38							
39							
40							
41							
42							
43**	3666.667	9300	5266.667	51285.19	44559.26	52125.93	10^-2/10^-2/10^-2
**FINAL SAMPLE TAKEN BY C. CRAYTON AT KOA							

Table C1. Results of weekly sample analyses (continued).

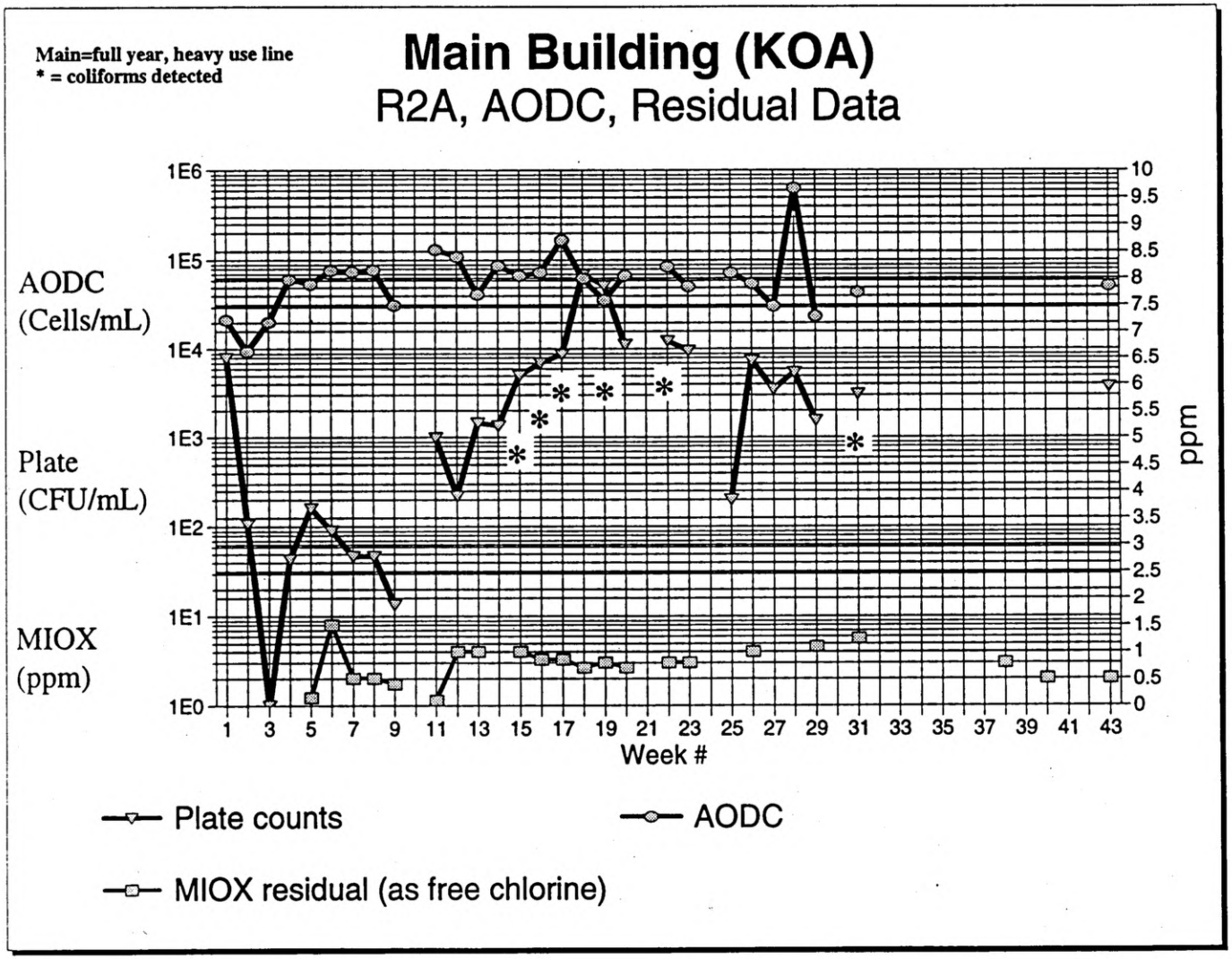


Figure C1. Weekly sample results: main building, KOA site.

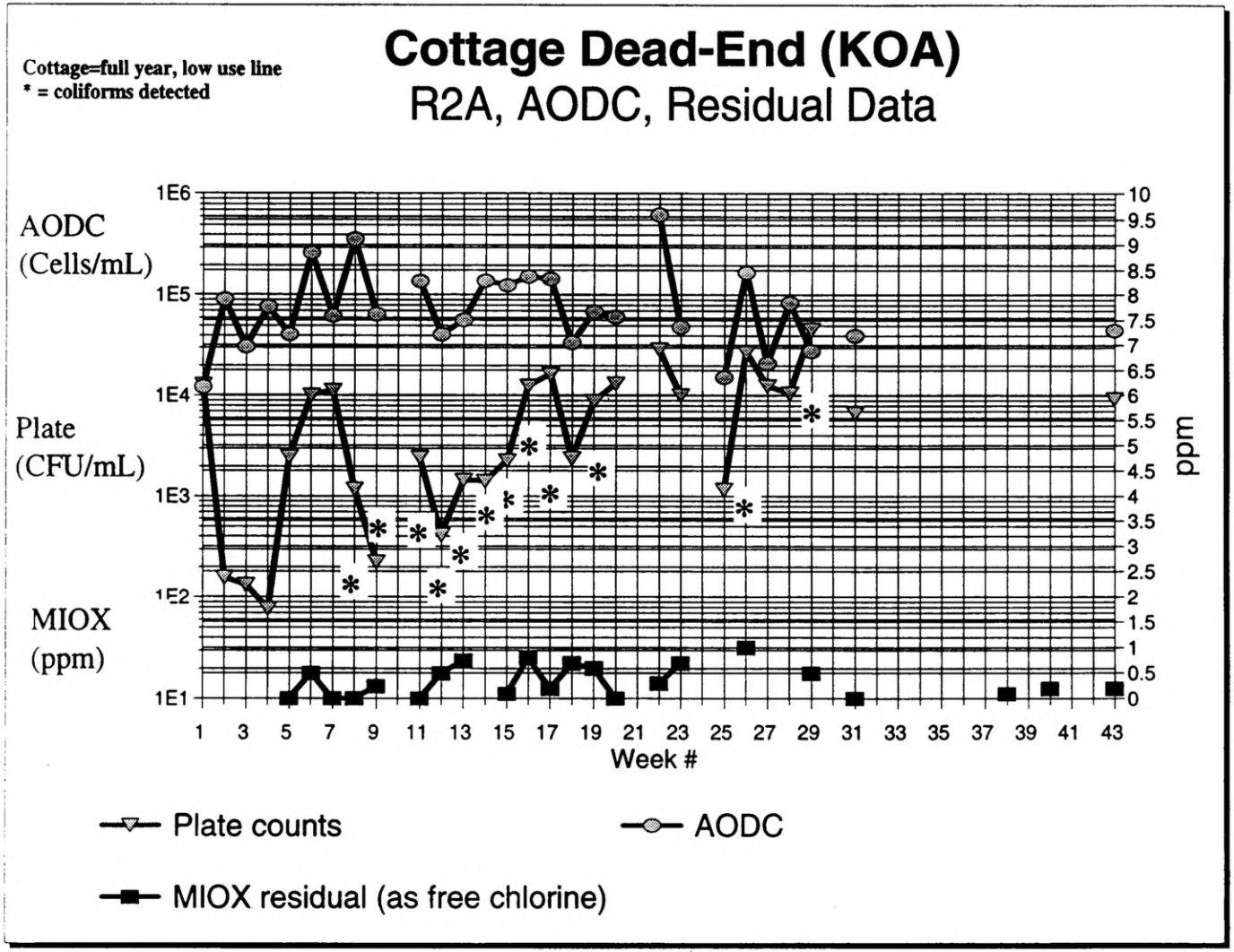


Figure C2. Weekly sample results: cottage dead-end, KOA site.

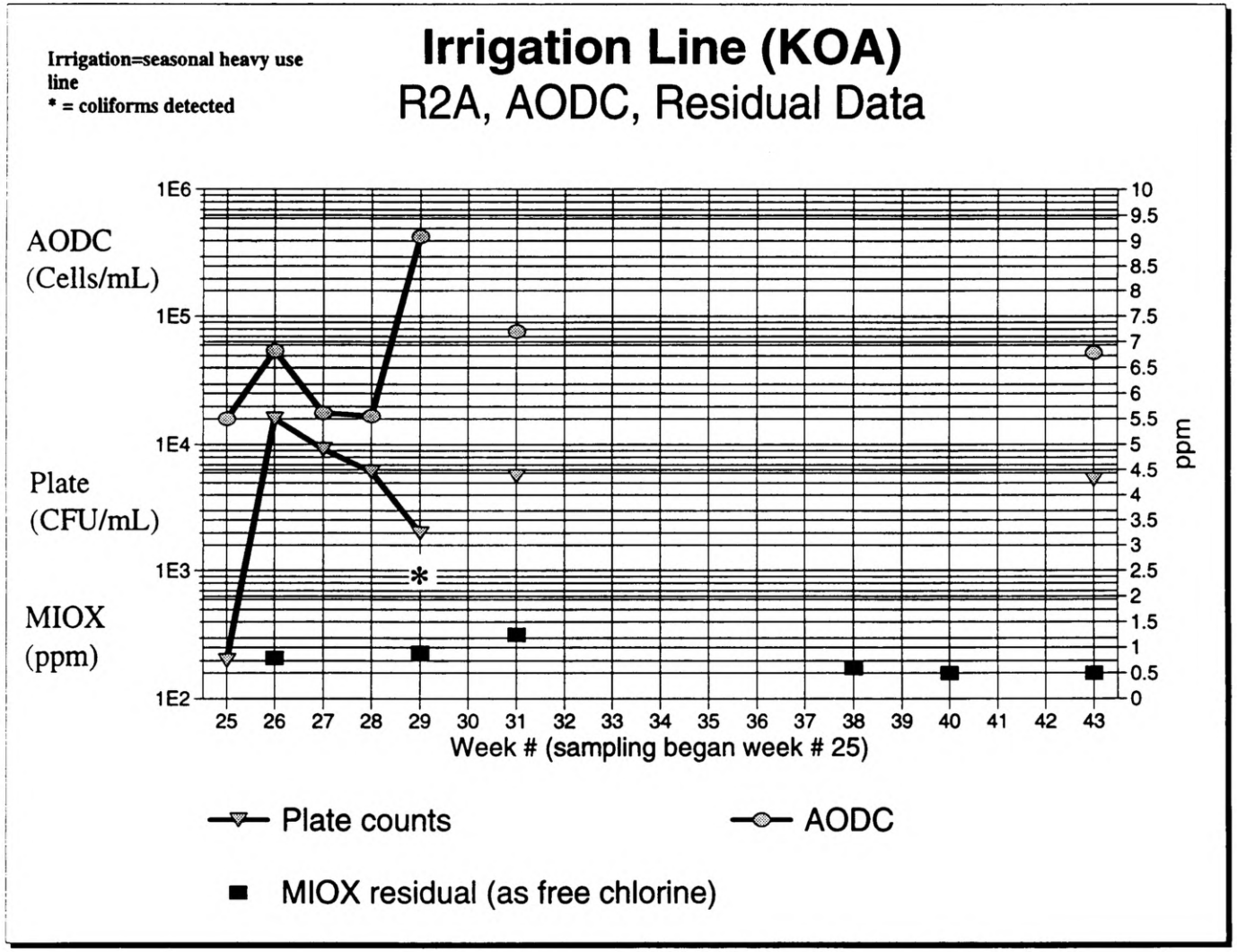


Figure C3. Weekly sample results: irrigation line, KOA site.

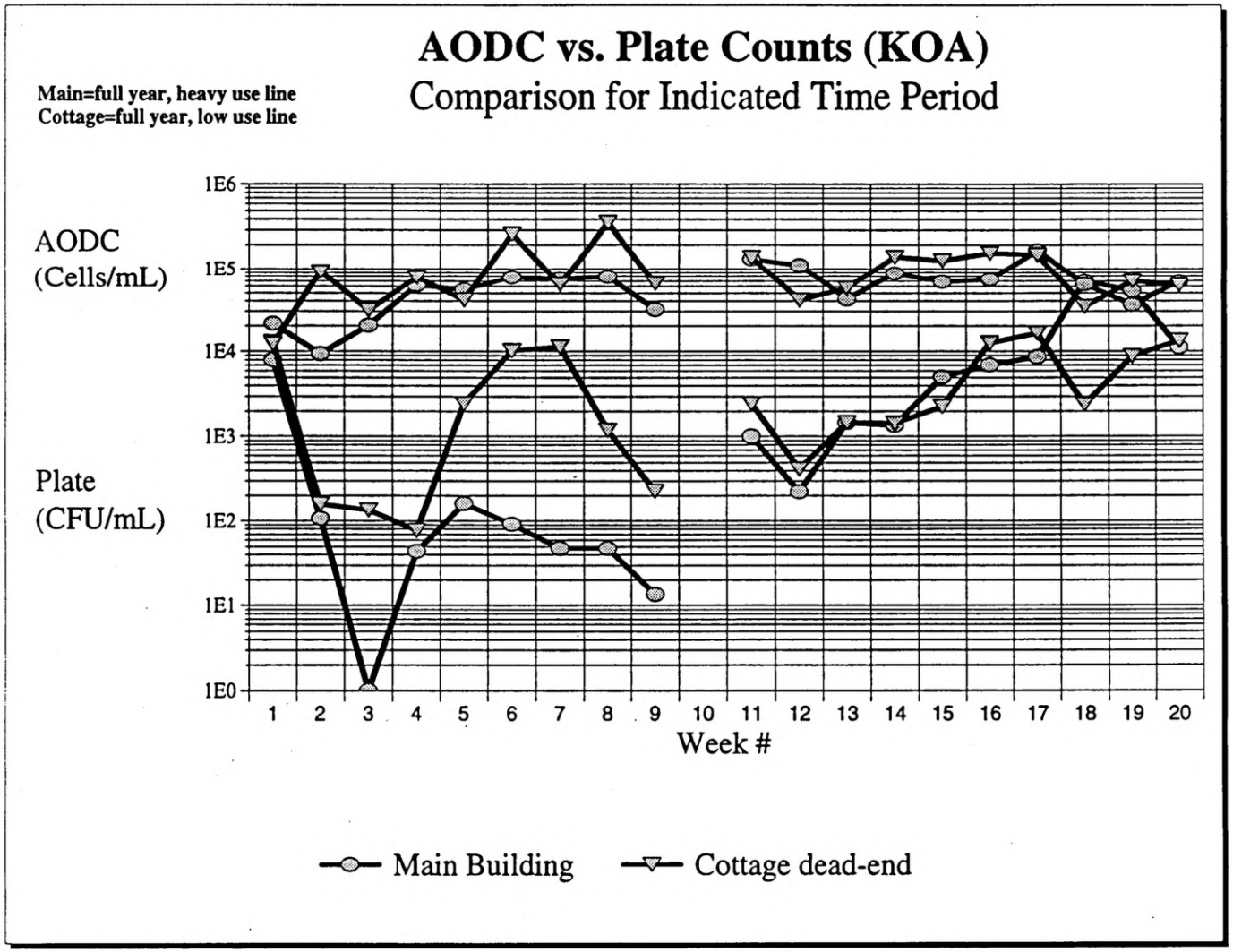


Figure C4. Comparison of sample sites for initial five months.

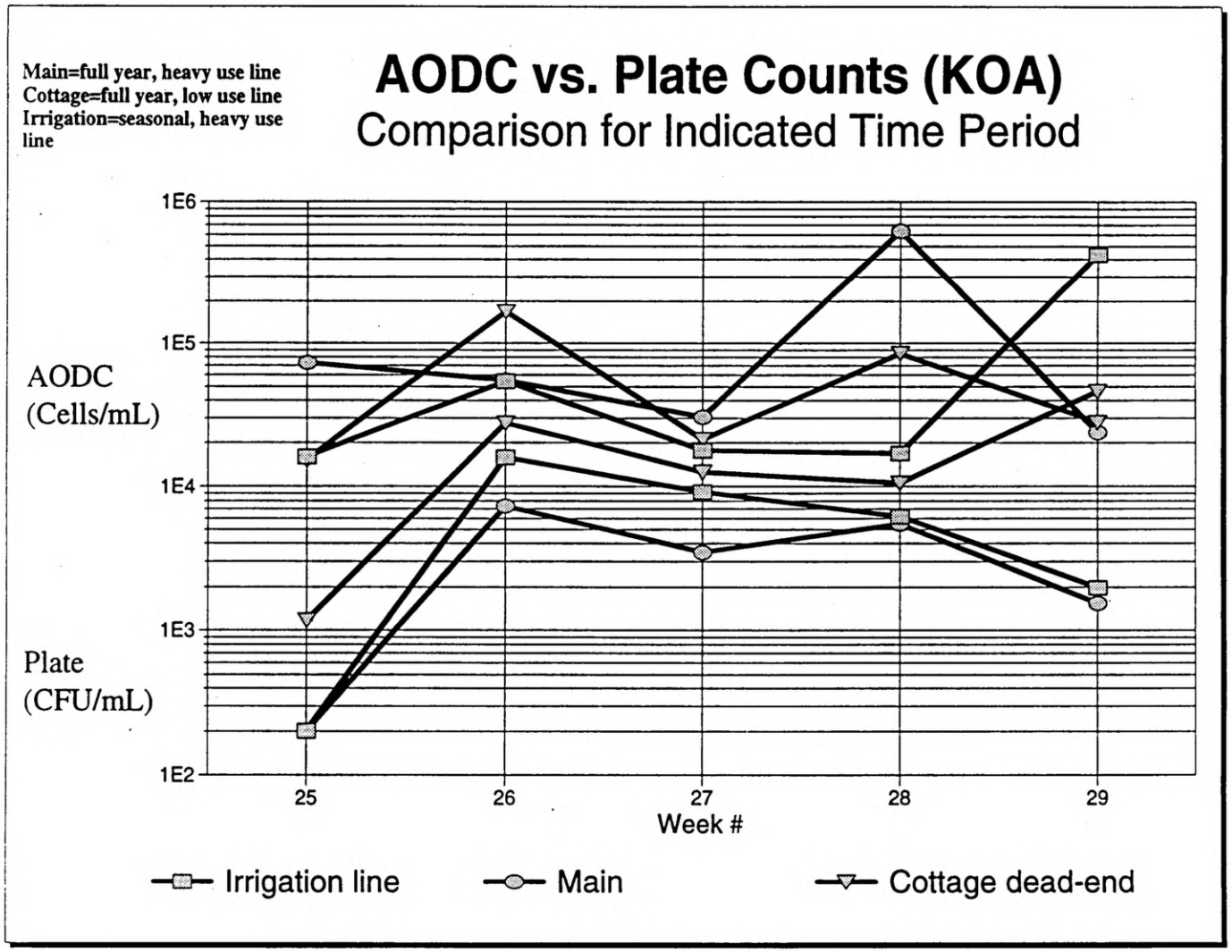


Figure C5. Comparison of all sample sites for weeks 25-29.

APPENDIX D

Initial 24-Hour Sampling Results

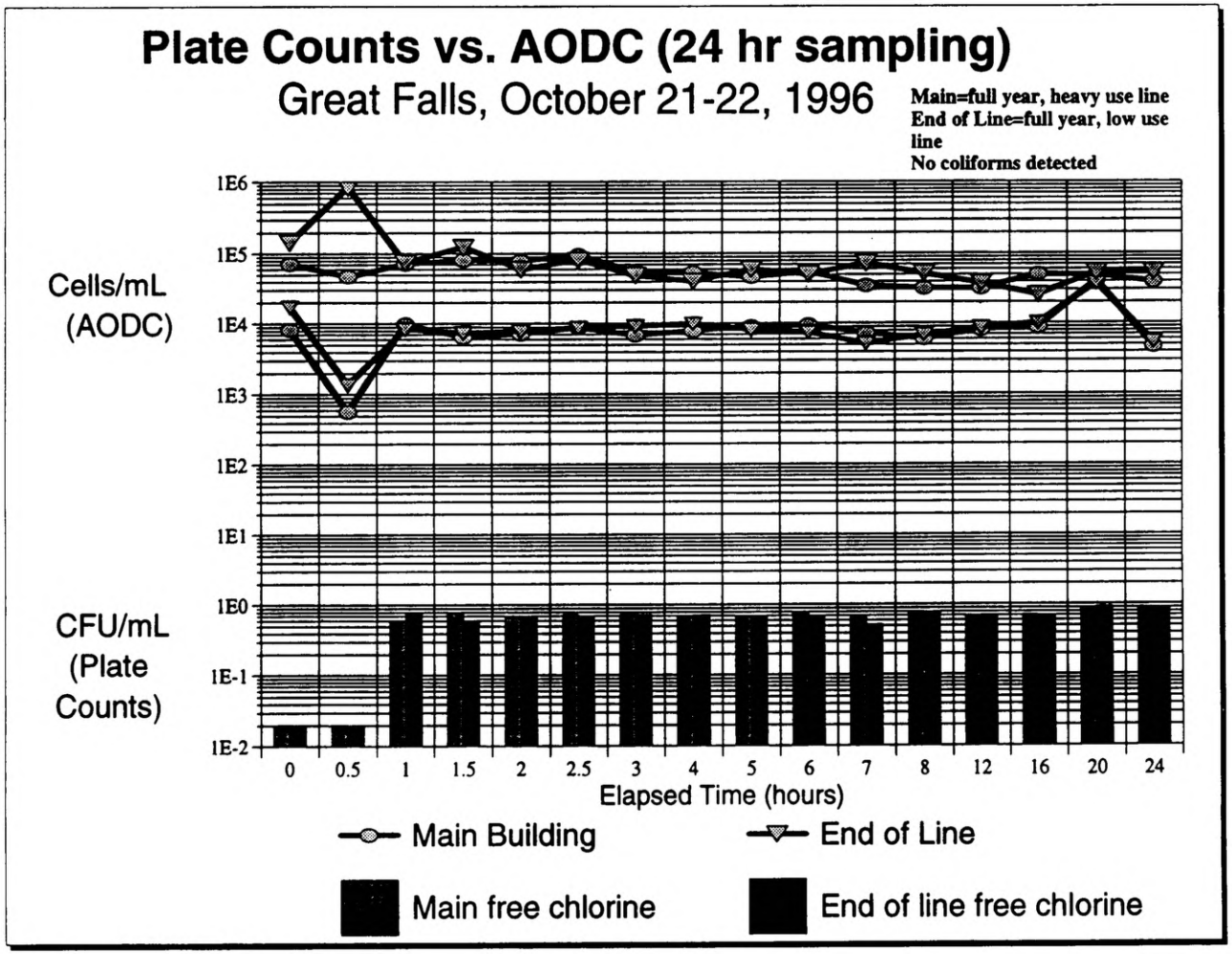


Figure D1. Initial effects on active biofilms (first 24 hour sampling).

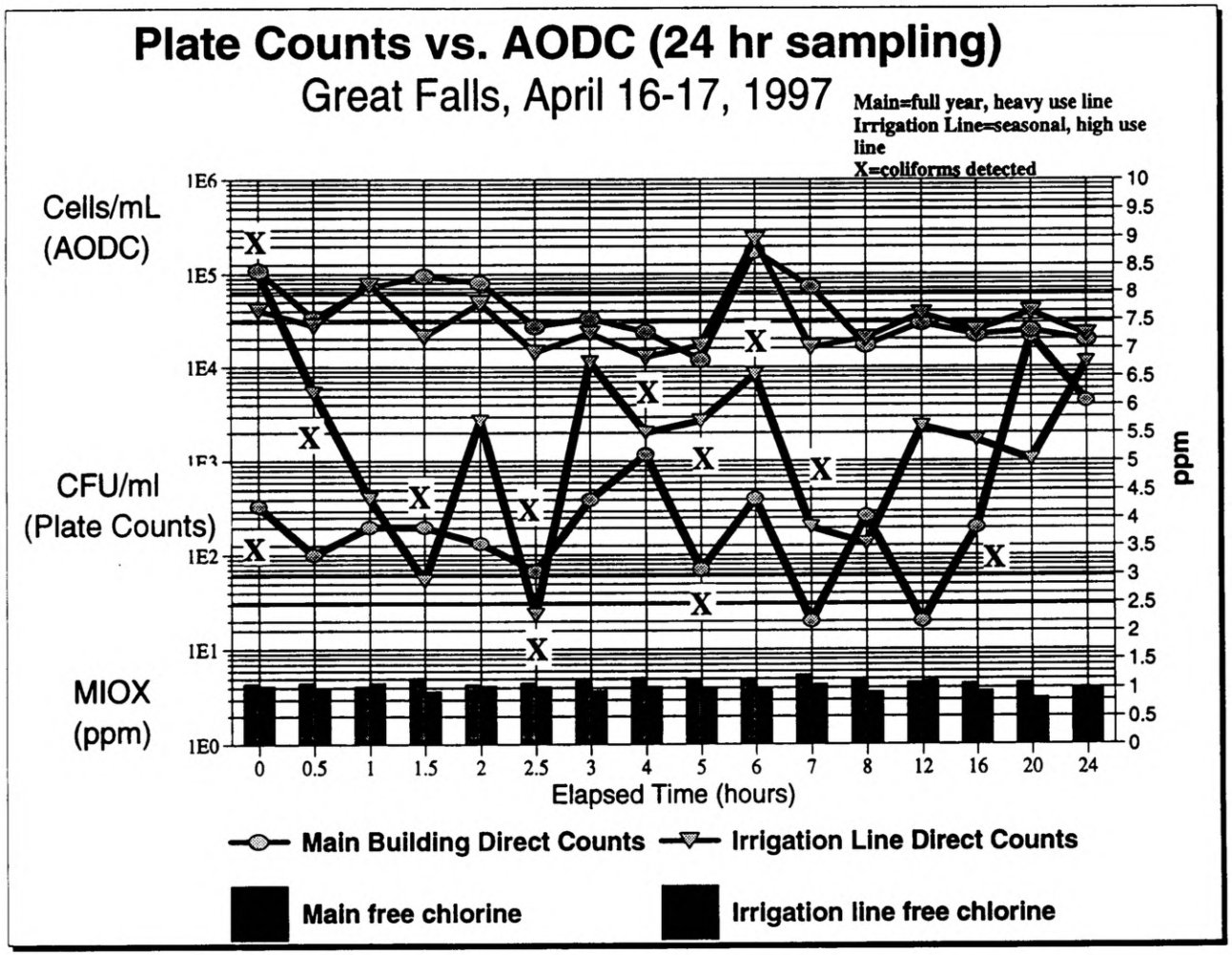


Figure D2. Initial effects on dormant biofilms (irrigation line) and active biofilms (main building): second 24 hour sampling.

APPENDIX E

Exit Interview

Exit Interview

This Appendix presents the information acquired from the exit interview in its entirety.

Coliform compliance:

- before MIOX: after sporadic positive samples 4 years ago, packed chlorine (as powdered sodium hypochlorite) in filters every two weeks; after a boil order was posted 3 years ago, up to 1000 ppm put into lines, but still had problems.
- after MIOX: not a single positive sample.

Overall impression of operational ease:

MIOX vs. Chlorine: Initially, no real chlorine system in place--packed filters every two weeks, throttled back flow valves. This provided better residual over 24 hr period than slug dosing with liquid bleach. Very labor intensive compared to MIOX. Disinfectant concentrations easy to control in both systems, but MIOX requires less hands-on and goes into solution much easier. When MIOX unit was down, it was easier to add powdered sodium hypochlorite to water than before since could use MIOX tank and venturi to inject.

Advantages of MIOX over Chlorine:

non-toxic solution; no chlorine smell; no corrosive off-gassing that can destroy equipment--cost of redoing electrical equipment in control room would be $4000-$5000; integrates easily with other disinfection system; much less labor intensive--easier to work with; very responsive to manipulation of injection stream and generation of solution; unlike chlorine systems, unit can be sited anywhere--next to offices or other populated areas.

Problems/drawbacks/disadvantages of Chlorine:

Powdered chlorine does not dissolve completely--granules remain in the slurry solution. Requires very frequent cleaning and constant monitoring. A clog caused the backflow preventer on the injector to malfunction and disinfectant tank emptied onto floor--very toxic mess to clean up. No advantages of liquid or powdered chlorine over MIOX system perceived at all.

Problems/drawbacks/disadvantages of MIOX:

Potential for scaling is a problem requiring careful and consistent monitoring, frequent cleaning, and experimentation with water softener settings. An alarm system would be very helpful in correcting potential problems before they escalate. Unit must be situated in an area where it can be easily gotten to for maintenance and monitoring.

Computer needs a self-check/self-monitoring option so that an automatic restart capability exists. Unit goes into fault mode when system pressure drops below 25 psi. Restart option would get unit back on line after short fluctuations in system water pressure. Injector system needed revision to work efficiently at KOA. A venturi injector with a bypass was installed to more effectively deal with varying pressures and disinfectant requirements. On the MIOX unit, a booster pump with an injector or an injector pump would be preferable to the existing set-up. For the KOA's requirements, a 1/2 hp brine pump would be more efficient than the 3/4 pump on their SAL40 unit. The water softening system may require adjustment of salts to prevent excess scaling of MIOX unit orifices.

Effects of MIOX on:

- filters: Main filter cleaned up (biofouling removed) immediately after MIOX unit put on line; corrosion product deposition removed, but permanent rust staining on porous pipe material not affected. Prior to MIOX (with or without chlorine dosing), all filters required cleaning every 2-3 days. After MIOX unit put on line, filters required cleaning at the same rate for the first couple of weeks, and then cleaning times decreased to every 3 weeks. Frequency now at every 3-4 weeks, and pressure loss across bath filters, for example, is only 3 pounds (much less than at cleaning time before MIOX). Cleaning is now considered more routine maintenance than an operational necessity.
- pipes: Three months after MIOX unit put on line for all new water park (contact water disinfection), PVC pipe was free from deposition of corrosion products from well casing. All other pipes removed for sampling or repair had substantial deposits of corrosion products. After two seasons of water park operation and a dormant winter season, a visual inspection of pipes revealed no visually detectable accumulation of corrosion products or biofilms. Corrosion products seemed to have been removed from older PVC pipes and deposition on new PVC pipes was essentially prevented. Irrigation lines initially required cleaning of all emitters and drippers, but are now exhibiting better pressure and less clogging than before using MIOX.
- water pressure: Two years ago, when pressure was frequently lost during power outages caused by repeated fuse blowing (electrical problem now corrected), flushing of the distribution system was always required--sloughing of biofouling was induced and caused very orange water in all areas of the campground (toilets, showers, sinks, filters, etc.). Camper satisfaction was compromised. A recent loss of pressure this summer created no such problems--all water was clear, no flushing required, no camper complaints. An increase in water pressure (faster fill times for tub and sinks and better pressure in the shower) was observed at the campground manager's residence following a short sloughing period (reddish water when first turned on, clearing after short run).
- water quality: During periods of chlorine dosing, there were complaints of chlorine taste/odor. At 1 ppm of MIOX, there is a slight chlorine taste, but no

consumer complaints and never as much chlorine taste as with previous disinfection methods. Injected levels and residuals are now at 0.5 to 0.7 ppm, with no detectable taste or odor.

- water park operation: There have been comments, never a complaint, that the water in the water park/spa area seems salty. This is because the MIOX waste stream is put into the disinfected pool area water stream. All the water evaporates fairly quickly leading to a sodium build-up. No cleaning of this excess sodium has been required yet. The pool is a shallow pool, so there is no volume reserve of disinfectant available. The short recirculation time (1 hr compared to 6-8 for a conventional pool) along with very heavy usage requires that the pool be dosed continuously with the MIOX solution. To maintain the 2-3 ppm required chlorine concentration, powdered sodium hypochlorite is added 1-2 times per day. Installing a larger disinfectant reservoir tank and adding a parallel injector to the MIOX system would eliminate this need for extra dosing.
- shower/bathroom areas: Mold and black slime in these areas appears to be less than before MIOX usage.
- kitchen areas: No specific effects observed. A dilution (50%) of the MIOX solution is used for sanitation in camper kitchen areas, eliminating the need for liquid bleach use (less chlorine smell).
- pump, well, pressure tanks: no problems
- winter vs. summer operation: Essentially no difference in seasonal operation except for the amount of salt used. One 50 pound bag/day is max in summer. The well is deep and the control room well-insulated, so operational temperature is quite constant seasonally. Due to periods of very low use last winter, residual levels at end-of-line points was hard to maintain. Flushing was required to ensure adequate disinfectant residual. During summer, water use is high enough that the residual levels are essentially the same as the injected levels of chlorine.
- power use/requirements: With 8 pool pumps and 6 long rows of electrical outlets (at more than 100 separate campsites), a typical summer monthly power bill can be $3000. Even though the MIOX generator may run up to 20 hours per day in the summer, its power usage is negligible comparatively. During the winter, average monthly use is only 16 hours.

Ease of obtaining technical assistance, replacement parts, advice:

Good advice on all aspects of operation and installation available on phone. Next day service on all parts needed. Staff always willing and able to help.

MIOX unit downtime:

- backup system used: Powdered sodium hypochlorite mixed in MIOX and tank and injected with existing venturi.
- amount of downtime: Only 1 week total since July 1, 1996. Well, pump, pipeline, etc., (non-MIOX related) problems caused as much or more down-time.
- comparable to expected downtime for chlorination? Potential for downtime of

system due to clogging of back-flow prevention valve by undissolved powdered sodium hypochlorite is greater than expected downtime for MIOX unit if properly maintained.

Observed effects of corrosion by MIOX:

Must have no metal in contact with the MIOX solution in the undiluted form--use only PVC piping. The stainless steel surfaces on the float gage corrodes very easily. Regular maintenance now includes thorough cleaning of the gage at least monthly. MIOX cleaned up corrosional products previously deposited on filters and visible surfaces of pipes, but did not affect rust stains on these surfaces. Since MIOX solution is delivered to the water after pumping form the well, no additional corrosion of well casing is expected. MIOX obviously has removed corrosion products from older PVC pipes and seems to have prevented the deposition of corrosion products on new PVC pipe surfaces.

Operational Costs:

- average flow rates to be treated: In summer (peak season), flow is approximately 100,000 gallons per day serving an average of 300 people. Winter usage drops to approximately 200-1000 gallons per day serving and average of 10 people.
- amount of salt used: One 50 lb. bag per day maximum
- cost of salt: Actual cost is $2.79 per bag. Salt is readily available at a local supplier. Salt is picked up at supplier during regular errand runs, requiring no extra delivery costs. Bags are stored in close proximity to MIOX unit (no special storage considerations) for ease of operation.
- training time: Very limited requirement or investment of hours/cost per person. Training areas include orifice maintenance (which orifices to clean, how to clean, and which cleaners to use), fault mode checks (what to check if unit is in fault mode, how to hit restart, or which systems to turn off to raise pressure) and salt addition.
- monitoring costs: Only a small colorimetric chlorine testing kit is required for monitoring of chlorine levels. Regular maintenance schedules for chlorine concentrations, scaling of orifices, etc., require minimal time. Monitoring of the water softening system that pretreats water may be necessary to prevent excess scaling of the MIOX orifices.
- filters: Replacement and cleaning time are at a minimum now--much less required than before MIOX--a labor costs savings over previous disinfection method.
- power requirements, pressure losses: No real difference in power usage before and after MIOX installation. The unit generates an adequate disinfectant solution at the average rate of 15-16 gal/hr. It operates 16 hr/month in the off-season, and 16 hr/day during peak campground season. MIOX operation has no noticeable effect on the operation of other related systems or their water pressures. There are only minute pressure losses across the saddle taps. For this system, a venturi injector with bypass is a more effective delivery system than the standard injector on the MIOX unit--provides better, more controllable operation for varying flow

rates/pressures.

Concentrations of MIOX:

- initial level: Injected at 1 ppm for all water use. Residual levels were low due to high demand in distribution system at first. Bumped injected levels occasionally to try to maintain a 0.2 ppm residual at end of lines.
- subsequent levels: 1 ppm was not adequate to prevent the growth of algae in the pool/spa area, so injected levels into that system was increased to 2-3 ppm. No algae growth is occurring now. Need to install another injector in parallel with existing one to handle higher peak demands. Need a larger brine reservoir tank to be able to eliminate the need for addition of extra doses of powdered sodium hypochlorite to maintain residual during peak use times. After removal of biofouling from distribution system, the injected concentration of MIOX solution was reduced to 0.7 ppm. The current residuals this summer are holding steady at 0.5 to 0.7 ppm.
- system observations: The system is very responsive to the "tweaking" of the chlorine concentrations. During periods of regular to high usage, it takes about 1 hour for disinfectant to reach end points of system. During periods of low usage, flushing of the system was required to get disinfectant to all points. Regular flushing will become a routine during the off-season.

Adequacy of present system:

The MIOX unit is currently producing 15-16 gal/hr of disinfectant solution. Since its operational capacity is 20-30 gal/hr, there is adequate potential for all anticipated system expansion. As previously indicated, the addition of another injector and a larger brine reservoir tank are being seriously considered.

The campground manager is satisfied with the system and has no plans for changing to another method of disinfection.

Employee comments, complaints, observations:

The employee responsible for the cleaning of all filters is quite satisfied with the improvement (reduced maintenance requirements) exhibited by MIOX. He is now cleaning filters every 3-4 weeks as compared to every other day before MIOX. He has observed an increase in water pressure (as large as 10 psi) and more consistent flow throughout the system since the pipes have been "cleaned out" by MIOX. He has heard no complaints from the campers concerning the taste or odor of the water. During dosing of the system with sodium hypochlorite, there were always complaints of chlorinous taste and odor. The water in the bathrooms is now clean whenever pressure in the system is regained following a pressure loss. Previously (before MIOX), he had to do substantial cleaning of all fixtures.

Overall impression of operational efficiency:

KOA staff is very satisfied with MIOX operational efficiency.

Overall satisfaction with system:

Staff and campers are satisfied.

Recommendations/suggestions to new users:

- Access to the unit for addition of salt, maintenance, and monitoring is the main issue. Be sure to site the unit in a location to provide ease of use. Installing the unit in an area that is "well-populated" by staff will allow more consistent monitoring.
- Pipe the MIOX solution to the well, not the other way around.
- Store the salt with the unit.
- Watch the pressure carefully for drops leading to unit fault mode. Ask for computer to be programmed to restart automatically and to provide an automatic self-check mode, if possible.
- Install or request an alarm system to advise of fault mode or other system malfunctions.
- Consider a smaller injection pump to reduce friction and pressure losses in smaller conduit.

Price of MIOX unit:

Price of the SAL40 unit is around $10,000-$12,000, not including installation (as quoted to campground manager). All installation was done in-house and was therefore "relatively cheap", but would have essentially doubled the price of the system if installation was done by the provider. This price was considered to be too high to pay, even with the great number of benefits and advantages of the system. The system price would have to cut by at least 50% in order for it to be considered as a viable option for the campground. The campground manager indicated that similar systems are available at substantially lower costs.

APPENDIX F

Comparative Cost Analyses

DISINFECTION ALTERNATIVE COST EVALUATION

System Parameters:

Gallons treated per day:	172800
Chlorine dose:	1.0
MIOX system:	SAL20
Number of MIOX systems:	1

ITEM	COST ELEMENT	CHLORINE GAS, 1 TON CYLINDER	CHLORINE GAS, 150 # CYLINDER	SODIUM HYPOCHLORITE	CALCIUM HYPOCHLORITE	MIOX
	OPERATING COST:					
1	Concentration	100.00%	100.00%	12.50%	65.00%	
2	Unit of measure	pound	pound	gallon	pounds	gallon
3	Pounds per unit of measure	1	1	10.2	1	8.5
4	Degradation Factor, percent reduction (Note 1)	0%	0%	15%	10%	0%
5	Available chlorine per unit of measure, mg	454,000	454,000	468,247	263,361	1,323
6	Liters treated at desired dose (mg/L)	454,000	454,000	468,247	263,361	1,323
7	Gallons treated	120,106	120,106	123,875	69,672	350
8	Cost per unit (Note 2)	$0.90	$1.00	$1.24	$1.64	$0.017
9	Price per 1000 gallons, cents	0.75	0.83	1.00	2.35	4.58
	MAINTENANCE COST:					
1	Maintenance labor hours per year	20	20	200	200	25
2	Maintenance labor cost per hour	$20.00	$20.00	$20.00	$20.00	$20.00
3	Annual maintenance labor cost	$400.00	$400.00	$4,000.00	$4,000.00	$500.00
4	Maintenance parts	$1,350.00	$1,350.00	$800.00	$400.00	$600.00
5	Safety training hours	8	8	4	4	0
6	Safety training labor cost	$160.00	$160.00	$80.00	$80.00	$0.00
7	Safety equipment	$200.00	$200.00	$150.00	$150.00	$0.00
8	Insurance and other costs	$1,000	$500			$0
9	TOTAL ANNUAL MAINTENANCE COST	$3,110.00	$2,610.00	$5,030.00	$4,630.00	$1,100.00
	CAPITAL COST:					
1	Disinfection equipment	$10,000	$5,000	$1,500	$1,500	$10,793
2	Safety equipment	$10,000	$10,000	$1,000	$1,000	$0
3	Scrubber (Note 3)	$80,000	$50,000			
4	TOTAL CAPITAL COSTS	$100,000	$65,000	$2,500	$2,500	$10,793

DISINFECTION ALTERNATIVE COST EVALUATION
(Concluded)

ITEM	COST ELEMENT	CHLORINE GAS, 1 TON CYLINDER	CHLORINE GAS, 150 # CYLINDER	SODIUM HYPOCHLORITE	CALCIUM HYPOCHLORITE	MIOX
	TOTAL COSTS AMORTIZED OVER:	**10**	**YEARS.**			
1	Chemical cost to treat water production	$4,726	$5,251	$6,314	$14,846	$28,910
2	Total maintenance cost	$31,100	$26,100	$50,300	$46,300	$11,000
3	Total capital cost	$100,000	$65,000	$2,500	$2,500	$10,793
4	Total costs over amortized period	$135,826	$96,351	$59,114	$63,646	$50,702
5	**Total cost per 1000 gallons treated**	**$0.431**	**$0.306**	**$0.187**	**$0.202**	**$0.161**

Note 1: Sodium and calcium hypochlorite degrade over time so that more has to be dosed into the system before the next batch is made.

Note 2: The price for sodium hypochlorite includes a $5 per drum (54 gallon) environmental cleaning fee. Hypochlorite prices from Van Waters and Rogers. Gas prices from Dixie Petro Chem.

Note 3: Gas scrubber prices from Matheson Gas Products.

DISINFECTION ALTERNATIVE COST EVALUATION

System Parameters:

Gallons treated per day:	324000
Chlorine dose:	1.0
MIOX system:	SAL30
Number of MIOX systems:	1

ITEM	COST ELEMENT	CHLORINE GAS, 1 TON CYLINDER	CHLORINE GAS, 150 # CYLINDER	SODIUM HYPOCHLORITE	CALCIUM HYPOCHLORITE	MIOX
	OPERATING COST:					
1	Concentration	100.00%	100.00%	12.50%	65.00%	
2	Unit of measure	pound	pound	gallon	pounds	gallon
3	Pounds per unit of measure	1	1	10.2	1	8.5
4	Degradation Factor, percent reduction (Note 1)	0%	0%	15%	10%	0%
5	Available chlorine per unit of measure, mg	454,000	454,000	468,247	263,361	2,363
6	Liters treated at desired dose (mg/L)	454,000	454,000	468,247	263,361	2,363
7	Gallons treated	120,106	120,106	123,875	69,672	625
8	Cost per unit (Note 2)	$0.90	$1.00	$1.24	$1.64	$0.019
9	Price per 1000 gallons, cents	0.75	0.83	1.00	2.35	2.84
	MAINTENANCE COST:					
1	Maintenance labor hours per year	20	20	200	200	25
2	Maintenance labor cost per hour	$20.00	$20.00	$20.00	$20.00	$20.00
3	Annual maintenance labor cost	$400.00	$400.00	$4,000.00	$4,000.00	$500.00
4	Maintenance parts	$1,350.00	$1,350.00	$800.00	$400.00	$600.00
5	Safety training hours	8	8	4	4	0
6	Safety training labor cost	$160.00	$160.00	$80.00	$80.00	$0.00
7	Safety equipment	$200.00	$200.00	$150.00	$150.00	$0.00
8	Insurance and other costs	$1,000	$500			$0
9	TOTAL ANNUAL MAINTENANCE COST	$3,110.00	$2,610.00	$5,030.00	$4,630.00	$1,100.00
	CAPITAL COST:					
1	Disinfection equipment	$10,000	$5,000	$1,500	$1,500	$12,061
2	Safety equipment	$10,000	$10,000	$1,000	$1,000	$0
3	Scrubber (Note 3)	$80,000	$50,000			
4	TOTAL CAPITAL COSTS	$100,000	$65,000	$2,500	$2,500	$12,061

DISINFECTION ALTERNATIVE COST EVALUATION
(Concluded)

ITEM	COST ELEMENT	CHLORINE GAS, 1 TON CYLINDER	CHLORINE GAS, 150 # CYLINDER	SODIUM HYPOCHLORITE	CALCIUM HYPOCHLORITE	MIOX
	TOTAL COSTS AMORTIZED OVER:	**10**	**YEARS.**			
1	Chemical cost to treat water production	$8,862	$9,846	$11,838	$27,837	$33,538
2	Total maintenance cost	$31,100	$26,100	$50,300	$46,300	$11,000
3	Total capital cost	$100,000	$65,000	$2,500	$2,500	$12,061
4	Total costs over amortized period	$139,962	$100,946	$64,638	$76,637	$56,599
5	**Total cost per 1000 gallons treated**	**$0.237**	**$0.171**	**$0.109**	**$0.130**	**$0.096**

Note 1: Sodium and calcium hypochlorite degrade over time so that more has to be dosed into the system before the next batch is made.

Note 2: The price for sodium hypochlorite includes a $5 per drum (54 gallon) environmental cleaning fee. Hypochlorite prices from Van Waters and Rogers. Gas prices from Dixie Petro Chem.

Note 3: Gas scrubber prices from Matheson Gas Products.

DISINFECTION ALTERNATIVE COST EVALUATION

System Parameters:

Gallons treated per day:	460800
Chlorine dose:	1.0
MIOX system:	SAL40
Number of MIOX systems:	1

ITEM	COST ELEMENT	CHLORINE GAS, 1 TON CYLINDER	CHLORINE GAS, 150 # CYLINDER	SODIUM HYPOCHLORITE	CALCIUM HYPOCHLORITE	MIOX
	OPERATING COST:					
1	Concentration	100.00%	100.00%	12.50%	65.00%	
2	Unit of measure	pound	pound	gallon	pounds	gallon
3	Pounds per unit of measure	1	1	10.2	1	8.5
4	Degradation Factor, percent reduction (Note 1)	0%	0%	15%	10%	0%
5	Available chlorine per unit of measure, mg	454,000	454,000	468,247	263,361	2,930
6	Liters treated at desired dose (mg/L)	454,000	454,000	468,247	263,361	2,930
7	Gallons treated	120,106	120,106	123,875	69,672	775
8	Cost per unit (Note 2)	$0.90	$1.00	$1.24	$1.64	$0.021
9	Price per 1000 gallons, cents	0.75	0.83	1.00	2.35	2.19
	MAINTENANCE COST:					
1	Maintenance labor hours per year	20	20	200	200	25
2	Maintenance labor cost per hour	$20.00	$20.00	$20.00	$20.00	$20.00
3	Annual maintenance labor cost	$400.00	$400.00	$4,000.00	$4,000.00	$500.00
4	Maintenance parts	$1,350.00	$1,350.00	$800.00	$400.00	$600.00
5	Safety training hours	8	8	4	4	0
6	Safety training labor cost	$160.00	$160.00	$80.00	$80.00	$0.00
7	Safety equipment	$200.00	$200.00	$150.00	$150.00	$0.00
8	Insurance and other costs	$1,000	$500			$0
9	TOTAL ANNUAL MAINTENANCE COST	$3,110.00	$2,610.00	$5,030.00	$4,630.00	$1,100.00
	CAPITAL COST:					
1	Disinfection equipment	$10,000	$5,000	$1,500	$1,500	$15,357
2	Safety equipment	$10,000	$10,000	$1,000	$1,000	$0
3	Scrubber (Note 3)	$80,000	$50,000			
4	TOTAL CAPITAL COSTS	$100,000	$65,000	$2,500	$2,500	$15,357

DISINFECTION ALTERNATIVE COST EVALUATION
(Concluded)

ITEM	COST ELEMENT	CHLORINE GAS, 1 TON CYLINDER	CHLORINE GAS, 150 # CYLINDER	SODIUM HYPOCHLORITE	CALCIUM HYPOCHLORITE	MIOX
	TOTAL COSTS AMORTIZED OVER:	**10**	**YEARS.**			
1	Chemical cost to treat water production	$12,603	$14,004	$16,836	$39,590	$36,837
2	Total maintenance cost	$31,100	$26,100	$50,300	$46,300	$11,000
3	Total capital cost	$100,000	$65,000	$2,500	$2,500	$15,357
4	Total costs over amortized period	$143,703	$105,104	$69,636	$88,390	$63,194
5	**Total cost per 1000 gallons treated**	**$0.171**	**$0.125**	**$0.083**	**$0.105**	**$0.075**

Note 1: Sodium and calcium hypochlorite degrade over time so that more has to be dosed into the system before the next batch is made.

Note 2: The price for sodium hypochlorite includes a $5 per drum (54 gallon) environmental cleaning fee. Hypochlorite prices from Van Waters and Rogers. Gas prices from Dixie Petro Chem.

Note 3: Gas scrubber prices from Matheson Gas Products.

DISINFECTION ALTERNATIVE COST EVALUATION

System Parameters:

Gallons treated per day:	1200960
Chlorine dose:	1.0
MIOX system:	SAL80
Number of MIOX systems:	1

ITEM	COST ELEMENT	CHLORINE GAS, 1 TON CYLINDER	CHLORINE GAS, 150 # CYLINDER	SODIUM HYPOCHLORITE	CALCIUM HYPOCHLORITE	MIOX
	OPERATING COST:					
1	Concentration	100.00%	100.00%	12.50%	65.00%	
2	Unit of measure	pound	pound	gallon	pounds	gallon
3	Pounds per unit of measure	1	1	10.2	1	8.5
4	Degradation Factor, percent reduction (Note 1)	0%	0%	15%	10%	0%
5	Available chlorine per unit of measure, mg	454,000	454,000	468,247	263,361	8,694
6	Liters treated at desired dose (mg/L)	454,000	454,000	468,247	263,361	8,694
7	Gallons treated	120,106	120,106	123,875	69,672	2,300
8	Cost per unit (Note 2)	$0.90	$1.00	$1.24	$1.64	$0.032
9	Price per 1000 gallons, cents	0.75	0.83	1.00	2.35	1.16
	MAINTENANCE COST:					
1	Maintenance labor hours per year	20	20	200	200	25
2	Maintenance labor cost per hour	$20.00	$20.00	$20.00	$20.00	$20.00
3	Annual maintenance labor cost	$400.00	$400.00	$4,000.00	$4,000.00	$500.00
4	Maintenance parts	$1,350.00	$1,350.00	$800.00	$400.00	$600.00
5	Safety training hours	8	8	4	4	0
6	Safety training labor cost	$160.00	$160.00	$80.00	$80.00	$0.00
7	Safety equipment	$200.00	$200.00	$150.00	$150.00	$0.00
8	Insurance and other costs	$1,000	$500			$0
9	TOTAL ANNUAL MAINTENANCE COST	$3,110.00	$2,610.00	$5,030.00	$4,630.00	$1,100.00
	CAPITAL COST:					
1	Disinfection equipment	$10,000	$5,000	$1,500	$1,500	$22,456
2	Safety equipment	$10,000	$10,000	$1,000	$1,000	$0
3	Scrubber (Note 3)	$80,000	$50,000			
4	TOTAL CAPITAL COSTS	$100,000	$65,000	$2,500	$2,500	$22,456

DISINFECTION ALTERNATIVE COST EVALUATION
(Concluded)

ITEM	COST ELEMENT	CHLORINE GAS, 1 TON CYLINDER	CHLORINE GAS, 150 # CYLINDER	SODIUM HYPOCHLORITE	CALCIUM HYPOCHLORITE	MIOX
	TOTAL COSTS AMORTIZED OVER:	**10**	**YEARS.**			
1	Chemical cost to treat water production	$32,847	$36,497	$43,879	$103,182	$50,664
2	Total maintenance cost	$31,100	$26,100	$50,300	$46,300	$11,000
3	Total capital cost	$100,000	$65,000	$2,500	$2,500	$22,456
4	Total costs over amortized period	$163,947	$127,597	$96,679	$151,982	$84,120
5	**Total cost per 1000 gallons treated**	**$0.075**	**$0.058**	**$0.044**	**$0.069**	**$0.038**

Note 1: Sodium and calcium hypochlorite degrade over time so that more has to be dosed into the system before the next batch is made.

Note 2: The price for sodium hypochlorite includes a $5 per drum (54 gallon) environmental cleaning fee. Hypochlorite prices from Van Waters and Rogers. Gas prices from Dixie Petro Chem.

Note 3: Gas scrubber prices from Matheson Gas Products.

REFERENCES

REFERENCES

1. **Abernathy, Calvin.** Unpublished data; personal interview. Center for Biofilm Engineering, Bozeman, Montana.

2. **American Water Works Association.** 1996. Problem organisms in water: identification and treatment. AWWA Manual M7, Second Edition.

3. **AWWA Exhibitors.** 1997. Mixed oxidant system takes on manganese. Wat. World. 13:20, 27.

4. **Barton, L. L.** 1993. Evaluation of the MIOX system for killing coliform bacteria in sewage water. University of New Mexico Department of Biology Bacteriological Study, Albuquerque, New Mexico.

5. **Barton, L. L.** 1994. Evaluation of the MIOX system for killing coliform bacteria and T-2 virus. University of New Mexico Department of Biology Bacteriological Study, Albuquerque, New Mexico.

6. **Bradford, W. L.** 1993. Design, fabrication, and testing of a laboratory test electrolytic water disinfection unit (LTEWDU). Los Alamos technical report LATA/MX-93-0003. Los Alamos Technical Associates, Inc., Albuquerque, New Mexico.

7. **Bureau of National Affairs.** 1995. Technology report: US EPA evaluation of mixed oxidants water disinfection. BNA, Washington, D. C.

8. **Camper, A. K., W. L. Jones, J. T. Hayes.** 1996. Effect of growth conditions and substratum composition on the persistence of coliforms in mixed-population biofilms. Appl. Environ. Microbiol. 62:4014-4018.

9. **Camper, A. K.** (preparer). 1996. Factors limiting microbial growth in distribution systems: laboratory and pilot-scale experiments. AWWA Research Foundation, Denver, Colorado.

10. **Daniel, E.** 1995. MIOX: On-site mixed oxidant generator. Pilot Study/Engineering Report for Cash Water Supply Corporation, Greenville, Texas.

11. **Dobbs, Bruce.** 1996. An innovative clean-up technology using mixed-oxidant (MIOX). Los Alamos Technical Associates Report, Albuquerque, New Mexico.

12. **Dobbs, Bruce.** 1997. Personal interview. Los Alamos Technical Associates, Albuquerque, New Mexico.

13. **Dowd, M. T.** 1994. Assessment of THM formation with MIOX. Thesis for Master of Science in Envi. Eng., Chapel Hill, North Carolina.

14. **Federal Register.** August 11, 1997. SWTR compliance technology: disinfection. 62:154(42990).

15. **Greenberg, A. E., L. S. Clesceri, A. D. Eaton.** 1992. Standard methods for the examination of water and wastewater, 18th ed. APHA, AWWA, WEC, Washington, D. C.

16. **Jayaraman, A., J. C. Earthman, and T. K. Wood.** 1997. Corrosion inhibition by aerobic biofilms on SAE 1018 steel. Appl. Microbiol. Biotechnol. 47:62-68.

17. **LeChavallier, M. W., and G. A. McFeters.** 1985. Enumerating injured coliforms in drinking water. J. Am. Water Works Assoc. 77(6):81-87.

18. **Los Alamos Technical Associates (LATA).** 1997. Disinfection alternative cost evaluation. LATA Technical Report, Albuquerque, New Mexico.

19. **Morin, P., and A. K. Camper**. 1997. Attachment and fate of carbon fines in simulated drinking water distribution system biofilms. Wat. Res. 3:399-410.

20. **Morin, P., A. K. Camper, W. L. Jones, D. Gatel, and J. C. Goldman.** 1996. Colonization and disinfection of biofilms hosting coliform-colonized carbon fines. Appl. Environ. Microbiol. 62:4428-4432.

21. **Mueller, R. F.** 1996. Bacterial transport and colonization in low nutrient environments. Wat. Res. 11:2681-2690.

22. **Provost, M., A. Rompre, H. Baribeau, J. Coallier, and P. Lafrance.** 1997. Service lines: their effect on microbiological quality. J. Am. Water Works Assoc. 89:78-91.

23. **Reiff, F.** 1988. Drinking water improvement in the Americas with mixed oxidant gases generated on-site for disinfection (MOGGODD). Special Report, Pan Am. Health Org. Bulletin. 22:4.

24. **Reyes, S.** 1995. Use of mixed oxidants to control sewage odors and concrete pipe corrosion in the Albuquerque wastewater collection system. MIOX Corporation Research Report, Albuquerque, New Mexico.

25. **Robson, M.** (ed.) 1984. MIOX operations user's guide. MIOX Corp., Albuquerque, New Mexico.

26. **Robson, Mike.** 1997. Personal interview. MIOX Corp., Albuquerque, New Mexico.

27. **Ruda, Tom.** 1997. Microbial regrowth and distribution system management. AWWA Opflow. 23:1-6.

28. **Shelton, S.** 1993. Evaluation of MIOX for the inactivation of microorganisms. MIOX Corporation Research Report, Albuquerque, New Mexico.

29. **United States Environmental Protection Agency, Office of Water.** August, 1997. Small system compliance technology for the surface water treatment rule. EPA 815-R-97-002.

30. **Venczel, L. V., M. Arrowood, M. Hurd, and M. D. Sobsey.** 1997. Inactivation of *Cryptosporidium parvum* oocysts and *Clostridium perfringens* spores by a mixed-oxidant disinfectant and by free chlorine. Appl. Environ. Microbiol. 63:1598-1601.

31. **Venczel, L. V., M. Arrowood, M. Hurd, and M. D. Sobsey.** 1995. Inactivation kinetics of waterborne pathogens using a mixed oxidant disinfectant. Proceedings of the American Water Works Association Water Quality Technology Conference, Denver.

32. **Videla, H. A.** 1996. Manual of biocorrosion. CRC Press, Inc., Boca Raton, Florida.

33. **Waldroup, A. L., M. Doyle, and M. K. Scantling.** 1996. Effects of on-site generated chlorine (MIOX) on the microbial content of poultry chill water. University of Arkansas Department of Poultry Science Research Report, Fayetteville, Arkansas.

34. **White, G. C.** 1992. The handbook of chlorination and alternative disinfectants, third edition. Van Nostrand Reinhold Co., New York, New York.