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Environmental Technology Verification Report

NSF International • Ann Arbor, Michigan

Inactivation of *Cryptosporidium parvum* oocysts in Drinking Water

Calgon Carbon Corporation's Sentinel™ Ultraviolet Reactor

ETV ETV ETV

EPA/600/R-98/160
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Calgon Carbon Corporation's Sentinel™ Ultraviolet Reactor

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Notice

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Foreword

The following is the final report on an Environmental Technology Verification (ETV) test performed for the NSF/USEPA by Cartwright, Olsen and Associates, LLC, in cooperation with Calgon Carbon Corporation. The test was conducted during March and April of 1998 at the Mannheim Water Treatment Plant in Kitchener, Ontario, Canada.

Throughout its history, the USEPA has evaluated technologies to determine their effectiveness in preventing, controlling, and cleaning up pollution. EPA is now expanding these efforts by instituting a new program, the Environmental Technology Verification Program—or ETV—to verify the performance of a larger universe of innovative technical solutions to problems that threaten human health or the environment. ETV was created to substantially accelerate the entrance of new environmental technologies into the domestic and international marketplace. It supplies technology buyers and developers, consulting engineers, states, and the U.S. EPA regions with high quality data on the performance of new technologies. This encourages more rapid availability of approaches to better protect the environment.

The USEPA has partnered with NSF, an independent, not-for-profit organization dedicated to public health, safety and protection of the environment, to verify performance of small package drinking water systems that serve small communities. A goal of verification testing is to enhance and facilitate the acceptance of small package drinking water treatment equipment by state drinking water regulatory officials and consulting engineers while reducing the need for testing of equipment at each location where the equipment's use is contemplated.

This verification testing program is being conducted by NSF International with participation of manufacturers, under the sponsorship of the EPA Office of Research and Development, National Risk Management Research Laboratory, Water Supply and Water Resources Division (WSWRD) - Cincinnati, Ohio. It is important to note that verification of the equipment does not mean that the equipment is "certified" by the NSF or EPA. Rather, it recognizes that the performance of the equipment has been determined and verified by these organizations.

Preface

The following is a report on the Environmental Technology Verification (ETV) test of the Calgon Carbon Corporation Ultraviolet Reactor being marketed under the name Sentinel™. The study was conducted at the Mannheim Water Treatment Plant in Kitchener, Ontario, Canada in the spring of 1998.

It is important to note that the purpose of the ETV program is to verify field performance of commercially available, innovative drinking water technologies. As such, it is clearly not a scientific study of discovery and is not intended to establish scientific principles or to explore new findings; nor is the intent to establish or evaluate testing and analytical protocols. Scientific methods are followed to the extent that they are methodical and rigorous, and that the data are gathered without contamination, but these are tests conducted in the field, and subject to the field conditions of unpredictability.

The purpose of the testing is to present to state regulators and water treatment specialists reasonable expectations of performance to allow them to evaluate the technology for application to specific needs, and is specifically targeted to small systems where extensive pilot testing may prove prohibitive. It can not be expected to answer all their questions, however, it may serve as an introduction to those technologies.

To that end, the basics of the technology are presented, and a fair and comprehensive report of the procedures and methods of the test is illustrated. It is not intended as a tutorial of the technology and certainly not of the underlying scientific principles either of the technology or of the testing and analytical procedures. It is expected that if additional information at a deeper level is required, the reviewers will be capable of independent research.

The study was conducted by Cartwright, Olsen and Associates, LLC (COA), as a qualified Field Testing Organization (FTO) on behalf of the NSF and EPA. The design of the test was based on Protocols and Test Plans developed through consensus of stakeholders and approved by the EPA and NSF, and was specified in a Field Operations Document (FOD). The FOD was approved by NSF and EPA prior to beginning the verification study. The FOD is an on site, working document which is specific to the technology under study, and is based on the NSF/EPA test plan. It is an effort to anticipate on site problems and performance, and to guide the operators in conducting the test.

The challenge employed live *Cryptosporidium parvum* oocysts and *Giardia muris* cysts. The test plan specified *C. parvum*, the manufacturer elected to challenge *G. muris* as well. *G. muris* is accepted as a test organism by the NSF/EPA test plan and has the advantage of being non-infectious to humans, however, *G. muris* is considered by some to be a more fragile cyst than *G. lamblia*. In hindsight, the challenge of *G. muris* was probably irrelevant and unnecessary, but the design included that challenge in an effort to establish a dose/kill relationship. Given the limitations of time and budget however, laboratory facilities allowed for a near simultaneous challenge of the two organisms selected. Accordingly, this report will focus on the effect of the

reactor on *C. parvum.* No inference can be made concerning *G. muris* with respect to inactivation nor to infectivity.

C. parvum was studied by vital dye, excystation and animal infectivity. The vital dye or excystation were required by the test plan; however, in collimated beam bench testing, Calgon Carbon Corporation (CCC) had determined that animal infectivity was a better indication of UV performance. The reasons are not known, and could be the subject of future research, but because of the bench testing CCC elected to add the optional animal infectivity study to the mandated vital dye and excystation procedures.

Different researchers have utilized several different methods and designs to determine UV dosages so care must be taken when comparing different studies. The information presented in this report is scientifically sound and promising but warrants additional research and independent confirmation by other investigators to insure its validity.

It was hoped that a dose response would be established, although that was not the primary intent of the study. The UV reactor proved to be more effective than expected at lower irradiance levels in inactivating the organism, hence too few data points were available to establish a UV dose response curve. None-the-less, the reactor proved to inactivate the organism as verified by animal infectivity

Several essential but controversial issues arose: 1) there is no consensus in the microbiological community with respect to methods to determine viability/infectivity of *C. parvum*; 2) the methods through which UV irradiance is measured and/or calculated within a reactor is also subject to disagreement. There are also differences in individual preferences for establishing UV dose, proper selection of organism for test, methods of quality control and nomenclature. COA does not pretend to be a referee in these discussions, nor to have an opinion beyond that specific to this testing and verification study.

The report, along with the study, is a collaborative effort, and hence represents the styles of the various contributors. Appendices have been left intact and all commentary by COA has been confined to the document proper. The value of this report is to its intended audience, the purveyors of small system water plants, and any ancillary benefits to either the microbiological or UV scientific communities are beyond the concerns of this document.

The ETV program is an evolving program and thus subject to review and change. By its nature it will ever be addressing new and innovative technologies, where analytical and scientific techniques may be non-standard or uncertain, and often subject to dispute. As the program develops standard procedures may become formulated, and to that degree we are pleased to have made a contribution.

Please note that in the tables used for data collection as well as other support documentation the use of the term Rayox® UV Tower. The Sentinel™ UV Reactor (not Rayox® UV Tower) is the correct name for the equipment package studied in this performance evaluation.

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ACRONYMS, ABBREVIATIONS, FORMULA AND SYMBOLS

AOC - Assimilable Organic Carbon

AWWA – American Water Works Association

AWWARF - American Water Works Association Research Foundation

CCC – Calgon Carbon Corporation

CEC – Clancy Environmental Consultants, Inc.

COA – Cartwright, Olsen and Associates, LLC

DOC – dissolved organic carbon

ETV - Environmental Technology Verification.

Flowrates - Flowrates are expressed as US gallons per minute (gpm).

FOD – Field Operations Document

FTO – Field Testing Organization

Gallons - Gallons are expressed as US gallons, 1 gal = 3.785 liters = 0.833 imperial gallons
1 imperial gallon = 4.54 liters = 1.2 US gallons.

Lamp Fouling - Lamp fouling is the reduction in UV Irradiance caused by the presence of certain organic and inorganic ions in the water that can result in the accumulation of mineral deposits or biofilm on the quartz sleeves covering the lamps. Chemical or mechanical cleaning is needed to restore the UV Irradiance to design conditions.

LED – light emitting diode

Low Pressure Lamps - Low pressure lamps operate at a temperature between 38° and 49°C (100 and 120°F) to produce near monochromatic radiation at 253.7 nm. These lamps typically have a linear power density of about 0.3 W/cm.

Medium Pressure Lamps - Medium pressure lamps produce a broad spectrum of UV light (extending over the 200-300 nm range of microbiological sensitivity with a maximum output at about 255 nm) with a higher irradiance and operating at a much higher operating temperature (surface temperatures >500°C) than do low pressure Hg lamps. The linear power density is also much higher (typically 100-300 W/cm).

MPN – Most Probable Number

MPSS – Multiple Point Source Summation

NIST - National Institute of Standards and Technology

NSF – NSF International

O&M – Operations and Maintenance

OSHA – Occupational Safety and Health Administration

PLC – Programmable logic controller

RMP – Residual Management Plant

SCADA – Supervisory Control and Data Acquisition

SD – Standard Deviation

SiC – Silicon carbide

SWTR - Surface Water Treatment Rule

TOC - Total Organic Carbon

USEPA - United States Environmental Protection Agency

UV Absorbance - Absorbance through a fixed pathlength is related as:

$$A = - \log T.$$

The relationship is often expressed as *Transmittance* where:

$$\%T = 100 \times 10^{-A}.$$

UV Absorption is the transfer of energy from an electromagnetic field to a molecular entity. It is expressed by an absorption coefficient which is the absorbance divided by the optical pathlength, *l*. Thus,

$a = A/l = -(1/l) \log T$ Since A is dimensionless, a is often given the unit m^{-1} or cm^{-1}

UV Absorption was measured as in Standard Method 5910.

UV Dose - The UV energy is quantified to a dose by multiplying the average UV irradiance (the UV irradiance averaged over the exposed volume of the reactor) by the actual exposure time:

$$\text{Dose } (\mu W\ s/cm^2) = \text{Average UV Irradiance } (\mu W/cm^2) \times \text{Exposure Time (s)}$$

To avoid the use of large numbers and the potential for error, UV dose is often indicated as mW s/cm^2, where 1 mW s = 1000 μW s.

UV Intensity - Irradiance is often referred to as *intensity*. Intensity is the traditional term for photon flux, fluence rate, irradiance or radiant power (radiant flux). It is recommended the term be used only for qualitative descriptions.

UV Irradiance - The UV power on a specific area (usually 1 cm²) coming from all incident directions and expressed as microwatts per square centimeter (μW/cm²) or milliwatts per square centimeter (mW/cm²). This is occasionally (and erroneously) referred to as UV Intensity.

UV Output - The amount of power (in the wavelength range of 200-300 nm) delivered from the lamp into the water and described in terms of watts (W) per lamp. The absolute free-standing UV power of the lamp is decreased by end loss and by transmission losses through the quartz sleeve. The UV output can be reduced because of lamp aging, water temperature, and lamp fouling.

UV Power - The amount of power at all wavelengths in a specific range delivered to the water.

UV Transmittance - The ability of the water to transmit UV light. Transmittance of a water sample is generally measured as the percentage (%T) of the ratio of transmitted light irradiance (E) to incident light irradiance (E_o) through an operationally defined pathlength (L). Many commercially available spectrophotometers actually report the Absorbance (A) for a fixed pathlength (L) of the sample. Percent Transmittance and Absorbance can be related through an operationally defined pathlength (L) as $\%T = 100 \times 10^{-A}$. Many naturally occurring organic and inorganic constituents (e.g., natural organic matter, iron, nitrate) will absorb energy in the UV wavelengths, thus reducing the transmittance of the water. This reduced transmittance often interferes with the disinfection efficiency of a UV disinfection system.

Vital Dye – DAPI/PI (4', 6-diamidino-2-phenylindole and propidium iodide)

WSWRD – Water Supply and Water Resources Division

WTP – Water Treatment Plant

ACKNOWLEDGMENTS

The Field Testing Organization, Cartwright, Olsen and Associates, LLC (COA) was responsible for all elements in the testing sequence, including collection of samples, calibration and verification of instruments, data collection and analysis, test data management, data interpretation and the preparation of this report.

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Animal Infectivity Studies:

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(520) 621-4439 Fax (520) 621-3588

Additional, non-microbiological, analytical work was performed by:

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The Manufacturer of the Equipment was:

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We wish to thank the participants in this test, especially Brian Pett and staff of the Mannheim Water Treatment Plant for their generous cooperation and hospitality, and the members of the Grand River Conservation District for their courtesy and informative resources.

Chapter 1
Verification Statement

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Office of Research and Development
Washington, D.C. 20460

ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM
VERIFICATION STATEMENT

TECHNOLOGY TYPE:	**ULTRAVIOLET RADIATION USED IN PACKAGED DRINKING WATER TREATMENT SYSTEMS**
APPLICATION:	**MICROBIOLOGICAL CONTAMINANT INACTIVATION**
TECHNOLOGY NAME:	**SENTINEL™ ULTRAVIOLET REACTOR (R-11, Model 6-1)**
COMPANY:	**CALGON CARBON CORPORATION OXIDATION TECHNOLOGIES**
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The U.S. Environmental Protection Agency (EPA) has created a program to facilitate the deployment of innovative technologies through performance verification and information dissemination. The goal of the Environmental Technology Verification (ETV) Program is to further environmental protection by substantially accelerating the acceptance and use of improved and more cost effective technologies. The ETV Program is intended to assist and inform those involved in the design, distribution, permitting, and purchase of environmental technologies. This verification statement provides a summary of the performance results for the Calgon Carbon Corporation (CCC) Sentinel™ Ultraviolet Reactor, R-11, Model 6-1 (Sentinel™). The Sentinel™ is a package drinking water treatment system that uses medium-pressure ultraviolet (UV) lamps operating at a higher temperature than low-pressure lamps to produce a broad spectrum of UV light with a higher irradiance to inactivate microbiological contaminants.

ABSTRACT

The EPA and NSF International (NSF) verified the performance of the Sentinel™ under the EPA's ETV program. The Sentinel™ obtained an estimated 3.9 $\log_{10}$ inactivation of *Cryptosporidium parvum* (*C. parvum*) as determined by animal infectivity methods, at an estimated UV dose of 20 mW-s/cm^2, when fed finished (treated but not chlorinated) water that was seeded with *C. parvum* at a flow rate of approximately 215 gallons per minute (gpm). When using other methods (vital dyes and *in vitro* excystation), a maximum of 1.2 $\log_{10}$ inactivation of *C. parvum* was observed. During the microbiological seeding challenge, the finished water fed to the system had these characteristics:

- turbidity less than or equal to 0.11 NTU
- nitrate less than or equal to 4.0 milligrams per liter (mg/L)
- pH range of 7.40 - 7.76

- temperature range of 8.8 - 12.3 ^{o}C
- UV_{254} absorption coefficient ranges 0.02-0.06 cm^{-1}.

At a flow rate of 25 gpm, the Sentinel™'s power requirements were verified as 1.046 ± 0.046 kW per lamp at full power. Three of the UV irradiance sensors failed and some of the automatic quartz sleeve wipers had operational difficulties including a broken weld. CCC informed NSF of their intent to improve these portions of the Sentinel™.

Details of the verification testing, including the testing data and discussion of results, may be found in the report entitled "Environmental Technology Verification Report: Inactivation of *Cryptosporidium parvum* oocysts in Drinking Water: Calgon Carbon Corporation's Sentinel™ Ultraviolet Reactor" (EPA/600/R-98/160).

PROGRAM OPERATION

The EPA, in partnership with recognized verification organizations, objectively and systematically evaluates the performance of innovative technologies. Together, with the full participation of the technology developer, they develop plans, conduct tests, collect and analyze data, and report findings. The evaluations are conducted according to a rigorous demonstration plan and established protocols. NSF, a not-for-profit organization dedicated to public health safety and protection of the environment, assured data quality objectives were met during testing through their oversight and management of verification activities. The verification testing of the Sentinel™ was performed by Cartwright, Olsen and Associates, LLC (COA), an NSF-qualified Field Testing Organization for the Package Drinking Water Treatment Systems (PDWTS) ETV Pilot.

TECHNOLOGY DESCRIPTION

The Sentinel™ is a medium pressure UV water treatment system designed to inactivate microbiological contaminants. There are two major UV light technologies: low-pressure and medium pressure lamps. The low-pressure lamp UV light technology emits most of its energy at the 253.7 nm wavelength. The medium pressure lamps produce a broad spectrum of UV light (extending over the 200-300 nm range with a maximum output at about 255 nm) with a higher irradiance and operating at a much higher operating temperature (surface temperatures >500°C) than low pressure lamps. The linear power density is also much higher (typically 100-300 W/cm).

The system is a skid-mounted, stand-alone system equipped with a control panel, power supply, transformer, and fail-safe and monitoring controls. The system has two UV reaction chambers contained within a stainless steel column (dimensions: 10" diameter, 80" tall). Each reaction chamber has three 1 kW medium pressure ultraviolet lamps. Each lamp can be operated at full or reduced power. Each lamp is contained within a quartz sleeve aligned perpendicular to and across the flow of the water. The UV dose for the system is calculated using a multiple point source summation (MPSS) model that is undergoing a peer review. The hydraulic design for the system is for continuous flow rates up to 500 gpm (0.7 mgd). Throughout the verification testing period, the system was operated at a flow rate of 25 gpm during regular flow conditions and at approximately 215 gpm (814 L/min) during inoculated feedwater conditions.

VERIFICATION TESTING DESCRIPTION

In March and April of 1998, the ability of the Sentinel™ Ultraviolet Reactor to inactivate the protozoa *C. parvum* oocysts was tested at the Mannheim Water Treatment Plant in Kitchener, Ontario, Canada.

The Grand River is the source water for the Mannheim Water Treatment Plant. Pretreated surface water (treated by coagulation, flocculation, sedimentation, ozonation, and filtration) was inoculated with *C. parvum* oocysts and fed to the Sentinel™. The pretreated surface water exhibited the following

characteristics during the microbiological seeding portion of the verification testing: turbidity concentrations less than or equal to 0.11 NTU; pH range 7.40-7.76; temperature range 8.8-12.3 ^{o}C; nitrate concentration less than or equal to 4.0 milligrams per liter (mg/L); total organic carbon (TOC) concentration less than or equal to 4.5 mg/L; UV_{254} absorption coefficient range 0.02-0.06 cm^{-1}.

Methods

During each day of the verification test, samples of the feed and finished water were collected, labeled and analyzed. All analyses were performed in accordance with the procedures in *Standard Methods.*

The purpose of the microbiological challenge test was to demonstrate the effectiveness of the application of medium pressure UV lamps as configured in the Sentinel™ equipment in inactivating the protozoan oocysts in the field. The challenge testing was performed on finished water representing a uniform water quality matrix.

The Sentinel™ was challenged with live oocysts and consisted of the following steps:

1) the introduction of live oocysts into the water stream and their passage through the Sentinel™,
2) the recovery of the oocysts from the water stream,
3) the determination of their viability and/or infectivity,
4) the calculation of log_{10} inactivation.

The organisms were introduced upstream of a static mixer ahead of the reactor and collected on 1 µm filters after the reactor. The overall flow rate during the tests was approximately 215 gpm (814 L/min). The filters were shipped to Clancy Environmental Consultants, Inc. (CEC) in Vermont where the organisms were isolated, concentrated and subjected to analysis by *in vitro* methods to determine viability. Additionally, for *C. parvum* oocysts, animal infectivity experiments were also conducted to ascertain the levels of inactivation demonstrated by *in vitro* assays and to provide further evidence for the correlation between *in vitro* methods and neonatal mouse infectivity, following oocyst exposure to UV light. The details of the seeding, recovery, and viability assays are found in Clancy et al. (1998).

VERIFICATION OF PERFORMANCE

The following is a summary of the findings of the verification testing of the Sentinel™:

Water Quality Results

The following two tables present the mean, minimum, and maximum water quality parameter concentration results of the influent and effluent samples collected during the verification testing:

On-Site Water Quality Sampling Results (March 30 through April 13)

	Temp. (^{o}C)[1]	pH[2]	Bench Turbidity[3]	In-Line Turbidity[4]
Mean	10.4/11.4	7.6/7.6	0.095/0.094	0.072/0.077
Minimum	8.8/8.8	7.4/7.4	0.056/0.053	0.041/0.041
Maximum	11.0/12.4	7.8/7.7	0.147/0.134	0.112/0.147

1 - Temperature from influent/effluent of reactor.
2 - pH from influent/effluent of reactor.
3 - Turbidity in NTU from bench influent/effluent of reactor.
4 - Turbidity in NTU from on-line turbidimeter, filter 3/filter 4.

Laboratory Water Quality Sampling Results (microbial challenge test days)

	Alk (mg/l)[1]	Al (mg/l)[1]	Color (TCU)[1]	Iron (mg/l)[1]	Mang (mg/l)[1]	NO3 (mg/l)[1]	UV254 (cm^{-1})[1]
Mean	164/164	0.26/0.3	5/5	0.15/ND	0.01/.01	3.58/3.34	0.0464/0.0366
Minimum	150/150	0.06/0.08	5/5	ND/ND	ND/ND	3/3	0.0365/0.0214
Maximum	180/180	0.86/0.48	5/5	0.5/ND	0.03/0.02	4/3.7	0.0551/0.0427

1 – Concentration from influent/effluent of reactor.
ND = Not Detected

Microbiological Results

Results of the *C. parvum* inactivation by the Sentinel™ as determined by animal infectivity, vital dyes, and *in vitro* excystation studies are presented in the following table:

Summary of the Results of *C. parvum* inactivation by the Sentinel™

Challenge Date	Sentinel™ UV Dose at 215 gpm ($mW\text{-}s/cm^2$)	%Trans-mittance	Log_{10} Inactivation via animal infectivity	Vital dyes assay (DAPI/PI)	*In vitro* excystation
3/31/98	167 (High) – 2 lamps full	90.0	>4	1.2	0.4
4/6/98	152 (High) – 2 lamps full	89.4	Not Done	0.9	0.4
4/7/98	137 (High) – 2 lamps full	87.9	Not Done	0.5	0.2
4/1/98	69 (Medium) – 2 lamps reduced	90.1	>4	0	0
4/8/98	20 (Low) – 1 lamp reduced	91.1	3.9	0	0

Mouse infectivity assays with high and medium UV doses demonstrated no infection in neonatal mice despite oral inoculation of up to $1x10^5$ oocysts. The oocysts which had been exposed to a low UV dose resulted in 4.5% infection (1 of 22 mice) with an inoculum of $1x10^5$ UV exposed oocysts per mouse; however, no mice were infected when inocula of either $1x10^4$ or $1x10^3$ UV exposed oocysts were administered into a total of 36 mice.

Operations and Maintenance Results

During the verification period, aspects of the operation were evaluated to determine insofar as is possible over a brief period, the degree of maintenance and "hands on" attention required. For this observation the equipment was run continuously and monitored 24 hours a day until the completion of a period of 27 days. Results observed included:

- Three of the contained irradiance sensors failed due to unexpected electronics problems. CCC is taking action to redesign the sensor circuit board.
- The automatic quartz sleeve wipers ceased operating for many reasons including a broken weld. The wiper mechanism is being redesigned and will be the subject of a separate ETV evaluation. CCC has determined that the cause of wiper failure was the impact force of the brush with the wiper stop at the end of the extended travel position.
- During the maintenance period the power consumption was approximately 1.046 ± 0.046 kW per lamp. Assuming daily operation of six lamps at full power, the power demand is estimated at 150.6 kW per day.

- The O&M manual supplied by the manufacturer was specific to this equipment and included all the components of the pilot plant. Drawings and illustrations showing the positions of the meters and controls are included along with explanations of control functions and step-by-step instructions for common maintenance functions, such as: replacement of lamps, quartz tube cleaning and reactor cleaning. Complete instructions for equipment start-up and shut-down procedures were listed in this guide. The control panel is thoroughly explained so that all programmable functions, including wiper cycles, lamp set-points for alarms and other PLC parameters are easily learned by even inexperienced personnel. Safety measures included detailed instructions concerning high voltage, protection against UV irradiance, and the procedures for mercury spills in the event of lamp breakage. A trouble shooting guide was furnished.

Conclusions

Through this testing it was established that at a process flow rate of approximately 215 gpm the Sentinel™ could obtain an estimated 3.9 $\log_{10}$ inactivation of *C. parvum* oocysts as determined by animal infectivity results with one lamp illuminated (out of six) at reduced power (0.5 kW). Greater (> 4 $\log_{10}$) inactivation was achieved at 215 gpm with higher UV doses, respectively, with two lamps at reduced power (0.5 kW each), and with two lamps at full power (1.0 kW each), again as determined by animal infectivity results.

Furthermore, the use of *in vitro* methods (vital dyes and *in vitro* excystation) significantly under-estimated oocyst inactivation when compared to neonatal mouse infectivity.

During the verification period, water quality parameters that influence UV absorbance were measured to assist in evaluating other waters for application of this UV system. During the challenge periods, UV_{254} absorption coefficient was between 0.02 and 0.06; turbidity was ≤0.11 NTU. No iron or manganese was detected in the sample water; nitrates were no greater than 3.7 mg/L and total organic carbon was no greater than 4.3 mg/L.

Also of importance to this study was the operation of the equipment in the field. Several deficiencies were noted with wiper failures, irradiance sensor, and attenuation tubes. CCC has informed COA and NSF that they are taking action to improve these portions of the system.

Limitations

The PDWTS ETV Pilot verifies the performance of innovative water treatment systems using consensus methods and procedures. This verification identified limitations associated with the use of non-standard methods. For example, the verification identified concerns about the methods for assessing oocyst viability and estimating UV dose. The lack of consensus on evaluation methods and procedures or the application of a technology is a reflection of the uncertainties associated with emerging technologies, developing analytical techniques and engineering applications. The resolution of these uncertainties is within the purview of rigorous scientific research and not the ETV program. A detailed description of the methodology limitations associated with this performance testing is provided in the Verification Report (EPA/600/R-98/160).

Original Signed by
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NOTICE: Verifications are based on an evaluation of technology performance under specific, predetermined criteria and the appropriate quality assurance procedures. Mention of corporate names, trade names, or commercial products does not constitute endorsement or recommendation for use of specific products. This report is not a NSF Certification of the specific product mentioned herein.

Availability of Supporting Documents

Copies of the *ETV Protocol for Equipment Verification Testing for Inactivation of Microbiological Contaminants* dated March 8, 1998, the Verification Statement (EPA/600/R-98/160VS), and the Verification Report (EPA/600/R-98/160) are available from the following sources:

(NOTE: Appendices are not included in the Verification Report. Appendices are available from NSF upon request.)

1. Drinking Water Systems ETV Pilot Manager (order hard copy)
   NSF International
   P.O. Box 130140
   Ann Arbor, Michigan 48113-0140

2. NSF web site: http://www.nsf/etv (electronic copy)

3. EPA web site http://www.epa.gov/etv (electronic copy)

Chapter 2
Introduction

2.1 Historical Background

Ultraviolet light for disinfection of water and wastewater has grown in popularity throughout North America in recent years, although it has been employed in Europe since the 1950s. There are some 500 UV installations in North America, and it is estimated there are over 2,000 in Europe (USEPA 1996). Improvements in the lamps, both mechanically and in their irradiance and power, have made UV a more attractive solution to disinfection problems. It is often preferred over chemical disinfection methods because:

- it has a proven effectiveness in inactivating many pathogens, especially bacteria and viruses (USEPA 1996);
- it requires relatively short contact times;
- it has reduced O&M costs and space requirements;
- there is lesser risk of by-product formation than chlorine, ozone or chlorine dioxide;
- there are lower capital costs than many alternative technologies;
- there is no likelihood of overdosing, or residual formation.

The disadvantages inherent in the technology include:

- the relative lack of information about inactivation of protozoa;
- the lack of residual (although it is acknowledged that by employing UV, lower levels of traditional chemical disinfectants can be used);
- some uncertainties in measuring UV dose (an issue discussed in Section 3.4);
- some possible limitations on total capacity (Wolfe, 1990);
- UV irradiance in water may have restraints determined by water chemistry, for example, turbidity, pH, temperature, UV absorption, nitrates, TOC and True Color.

Ultraviolet light has often been used in water and wastewater treatment to destroy bacteria and viruses, an application for which there is considerable documentation. In recent years, especially with the outbreaks of infection from protozoan cysts and oocysts, such as *Giardia lamblia (G. lamblia)* and *Cryptosporidium parvum (C. parvum)* respectively, and with the increased public awareness and concern (MacKenzie et al., 1994), efforts to capture or inactivate these microbes have accelerated. US drinking water utilities rank *Cryptosporidium* research as their highest priority resulting in increased research funding by US utilities, AWWARF and the USEPA (Frey et al., 1997).

Conventional methods of water treatment including gravity filtration and chlorination have not been effective against protozoan oocysts, especially *Cryptosporidium*, in part because of their size and resistance to chemicals. Treatment plants that are otherwise in compliance with public health treatment standards are thus vulnerable to outbreaks of disease (Kiminski 1994, LeChevallier et al., 1991, Korich et al., 1990).

With the increased awareness of pathogens resistant to traditional disinfection techniques, specifically the parasitic oocysts of *G. lamblia* and *C. parvum*, and with the implementation of the Enhanced Surface Water Treatment Rule (SWTR) and the Groundwater Rule in the near future, it is expected that the search for alternative disinfection technologies will grow significantly. This verification study specifically addresses *C. parvum*.

As of this date, it is generally accepted that low pressure, low power UV lamps have not been effective against protozoan (oo)cysts (USEPA 1996). While this study does not attempt to address the parameters of either wavelength or irradiance specific to the inactivation of the pathogens, it was intended to demonstrate the effectiveness of the Sentinel™ UV Reactor in their inactivation. The Sentinel™ UV Reactor differs from more common UV schemes in that it utilizes medium pressure, high powered UV lamps.

Among the concerns inherent in the use of UV disinfection is that of UV dose and its measurement. UV dose is related to the UV energy delivered to the microorganism by the UV lamp through the water and is a function of residence time (exposure) and average UV irradiance in the water. Factors that affect the irradiance delivered are the wattage and the spectral radiant power of the lamp (the spectrum of which is dependent on the pressure). Factors inherent in the water include the absorbance of the water over the wavelength range of interest, which is itself a function of the true color, turbidity and the composition of the water, especially the dissolved organic matter. The geometry of the reactor was addressed in the test design for the Sentinel™ UV Reactor. Thus, careful attention has been paid to the feedwater characteristics, the physics of the reactor and to the calculation of the irradiance of the lamps. The ability to perform in a test situation, however, is not always sufficient for a proper evaluation. Thus, the ETV Test Plan requires additional parameters to offer engineers and public health regulators a forthright appraisal of the equipment and its applicability to small drinking water systems.

Chapter 3
Procedures & Methods Used In Testing

3.1 Equipment Capabilities and Description

The equipment tested was a medium pressure ultraviolet light disinfection system designed to inactivate microorganisms including *C. parvum* protozoan oocysts.

3.1.1 Equipment Description

The equipment tested was referred to during testing as a CCC 6 kW Rayox® Ultraviolet Tower. Subsequent to the testing and verification period, CCC changed the name of the UV reactor to the Sentinel™ Ultraviolet Reactor System for commercial marketing purposes. The equipment specifications are the same.

Two UV reaction chambers are contained within a stainless steel column with six 1 kW medium pressure ultraviolet lamps, three in each chamber. Each lamp can be powered at full or reduced power. The lamps are each contained within a quartz sleeve aligned perpendicular to and across the flow of the water. Figure 3-1 shows an illustration of the Sentinel™ UV Reactor.

There are two major UV light technologies: low-pressure and medium pressure lamps. The low-pressure lamp UV light technology emits most of its energy at the 253.7 nm wavelength. The medium pressure lamps produce a broad spectrum of UV light (extending over the 200-300 nm range with a maximum output at about 255 nm) with a higher irradiance and operate at a much higher temperature (surface temperatures >500°C) than low pressure lamps. The linear power density is also much higher (typically 100-300 W/cm).

The maximum design temperature is 60°C and maximum design pressure 50 psi. The equipment that was furnished on site was R-11, Model 6-1. It has a footprint of 44-1/2 inches by 150-7/8 inches (1.13 meters by 3.83 meters) including the static mixing cylinder. The main body is 44-1/2 inches by 81 inches (1.13 meters by 2.06 meters). It stands 94 inches tall (2.39 meters). The UV reactor proper is a cylindrical vessel 10 inches in diameter and 80 inches tall. The system is a stand-alone with control panel, power supply and transformer, along with fail-safe and monitoring controls on a skid mounted platform.

The lamps are contained within a quartz sleeve; the sleeves are cleaned automatically by a pneumatically powered stainless steel brush. The automatic cleaning device was proprietary to CCC and has been patented. The cleaning cycles are controlled by a programmable logic controller (PLC) and can be programmed according to the fouling conditions of the subject water. A pneumatic valve was triggered by the PLC and the brushes move along the quartz tube. Following a brief (and adjustable) period, the brushes return and are reset for the next sequence.

UV sensors are located within the chamber, 7.5 centimeters from—and aimed at—the center of each lamp, through an external Teflon probe. They measure lamp irradiance as transmitted to the sensor through the Teflon, the quartz sleeve and the surrounding water. The UV irradiance

detectors are mounted on a circuit board located within the chambers to measure the UV irradiance and are calibrated to read out in mW/cm² to a meter. Factors included in calculating the response of the irradiance sensors include the quartz sleeve, the spectral emission of the UV lamp, the UV absorbance of the water, and the attenuation of the Teflon probe ends. The measured irradiance was converted through factors to account for the Teflon tube, the fiber optic cable and the sensor.

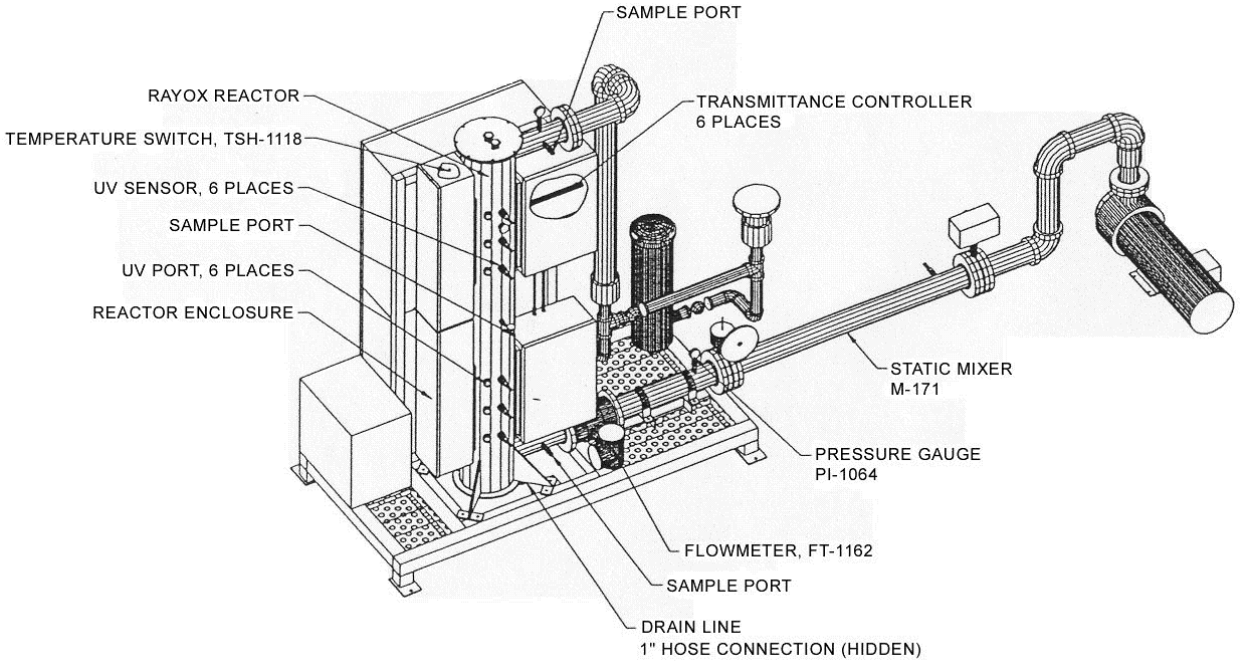

Figure 3-1. Illustration Of The Sentinel™ UV Reactor

3.1.2 Instrumentation and Controls

The package plant as shipped contains a flow meter, irradiance sensors, volt and amp meters for each lamp. In addition, there were a number of instruments added to the package plant specific for this test.

The fail-safe system includes a power drop sensor that indicates if a lamp has failed and can be programmed to send an alarm, shut down the system (ceasing the flow) or both. There is a dual point sensor such that an alarm can be triggered at one level or the unit aborted if required.

The flowmeter used to measure the flowrate through the treatment reactor is an Endress and Hauser Promag 30F, factory calibrated and shop verified.

The on-board SiC detectors are calibrated with a portable IL 1700 radiometer. Each in-line sensor reads to a PLC driven digital display that shows lamp hours, starts, irradiance levels and other system parameters including flow rates and lamp cleaning cycles.

3.2 Testing Overview

The testing was conducted during portions of March and April 1998 and consisted of an operations study where the performance of the package system was evaluated, and a verification study, where the package plant was challenged with *C. parvum*. According to the Mannheim WTP's records (Appendix A), the dissolved organic carbon (DOC) was higher in summer and autumn of 1997 than in the spring of that year, along with true color. The testing period was selected in part because it represents an "ice out" and higher spring run-off river flow period that may tax the water treatment plant. Also, this season allowed for expediency of the testing.

Because the manufacturer recommends use of this product on pretreated surface water feed, only one performance verification period was required. This selection assumes that the pre-treatment within the water treatment plant will provide relatively consistent quality throughout the year, a condition that was confirmed by prior treatment plant records (Appendix A).

While the river is changing from season to season and, for that matter, from day to day, the water treatment plant is producing water of consistent quality. The readings and measurements such as absorbance and chemical and biological parameters are taken to assure consistency (even the best water plants are subject to some variability) and to account for changes in treatment methods. During each day of the test, samples of both the feed and finished water were taken, labeled and tested. These samples were taken prior to any microbiological inoculation.

The equipment was operated continuously for the verification testing period of 320 hours and the 27 day total operating period; however, brief interruptions for repair of the wipers and quartz shields were required. These interruptions are listed in Appendix B.

While the hydraulic design is for continuous flow at rates up to 500 gpm, or in excess of 0.7 mgd, this testing period challenged the device at flow rates closer to 215 gpm. The limiting factor in the challenge testing flow rate was the oocyst capture filters, which are limited to 50 gpm per cartridge. The housing contains four cartridges and has a total flow rate capacity of 215 gpm.

Previous work performed with a collimated beam unit using a medium pressure 1-kW UV lamp showed $\geq$3.9 log inactivation of *C. parvum* at dosages as low as 41 mW-s/cm^2 using the animal infectivity assay (Bukhari et al., 1999). The purpose of the microbiological challenge test was to demonstrate the effectiveness of the application of medium pressure UV lamps as configured in the Sentinel^{TM} equipment in inactivating the protozoan oocysts in the field. The challenge testing was performed on finished water representing a uniform water quality matrix. Additional studies of water quality were performed to assure conditions of the test and to enable the manufacturer to predict effectiveness in other applications.

Each test introduced either 2 or 4×10^8 live oocysts concentrated as a suspension in 200 milliliters of water. If vital dye and excystation alone was employed, 2×10^8 live oocysts were injected; if infectivity by inoculation into mice was employed in addition, 4×10^8 live oocysts

were injected. The injections took place evenly over a period of about two minutes, during which approximately 400 gallons of water were inoculated.
The static mixer was a Ross 4" × six -element motionless mixer in a stainless steel chamber. Vanes within the mixer assure complete mixing and distribution of the oocysts throughout the influent water. The expected pressure drop across the mixer at 215 gpm was 3.36 psig; the pressure drop was measured at 3.5 psig.

A 6 inch Watts RPZ Backflow prevention device was installed upstream of the challenge organism injection point to assure microbial contaminants were not able to migrate into the treatment process stream of the WTP.

The microbiological samples were analyzed using vital dye and excystation. Prior studies have indicated limited and conflicting results about UV inactivation as determined by excystation and vital dye (Campbell et al., 1995, Clancy et al., 1998). Due to these concerns, CCC elected to confirm *C. parvum* oocyst inactivation with animal infectivity studies.

More detailed procedures for vital dye, excystation and animal infectivity are summarized in the following sections.

3.3 Field Testing Methods

3.3.1 Water Quality

3.3.1.1 Test Site Description and Characterization

The site selected for this verification testing is a surface water source located within the Regional Municipality of Waterloo, Ontario, Canada. The cities of Kitchener and Waterloo (along with one other city and four townships in the Region) obtain their water from both ground and surface sources. Groundwater from 126 wells supplies 85% of the water to the communities served and the remaining 15% is taken from the Grand River. Many of the wells within the groundwater supplies in the area are heavily laden with iron and manganese, and others contain high levels of sulfur. The Grand River is a reliable source of water for the community with a flow from May through October averaging 10 cubic meters per second.

Grand River water is treated at the Mannheim Water Treatment Plant (WTP). The treatment plant is a state of the art facility with construction completed in 1993 and capable of treating 13.3 million gallons per day. It presently processes 5 million gallons per day.

Water is withdrawn from the river, piped and stored in a 26.6 million gallon reservoir for several days for turbidity reduction. It then is treated by coagulation, flocculation, sedimentation, ozonation, filtration and chlorination. This finished water is sent to a blending station for blending with groundwater prior to distribution to the municipality.

The Grand River is a major watershed of Southern Ontario and extends over 298 km (185 miles) in length, terminating at Lake Erie. The watershed itself is 6800 km² (2600 mi²). Four primary

tributaries feed the Grand—the Speed, Eramosa, Nith and Conestogo rivers along with a number of creeks.
While the region is primarily agricultural, there is a population of 732,000 within the watershed of which some 525,000 are urban. Up river from the Mannheim WTP are dairy farms, urban centers with wastewater effluent and chemical plants. One such plant in City of Elmira was the site of former toxic waste location. Although the river is not a major source of power, there are and have been power plants on the river in the past. There are three dams on the river used for flood control.

In 1994 the river was designated a Heritage River and is thus subject to careful scrutiny and control. A Grand River Conservation District oversees all river activities and is responsible for monitoring the quality of the watershed.

A preliminary analysis of the feedwater, as reported by the Waterloo WTP Authority, follows as Appendix A. This report contains analyses of the Grand River water at the effluent side of the filter and represents the general quality of water that was directed to the test station.

The water discharged during challenge was directed to the Residue Management Plant (RMP) which is an on site facility designed to contain the backwash water from the filters along with the sludge from the settling basins. The effluent from the test station was directed there during challenge periods.

At the RMP, a polymer is added, the resultant sludge is filter pressed and the cake is sent to a landfill. Prior to the 1993 outbreak of Cryptosporidiosis in the Waterloo region the supernatant water was recycled from the RMP to the head of the treatment plant. Following operational changes made after the outbreak, that practice was discontinued. The filter backwash water along with the settling sludge is assumed to have high levels of microorganisms, including *G. lamblia* and *C. parvum.* The facility meets the requirements of the Canadian/Ontario Ministry of the Environment and Energy as well as the Region's authorities. Supernatant now flows to a designated collection/management area.

3.3.1.2 Water Analysis

In addition to earlier written reports of water quality from regional authorities, the parameters of the water that impact on the verification study were identified and measured. Included are those parameters that are required as a part of the regular scheduled testing. They include: temperature, turbidity, UV absorption, ozone, total organic carbon, true color, pH, total alkalinity, calcium hardness, nitrate, iron, manganese and aluminum. Although the test plan suggests coliform testing, since the source is filtered and ozonated, and because the WTP routinely tests for coliform bacteria and does not allow release of water with a coliform count, this test was eliminated. Moreover, the presence or absence of coliform bacteria would not affect the verification of oocyst inactivation.

During each day of the test, samples of both the feed and finished water were taken, labeled and tested. The testing schedule for water quality parameters is shown in Table 3-1.

All testing was performed in accordance with the procedures and protocols established in *Standard Methods.*

Table 3-1. Testing Schedule for Water Quality Parameters

Parameter	Frequency	Where tested	Standard Method
Temperature	daily	on-site	2550B
pH	daily	on-site	$4500H^+$
Turbidity	daily	on-site	2130B
Ozone	daily	on-site	4500 0_3B
Total Alkalinity	semi-weekly	lab	2320B
Total Hardness	semi-weekly	lab	2340C
Total Organic Carbon	semi-weekly	lab	5310 C
True color	semi-weekly	lab	Hach SM2120
Nitrate	semi-weekly	lab	4500 NO_3:E
Iron	semi-weekly	lab	3113B
Manganese	semi-weekly	lab	3120
Aluminum	semi-weekly	lab	3120
UV Absorption	semi-weekly	lab	5910

All on-site testing instrumentation and procedures were calibrated and/or standardized daily by COA staff or agent. The on-site analyses were performed by Mannheim WTP Laboratory. Because the test location preceded the chlorination point, tests for free and total chlorine were eliminated; however, the possibility for residual ozone remained, so testing was performed daily and immediately preceding challenge testing to verify the absence of ozone in the process stream used for inoculation of challenge organisms.

Ozone, pH, temperature and turbidity were tested daily by the Mannheim WTP lab technician. On-site instruments were calibrated daily.

The on-site bench turbidimeter is a Hach Model 2100N and was used to reference the in-line meters. The in-line meters are Hach 1720C low range turbidimeters. Each filter has an in-line turbidimeter which are labeled 1, 2, 3, and 4. There is also a blended water turbidimeter. During this verification study, filters 3 and 4 supplied water to the pilot plant and thus only those in line turbidity meters were of concern. Turbidity was measured in accordance with SM 2130, bench top and in-line. On-line turbidimeters were compared daily to the bench turbidimeter.

There are two pH meters on site: an Orion Model 720A and a Hach EC-110. The pH probe is a Ross combination pH electrode and was calibrated daily at pH 4 and pH 7 with National Institute of Standards and Technology (NIST) traceable standard solutions in accordance with SM 4500-H^+.

The ozone testing was performed with a Hach Spectrophotometer, Model DR-2000 and employs the indigo tri-sulfonate procedure. Reagents for this procedure were prepared weekly on-site. Tests were performed in triplicate and averaged.

The ozone residual calculation used the following formula:

$$O_3 = \frac{[(\text{ABS blank} \times 100 \text{ mls}) - (\text{ABS sample} \times \text{TV sample})}{0.42 \times \text{SV}}$$

Where:

ABS sample is the absorbance of the sample at 600 nm
TV sample is the total volume of the sample = SV + 10 mls.
SV = sample volume (ml) = (final weight - initial weight) × 1.0 mL/g
0.42 = slope of calibration curve at 600 nm = constant

Samples for total organic carbon and UV absorption measurements were collected in furnished glass bottles, prepared as in SM 5010B and shipped at 4°C by overnight express to Spectrum Laboratories. Inorganic samples were also collected in accordance with SM 3010C and shipped to Spectrum Laboratories overnight at a temperature of 2-8°C.

Since medium pressure lamps are broad range across the spectrum between 200 and 300 nm, Spectrum Labs was asked to determine the UV absorption coefficient at 4 nm intervals between 200 and 300 nm.

All grab samples for water quality analyses, filter cartridges, travel blanks, and other material sent to outside laboratories for analytical work were taken, packaged and shipped with chain of custody forms within the same packaging.

3.3.2 Equipment Installation

The connection from the water treatment plant to the Sentinel™ UV Reactor included a Watts RPZ backflow prevention device along with a shut off ball valve and a manually adjustable diaphragm flow control valve. The adjustable diaphragm valve was used in conjunction with the flow meter to regulate the flow through the system. A schematic of the Sentinel™ UV Reactor and its installation in the plant is attached as Appendix C.

The Sentinel™ UV Reactor was installed in the lowest level of the Mannheim WTP, beneath the filter galleries. Thirty-six inch stainless steel pipe connected the bottom drains of the filters. The four filters are connected in pairs to this pipe, and separated by a full size automatic gate valve. The two filters supplying water to the CCC Sentinel™ UV Reactor were filters number 3 and 4. The thirty six inch automatic gate valve connecting the two filter banks remained closed during the entire testing period; no water from filters 1 and 2 was introduced into the pilot plant.

Feed water to the pilot plant was supplied through a 4" pipe connected to the 36" linking pipe. A 15 hp, single stage centrifugal booster pump was used to maintain 200 gpm across the pilot plant and capture filters. This pump was installed prior to the RPZ and included a recirculation loop with a diaphragm metering valve to reduce forward flow to the pilot plant between challenge test periods.

Although the equipment was installed prior to chlorination, there was a possibility of residual ozone. A chemical feed pump to inject sodium thiosulfate was installed and inserted into the feed line upstream of the RPZ.

Following installation of the reactor, it was determined it was not possible to return the effluent to the front of the plant as originally planned. The location of the pilot plant within the treatment facility prevented such return. That meant all the water would have to be directed to the RMP. Although the plant is intended to accept backwash and overflow water, it was not designed to accept an additional 200 gpm for 13.3 days, the period of the verification testing (3.8 million gallons). Flow through the system was thus reduced to 25 gpm during non-challenge periods. Flow rates were increased to approximately 215 gpm during the challenge periods.

3.3.3 Flow Measurements

The flow meter included as a part of the UV reactor is a Promag 30 series that uses the principle of voltage induced into a conductive fluid moving through a magnetic field. The induced voltage is proportional to the flow velocity, which can be calibrated. The instrument has a circuit that permits a stable zero point and is thus independent of the medium. The instrument was verified on-site by "bucket and stopwatch."

3.3.4 Operating Parameters

Among the items to be recorded daily were measurements of the equipment's physical performance, the pretreatment chemistry and filtration.

The conditions of the UV Reactor lamp output and irradiance were measured at two hour intervals, 24 hours per day. Rates of flow through the UV Reactor were also recorded. In addition, wattage measurements, cleaning cycles and the condition of the lamps was noted at two hour intervals.

Table 3-2 presents the schedule of collection of Operating Data.

The wiping mechanism consists of a circular stainless steel brush attached to a push rod that is activated by compressed air. On each cycle the brush travels the length of the quartz tube, pauses for a brief and adjustable time, usually about 5-10 seconds, then returns to the start position. The mechanism can be manually triggered by a special release valve using a pointed object, such as a pencil. The observer can look through a UV safe viewing glass and see the brush in the rest position. When the brush travels the length of the tube, the observer may see only a shadow pass, and then a second shadow as the wiper returns to the rest position.

Table 3-2. Schedule of Collection of Operating Data

Parameter	Instrument	Record Frequency
Flow rate	Flow Meter	Every two hours (must not vary more than 10%)
UV Irradiance	Instrument	Every two hours.
UV Sensor	In line monitor	Note changes following cleaning
Lamp Fouling/Cleaning		Note frequency and time
Lamp hours		Daily
Power Consumption	Meter	Daily
Lamp cycles		Note on/off cycles

COA decided that due to the short duration of the test, a better demonstration of durability would be accomplished by stressing the wipers. The frequency of the wiping mechanism cycle was set for 300 seconds. Early on the first day of testing (3/31), the frequency was further shortened to 150 seconds, and then on 4/1 to 60 seconds.

3.3.5 Irradiance Measurement

The UV irradiance measurements were to be conducted via UV sensors contained within the reactor, with one sensor at the center of each lamp. The sensors are a silicon carbide (SiC) semiconductor that is sensitive to the range of 230-310 nm. The sensors begin to saturate at irradiance levels in excess of 0.5 mW/cm^2 so the UV must be attenuated before it reaches the sensor. Teflon tubes, inserted into the reactor, were used to attenuate the irradiance. The UV irradiance is thus measured as seen in the water through the quartz sleeve and through the Teflon tube, along with the intervening water. Factors included in calculating the irradiance from the sensors include the quartz sleeve, the spectral emission of the UV lamp, the UV absorbance spectrum of the water, and the fiber optic cable.

By using a fiber optic probe to read each attenuation tube (and thus the individual sensors), each of the UV sensors was compared and an attenuation factor established (see Appendix D). With that factor, the absolute irradiance of each tube was calculated. Finally, a PLC was programmed to convert the mA output from each UV sensor to a panel readout in mW/cm^2. A full calibration of each lamp was conducted before and after each challenge test period. Any changes in calibration were noted on a linear time line against irradiance readings.

During the initial operations period, three of the contained system irradiance detectors failed due to electronic problems. As a result, irradiance was then hand measured for all six lamps over the course of the verification period. For this, two-International Light radiometers were used. The first radiometer was model number IL1400A (serial number 2557) with UV detector probe model number SED 240 (serial number 2813). Calibration certificates are located in Appendix E. During April 8, 1998 of the verification period, it was observed that after the output reading

of this radiometer stabilized, it began to drift. Accordingly, a second radiometer (model/serial number IL1700/681) was calibrated to the first radiometer and used for the duration of the study.

Data was recorded for re-evaluation apart from this study with the three remaining system irradiance detectors that remained functional. These sensors are not a part of the fail safe system, which measures the power to the lamps and can be programmed to send an alarm signal, or shut down the plant (or both) upon failure. The consequences of the loss of the system sensors are beyond the bounds of this study; however, they do impact the future discussions regarding the establishment of a standardized protocol for irradiance measurement.

3.3.6 Microbiological Challenge Methods

The UV reactor was challenged with live oocysts and consisted of the following steps:

1) the introduction of live oocysts into the water stream and their passage through the CCC Sentinel™ UV Reactor,
2) the recovery of the oocysts from the water stream,
3) the determination of their viability and/or infectivity,
4) the calculation of $\log_{10}$ inactivation.

The organisms were introduced upstream of a static mixer ahead of the reactor and collected on 1 µm filters after the reactor. The overall flow rate during the tests was about 215 gpm (814 L/min). The filters were shipped to Clancy Environmental Consultants, Inc. (CEC) in Vermont where the organisms were isolated, concentrated and subjected to analysis by *in vitro* methods to determine viability. Additionally, for *C. parvum* oocysts, animal infectivity experiments were also conducted to ascertain the levels of inactivation demonstrated by *in vivo* assays and to provide further evidence for the correlation between *in vitro* methods and neonatal mouse infectivity, following oocyst exposure to UV light. The details of the seeding, recovery, and viability assays are found in Clancy et al. (1998).

3.3.6.1 Description of *Cryptosporidium parvum*

The *C. parvum* isolate used in this study was purchased from the University of Arizona and is also referred to as the Harley Moon or Iowa strain. This strain was originally isolated from a calf and has been maintained by passage through neonatal calves. A lot number was assigned to each calf on the day the calf was infected and a batch number was given for the day the oocysts were shed. These lot and batch numbers are recorded to validate oocysts' age. The oocysts excreted in the feces of experimentally infected calves were isolated from the feces by discontinuous sucrose gradients followed by microcentrifuge-scale cesium chloride gradients (Arrowood and Sterling, 1987; Arrowood and Donaldson, 1996). The purified oocysts were stored at 4°C in 0.01% Tween 20 solution containing 100 U of penicillin, 100 µg of streptomycin, and 100 µg of gentamicin per ml to retard bacterial growth.

3.3.6.2 Enumeration of oocyst Suspensions

A known number of oocysts were purchased and their numbers were confirmed by using a hemocytometer, according to the procedures detailed in USEPA Method 1622 (1998). The demonstration phase consisted of trip controls, a process control, three replicates at a high UV dose, one replicate at a medium UV dose and one replicate at a low UV dose. For the process controls and UV disinfection trials 2-4 $x10^8$ oocysts were used.

3.3.6.3 Challenge Seeding Schedule

The organisms were introduced upstream of a static mixer ahead of the reactor according to the schedule presented below. Sodium thiosulfate was injected prior to all seedings to neutralize any ozone residual.

There was a bypass around the capture filter housing so that the Sentinel™ UV Reactor could continue to operate while the filters were removed from the housing for shipment to the laboratory. During the challenge testing this bypass section was physically removed to insure that all microorganisms passed through the capture filter. The filters used in these studies typically capture greater than 7 log oocysts; the impact of the test over the natural number of oocysts in the RMP was minimal.

Table 3-3. *Cryptosporidium parvum* Challenge Seeding Schedule

Date	Run Type	Sample Number	Flow Rate	Lamp Power µW/cm²	UV Dose mW-s/cm² Calculated*
3/30	Process Control #1†	98090-6	211 gpm	Off	0
3/31	"High"	98091-1	212 gpm	#2—11.5 #5—9.4	167
4/1	"Medium"	98092-1	212 gpm	#2—6.15 #5—6.5	69
4/6	"High"	98093-8	209 gpm‡	#2—7.8 #5—7.5	152
4/7	Process Control #2	98094-13	213 gpm	Off	0
4/7	"High"	98094-14	213 gpm	#2—7.25 #5—7.0	137
4/8	"Low"	98099-7	214 gpm	#5—3.5	20

* Calculations are shown in Appendix F.

† The sizes of the process control doses were chosen to detect up to a two log decrease in oocyst viability caused by the process alone without UV treatment.

‡ The flow declined from 209 gpm to 191 gpm during the seeding.

The spiking protocol followed that indicated in the EPA/NSF Protocol (EPA/NSF, 1998).

The oocyst seeding protocol consisted of the following steps:

- The flow rate through the UV Reactor was adjusted to 190-215 gpm and the wipers were turned off.
- The metering pump was energized to inject 0.025 molar sodium thiosulfate solution into the feed water line at the rate of 100-150 mL/min at 78-80 psig.
- A sample of feedwater, downstream of sodium thiosulfate injection, was taken for absorption analysis.
- A feedwater sample, again downstream of sodium thiosulfate injection, was taken and immediately analyzed for ozone concentration to assure no ozone was present prior to oocyst seeding.
- The entire effluent stream from UV reactor was diverted through a stainless steel housing containing four each 3" diameter by 20" long 1.0 micron *absolute* track-etch polycarbonate membrane filter cartridges (Nucleopore, Inc.). The surface area of each filter was 2.8 m^2 (30.14 ft^2) for a total filter area of 120.5 ft^2. At 200 gpm the approach flowrate was 1.65 gpm/ft^2.
- The protozoan oocyst injection utilized a 250 mL graduated cylinder into which a suspension of 2 or 4×10^8 oocysts was placed. A Blue and White Model C-1500N metering pump equipped with PTFE tubing injected the organisms into the feed stream at a rate of 50 mL/min. The microorganisms were injected through a 1/4 inch compression fitting at the inlet end of the static mixer and out through a probe inserted to the approximate center of the mixing chamber.
- When the cylinder was ≈ 95% empty, it was refilled with incoming feed water and the flow rate was increased to 80 mL/min to ensure that all organisms were fed into the Sentinel™ unit and to flush the injection system.

Upon completion of the seeding operation, flow was diverted around the filter housing, the cartridges were removed, double bagged and shipped to CEC laboratories for processing.

3.3.6.4 Viability/Infectivity Analysis

The oocysts were isolated from the 1 µm filters, concentrated by centrifugation and divided for analysis by two *in vitro* methods (fluorogenic vital dyes; DAPI and PI and *in vitro* excystation) and neonatal mouse infectivity assays.

3.3.6.5 *In vitro* Viability Assays

The fluorogenic vital dyes assay, utilizing DAPI and PI, was performed according to the procedures described by Campbell et al. (1992) and *in vitro* excystation was performed by the procedures described by Robertson et al. (1993).

3.3.6.6 Neonatal Mouse Infectivity Assays

3.3.6.6.1 Preparation of Infectious Doses

The doses were prepared by removing an aliquot of the enumerated suspension and diluting with deionized water to a volume containing the target number of oocysts. These doses were again enumerated with a hemocytometer and analyzed with the Fisher Chi-Squared index. If the variance exceeded chance, the suspension was re-sampled and re-counted until an acceptable variance for a minimum of five replicate counts was obtained. The hemocytometer counts were then used to calculate the mean number of oocysts per 10 μL dose.

3.3.6.6.2 Infectivity Assays

One process control, one high UV dose, one medium UV dose and one low UV dose were evaluated by the neonatal mouse infectivity assays for *Cryptosporidium*. The UV doses (high, medium and low) were determined from the results of the previous bench-scale study on medium pressure lamps (Bukhari et al., 1999). No replicates were conducted due to the costliness of the animal infectivity procedures. The procedures for mouse infectivity assays were modifications of the original procedures described by Finch et al. (1993) and are described in Bukhari et al. (1999) and Korich et al. (1990).

3.3.6.7 Oocyst Trip Controls, Holding Times and Temperature

The trip controls were held at 4°C throughout the study, including all travel to and from CEC and the field site. The experimental and process control oocysts remained at 4°C until they were vortexed for 30 minutes (still chilled), then mixed in system water (approximately 10°C, see Table 4-1). The oocysts were then seeded into the test system and held on capture filters for the duration of the test, for a total time of 25 minutes at the temperature of the water. After collection on the filters, they were immediately chilled to 4°C, placed on ice packs and shipped to CEC for elution. The ice packs were still frozen upon arrival, maintaining the temperature at 4°C. The total time the oocysts were at temperatures higher than 4°C in the field was about 2 hours. Once they arrived at CEC, each filter was individually eluted, which took approximately about two hours per filter, so they were exposed to room temperature for this time, which involves elution, centrifugation, washing and centrifugation. Once they were eluted and concentrated, they were divided into two portions: one for shipment to the University of Arizona and the other to remain at CEC. CEC then held its portion at 4°C and conducted the vital dye and excystation the following day, which was the same day the University of Arizona was infecting the mice. CEC held the *in vitro* assays until the University of Arizona began infecting the mice so that all assays were done at the same time, eliminating another variable.

This means that CEC varied its procedures in that sample hold times and temperature to an extent were not met. However, this was inherent in the study design. The sample hold times were designed to be minimal, but this still meant a day for the exposure, a day to get the filters back to CEC and eluted, and a day to get the concentrates to the University of Arizona for infectivity, or a minimum of three days. The original excystation rates were done 1-2 days prior

to this at CEC. These were compared with the excystation rates generated at the University of Arizona when the oocysts were shipped to CEC. Losses of viability prior to the start of the study were then considered. There was excellent correlation between the two labs. This means that as many as 5-6 days elapsed from measuring the original excystation rate at CEC prior to the study and measuring the final excystation rate at the time the mice were infected. This is the nature of this work and cannot be avoided.

3.3.7 Log_{10} Inactivation Calculation

Logistic analysis, as proposed by Finch, et al. (1993) was used for analyzing oocyst dose response data. This method applies a logarithmic transformation that converts the normal dose response data into a form that can be readily analyzed by linear regression. Linear regression analysis yields an equation for the straight line of the type $y = b + mx$ where b and m are the intercept and slope of the line, respectively.

The transformation was accomplished by first defining the term response LOGIT for a given oocyst dose as the natural logarithm (ln) of the proportion of mice infected divided by one minus the proportion of mice.

That is: response logit = $\ln[P/(1-P)]$, where P is the proportion of mice infected with a given dose of oocysts (number of mice infected/number of mice inoculated).

The response logit values obtained experimentally were treated as the dependent (Y) variable for regression analysis with the $\log_{10}$ of the number of oocysts in each dose as the independent (X) variable. A regression analysis was used to perform the least squares regression, provide the regression equation parameters (b,m), and to test the validity of the resulting regression model equation.

The logit dose response model proposed by Finch and analyzed here produces a linear regression of the dose response function where the response lies between zero and 100%. Logarithmic transformations of zero and 100% responses cannot be done and are, therefore, not used in the logit model.

3.3.8 Health and Safety Measures

There were two major safety concerns for on-site staff with respect to this testing procedure.

1) The equipment to be tested is powered by 600 volt AC electricity and
2) The microbes to be tested are highly infectious.

Accordingly, built into the equipment were a number of safety features. Since this equipment has been designed for installation in water treatment plants, interlock connections, breakers and other protective devices have been included in its manufacture.

For protection against accidental infection by oocysts, strict environmental laboratory procedures were followed. Protective clothing such as gloves, glasses and lab coats was on hand and used

for shipment in protective containers. Handling of all live oocysts and oocyst containing materials was done by laboratory personnel trained in biological safety.

environment of the test station was in the underdrain area of the filter plant and test staff were exposed to the loud noise of rushing water and air scouring during backwash periods. Earplugs

The water treatment plant is located in Canada and thus not under the regulation of the Occupational Safety and Health Administration (OSHA); however, Canadian authorities have

requirements.

3.4

The UV dose is a function of the average UV irradiance (which is determined by the lamp power) and exposure time (which is determined by the flow rate through the reactor, and by the reactor

3.4.1 Estimation of Exposure Time

reactor, the velocity of the water through the reactor and thus the brief residence time (8.8 seconds at 200 gpm) within the reactor. The exposed volume of the reactor and the flow rate was

3.4.2

To determine the UV dose applied to achieve inactivation of a target microorganism requires a measurement of the UV irradiance and the time the organism is exposed to the UV radiation.

used for other water disinfectants. In the case of chemical disinfectants, such as chlorine, there is a standard procedure. The concentration of the chemical dose multiplied by the residence time
Ct value which can then be used to compute disinfection
Ct value are disinfectant demand (that of the

chemical, the blending of waters, the motion through a reactor and the mixing rates. Tracer tests can be performed for large size systems to follow the flow paths of the chemically treated and

In the case of UV disinfection, there is no residual whatsoever; UV light is effective only when a particle is exposed to it, thus further complicating the measurement. As a particle enters a

reactor containing more than one lamp, it will receive varying illumination levels from each lamp (in the case of the Sentinel™ equipment, several lamps). Depending on the particle's distance from each lamp, the exposure time will depend on the specific path of the particle through the reactor. The exposure of any specific particle to UV is difficult to determine, but certain assumptions can safely be made, one of which assumed that every particle that passes through the reactor with multiple sources, e.g., lamps, will be exposed to UV light.

The amount of UV light can be detected by silicon carbide detectors, and the irradiance levels can be calibrated to a standard measurement. The illumination detected however, is only that which is measured at a specific point, and only those photons that enter the detector on a plane can be detected. The sensors included in the Sentinel™ Reactor were designed to measure the irradiance at a point midway along the length of the UV lamp, and at a distance of 7.5 cm from the lamp (at the wall of the reactor). The sensors used were saturated by the UV intensity, and hence required an "attenuation" tube to limit the power of the UV light reaching them.

Conditions that contribute to the difficulty in measuring and thus limit the estimation of the UV dose include (USEPA, 1996):

- The UV absorbance of the feed water may vary temporally.
- Typically, UV irradiance is measured at only one point within the reactor and only that irradiance which enters the tube on a plane surface.
- The diode silicon carbide detectors may measure UV irradiance outside of the range of the path length of interest.
- There is difficulty with determining with confidence the path of any single particle as it passes through the reactor and hence the exposures to UV light.

3.4.3 Recognized Methods for Estimating UV Dose

The EPA recognizes three other means of establishing UV dose (USEPA, 1996) such as through "bioassay", actinometry, and via calculation.

In bioassay method, microorganisms are exposed to collimated beams of UV light. Collimated beams are those that reach the target in parallel beams and which can be produced in a laboratory. The irradiance is measured by a radiometer and the kill rate of the microorganism, along with a dose response, is established. The dose response can then be used to back calculate the UV dose. This procedure is explained in detail in the ANSI/NSF Standard 55, Annex B. Among the microbes that have been targeted are *Bacillus subtilis* and MS-2 phage. A standard method using *C. parvum* is not final, however, the results using this method have been compared to this verification test in a paper presented recently at the annual American Water Works Association (AWWA) conference (Bolton et al., 1998).

Actinometry measures UV light through a photochemical reaction. A chemical sensitive to UV light at the wavelength of interest is exposed and the resulting photochemical changes are studied. A cell containing the chemical is inserted into the reactor and exposed to the UV light. The chemical change produces a chemical product at a known rate and concentration relative to

the irradiance that can be used in part to calibrate photometers. This method is of value in calibrating radiometer readings. The measurement of UV irradiance by this method was described in a Section 3.3.5. As described in a later section of this report, there were difficulties in the direct measurement of UV irradiance using this method.

The third method cited by EPA is via calculation of the average irradiance across the reactor. It is this third method that was employed in this verification test, through a Multiple Point Source Summation (MPSS) model derived by Dr. Bolton. The model was then used to establish the UV doses during the challenge periods of the verification testing.

3.4.4 Multiple Point Source Summation Model for Estimating UV Dose

Following is a discussion of the model employed in this verification test which is similar to the MPSS method. This discussion is directed toward the layperson, is non-mathematical, and hence limited in scope, and is intended only as an introduction to some of the important concepts. For a more comprehensive explanation of the model, the reader is urged to consult Dr. Bolton's original paper, which is in press and will be available in early 1999.

Most UV light sources are long narrow lamps. The light output from such a lamp may be approximated by a large number (*n*) of “point sources” equally spaced along the lamp axis. The light from each point source is assumed to radiate equally in all directions and the irradiance across a small volume element in the reactor is then obtained by summing the irradiance at that volume element from all *n* point sources.

3.4.4.1 Model Assumptions

This MPSS model makes the assumption that the total illumination of a tube type lamp consists of a series of illuminating points along a line. It is further assumed that the light emanates radially, and in all directions from each point and that the total energy delivered is the sum of all the smaller, "point" sources. For a reactor that has several lamps then, additional summations are required for the illumination along the axis of the reactor as well, of course thereby complicating the formula. Add to that the notion that the light source is circular in cross section, and that a second and third lamp are illuminated in the same reactor, and the resulting determination of total irradiance at any point, or even average point, in the reactor is complex.

3.4.4.2 Model Adjustments for Factors Affecting UV Dose

The establishment of UV dose then must take into account the power of the lamp, the irradiance (which is the radiant power over an area) along with the factors that affect the passage through from the lamp to the point of interest or to the particle. These factors include the lamp glass itself, the air between the lamp and a quartz sleeve that protects the lamp, the quartz sleeve and its interface with both the air on one side and the water on the other, and the water itself. At each of the interfaces are reflections and refractions which are well described in optical physics. Add to this the characteristics of absorbance of the water and the calculation is very sophisticated.

The model employed here also describes a "volume of influence" for each lamp, and then calculates an average irradiance for several of the transmittance percentages (%T) within that volume. The irradiance values outside of that volume are estimated from the increasing distance from the lamp, and by assuming an average irradiance from the lamp. When the percentage transmittance (%T) is less than 65%, the contribution outside the volume of influence can safely be disregarded.

For this verification test only two lamps were illuminated during the challenge periods. The volume of influence in each reactor was 12.32 liters, thus each reactor had a "dark" volume of 43.8 liters. This was considered in the calculations.

When all of these considerations are taken together, a complex formula can be derived that allows a calculation, however tedious. These calculations are made for each of the challenge periods, for each water condition and lamp power, and are shown in Appendix F. A more detailed summary of the MPSS equations and assumptions of the model are presented in Appendix D.

3.5 Data Management

Data were collected in a bound logbook and on charts from the instrumentation panels and individual testing instruments. The visitors log, on-site testing data and turbidity meter readings were contained in pre-printed, bound pages. Preprinting the form served as a prompt for readings and allowed for distribution of tasks.

There is a single master logbook containing all on-site operating data which remained on site and contained instrument readings, on-site analyses and any comments concerning the test run with respect to either the nature of the feedwater or the operation of the equipment. This master logbook contained flow, irradiance, notes on the challenge seedings and equipment. Data were entered into a computer spreadsheet program on a daily basis from the logbook and from all analytical reports. A back-up copy of the log book and computer data was maintained off site. This log is consistent with standard laboratory practice.

All details affecting the operation of the equipment, whether by COA staff, laboratory staff or by CCC staff were logged in the experimental logbook, consolidated and entered into computer spreadsheets. The computer spreadsheets follow as Appendix G.

Each page of the logbook was sequentially numbered and signed by the on duty COA staff. Errors were crossed with a single line and initialed. Deviations from the FOD, whether by error or by a change in the conditions of either the test equipment or the water conditions, were noted in the logbook. Copies of the logbook are attached as Appendix H; copies of chain of custody forms are included as Appendix I. Original chain of custody forms traveled with the samples.

Although data were collected at four locations: the test site, CEC laboratories, the University of Arizona and Spectrum Labs, the COA offices were the central data collection point and all raw data and notes are on file.

Chapter 4
Results & Discussion

4.1 Feed Water Quality

4.1.1 On-Site Test Results

Table 4-1 presents the listing of on-site testing for the verification period.

Table 4-1. On-Site Testing for the Verification Period

Date	Temp.[1]	pH	Ozone[2]	Turbidity[3]	Turbidity[4]
3/30*	9.9/10.6	7.76/7.71	0.03/0.05	0.09/0.09	0.064/0.058
3/31*	10.6/11.7	7.71/7.68	0.03/0.04	0.093/0.109	0.101/0.110
4/1*	11/12.3	7.68/7.66	0.03/0.05	0.096/0.106	0.077/0.076
4/2	10.8/11.9	7.63/7.61	0.03/0.05	0.065/0.064	0.054/0.046
4/3	11.0/12.4	7.58/7.55	0/0	0.088/0.101	0.068/0.050
4/4	10.9/11.9	7.60/7.60	0/0	0.080/0.081	0.049/0.074
4/5	11/11.9	7.54/7.55	0/0	0.056/0.053	0.043/0.043
4/6*	11/11.9	7.59/7.58	0/0	0.098/0.092	0.088/0.047
4/7*	10.3/11.3	7.60/7.61	0/0	0.068/0.053	0.041/0.041
4/8*	8.8/8.8	7.50/7.50	0/0	0.094/0.093	0.096/0.093
4/9	10.1/11.0	7.47/7.46	0/0	0.087/0.077	0.064/0.095
4/10	10.0/11.0	7.47/7.47	0/0	0.136/0.132	0.067/0.147
4/11	10.2/11.2	7.40/7.40	0/0	0.132/0.123	0.100/0.088
4/12	10.2/11.3	7.45/7.47	0/0	0.098/0.098	0.052/0.074
4/13	10.6/11.6	7.62/7.65	0/0	0.147/0.134	0.112/0.114

Notes:
* Challenge test days.
[1] Temperature in ºC from influent/effluent of reactor.
[2] Ozone in mg/L from influent/effluent of reactor.
[3] Turbidity in NTU from bench influent/effluent of reactor.
[4] Turbidity in NTU from on-line turbidimeter, filter 3/filter 4.

4.1.2 Laboratory Test Results

Table 4-2 presents parameters measured at Spectrum Laboratories.

4.1.3 UV_{254} Scan

A representative scan and graph of the UV absorption coefficient at 4 nm intervals between 200 and 300 nm is included as Appendix J. This data was then used by the MPSS model in the calculation of UV Dose.

Table 4-2. Parameters Measured by Spectrum Laboratories

Date	Alk mg/L	Al mg/L	Color TCU	T.Hard mg/L	Iron mg/L	Mang mg/L	NO_3 mg/L	TOC mg/L	UV_{254} cm^{-1}
3-31I	180	0.86	5	260	0.1	0.03	4.0	4.5	0.0367
3-31E	180	0.26	5	250	ND	ND	3.7	4.3	0.0383
4-02I	150	0.20	5	210	0.5	ND	3.7	4.0	0.0519
4-02E	160	0.48	5	210	ND	0.01	3.1	3.8	0.0214
4-08I	160	0.08	5	220	ND	ND	3.0	3.5	0.0551
4-08E	150	0.08	5	220	ND	ND	3.0	3.5	0.0427
4-10I	160	0.10	5	230	ND	ND	3.4	3.4	0.0517
4-10E	160	0.23	5	230	ND	0.01	3.3	3.2	0.0423
4-13I	170	0.06	5	250	ND	ND	3.8	3.7	0.0365
4-13E	170	0.45	5	250	ND	0.02	3.6	3.4	0.0385

I = Influent; E = Effluent

4.2 UV Dose Calculation

4.2.1 Flow Rate Studies

The flow meter on-site was verified by "bucket and stopwatch". Following is the calculation performed. The flowmeter registered 256.8 gpm at the beginning and 257.2 gpm following for an average of 257 gpm. The entire volume was directed into a 36 inch diameter tank and the time to fill a 36 inch rise was measured.

The measured tank volume was 158.62 gallons, and it filled to that level in 36.24 seconds.

$$158.62/36.24 \times 60 = 262.62 \text{ gpm.}$$

The error from flowmeter to measured flow is +2.1%

4.2.2 Exposure Time

The following sections describe procedures for estimating exposure time and the model used to calculate the UV Dose. The reactor geometry has been described by CCC as follows:

2 identical cylindrical sections at top and bottom	V_a= 14.673 L
2 "flattened" cylindrical sections where the UV lamps are mounted	V_b= 27.378 L
1 cylindrical section in the middle	V_c= 29.346 L
less the volume of the 6 quartz sleeves	V_q= 0.342 L

$$2V_a + 2V_b + V_c - 6V_q = V_t = 111.396 \text{ L} / 3.785 = 29.43 \text{ gallons}$$

An estimate of exposure time was calculated from the flow rate and the volume of the reactor based on its geometry:

Exposure time (min) = reactor volume (gal)/flow rate (gpm)

Since the lamps illuminate the entire reactor (both chambers), the exposure time is equal to the residence time within the reactor itself.

At 200 gpm, the residence time is 8.829 seconds based on the flow rate and the geometry of the reactor. Each half chamber contains 14.71 gallons and the exposure time during those test periods when only one lamp was illuminated was 4.42 seconds.

The fluid dynamics of the system are as follows: at 200 gpm the velocity through the 4 inch static mixer was ≈ 5.1 feet per second. The water enters the first chamber at the bottom in a pipe tee 1-7/8 inches off the bottom of the chamber. This can be represented as the entrance of a pipe into a larger pipe or a tank at a right angle. The chamber is 10 inches in diameter, thus flow is turned upward through hydraulic resistance across and from the bottom of the chamber. The turn introduces turbulence. In the passage through the first chamber, the perpendicularly placed UV lamp sleeves introduce additional turbulence; at the midpoint and between the two chambers a separation plate narrows the flow to 4 inches in diameter through an orifice plate. Since all the water must pass through this orifice, additional turbulence is introduced as the water velocity increases, along with a pressure drop at the exit of the plate. The velocity of the water through the 10 inch diameter reactor at 200 gpm was .82 feet/sec.

The turbulent flow introduces a pressure drop across the system of approximately 16 psi at 200 gpm. To some degree a higher pressure loss across the reactor represents more turbulent flow. Measuring the pressure drops at several different flow rates allows for a prediction of turbulence.

4.2.3 Multiple Point Summation Model Results

The challenge testing was originally intended to produce UV doses of 400, 200, 100 and 0 mW-s/cm² (the last as a process control). Following initial lab testing (Bukhari et al., 1999) for UV_{254} and model calculation, those doses were adjusted downward to 200, 100, 50, and 0 mW-s/cm². To provide variable UV dose at the same flow, the theoretical challenge illumination for different numbers of lamps and at different power levels was calculated by the model. The theoretical doses are shown in Table 4-3.

The target doses for the demonstration study were selected as high (300 mW-s/cm^2), medium (100 mW-s/cm^2) and low (50 mW-s/cm^2) UV doses, delivered with medium-pressure lamps. However, as the absorbance of the water affects the actual UV doses that are delivered to the target organisms, re-calculation of the actual doses by using the MPSS model (see Sections 3.4 and 4.2) indicated that the actual UV doses that oocysts were exposed to were considerably lower than anticipated. Final doses as calculated by the model were 167, 152, 137, 69, and 20 mW-s/cm² (see Appendix F for the details of the MPSS model calculation).

The MPSS modeling which relates the above factors via a point source summation compares the irradiance measured at the sensor to the average irradiance of the entire reactor. The calculations are included as Appendix F. Correlation of radiometer readings to the MPSS model is discussed in Appendix D.

Although the radiometer readings were correlated to the MPSS model results, the readings were limited by the use of filters that attenuated the readings. Furthermore, the model UV dose estimates require validation through another method such as the bioassay method (see Section 3.4.3 for more discussion). Comparison of the UV dose estimated in this study by the MPSS method to the UV dose measured or estimated by another method is not recommended.

Table 4-3. UV Dose in mW-s/cm^2 as Calculated by the MPSS Model*

Number of Lamps on	Full Power	Reduced Power
6	814	280
5	678	233
4	543	187
3	407	140
2	271	93.2
1	136	46.8

*Note: At the time these calculations were performed, the absorbance of the water was relatively low (before spring run-off). When the actual tests were run, the absorbance of the water was higher and thus the delivered UV doses were lower.

4.2.4 UV Irradiance by Direct Measurement

During the testing and verification period (on 4/7/98) the treatment plant changed the pretreatment coagulant from poly aluminum chloride to aluminum sulfate as part of a routine springtime procedure. This change resulted in difficulties in maintaining plant turbidity levels below the goal of 0.1 NTU. The change, while it had no noticeable impact on the challenge periods did result in a diminution of the irradiance measurements during the latter stage of the verification period.

At the time it was thought that the diminution might be due to either increased turbidity or to a reduction in lamp irradiance caused by aging or some other problem. When the treatment plant stabilized and the turbidity levels dropped, the irradiance levels rose slightly, suggesting that the water quality was in part a cause of the reduction. The quartz tubes were not noticeably fouled, and absorption coefficients were not appreciably different. The attenuation tubes had bleached out (from UV light) and that, along with a slow degradation in the irradiance due to lamp aging and a change in water quality and absorbance, may have contributed to the loss.

The average irradiance, as shown in Figure 4-1, shows a decline over time.

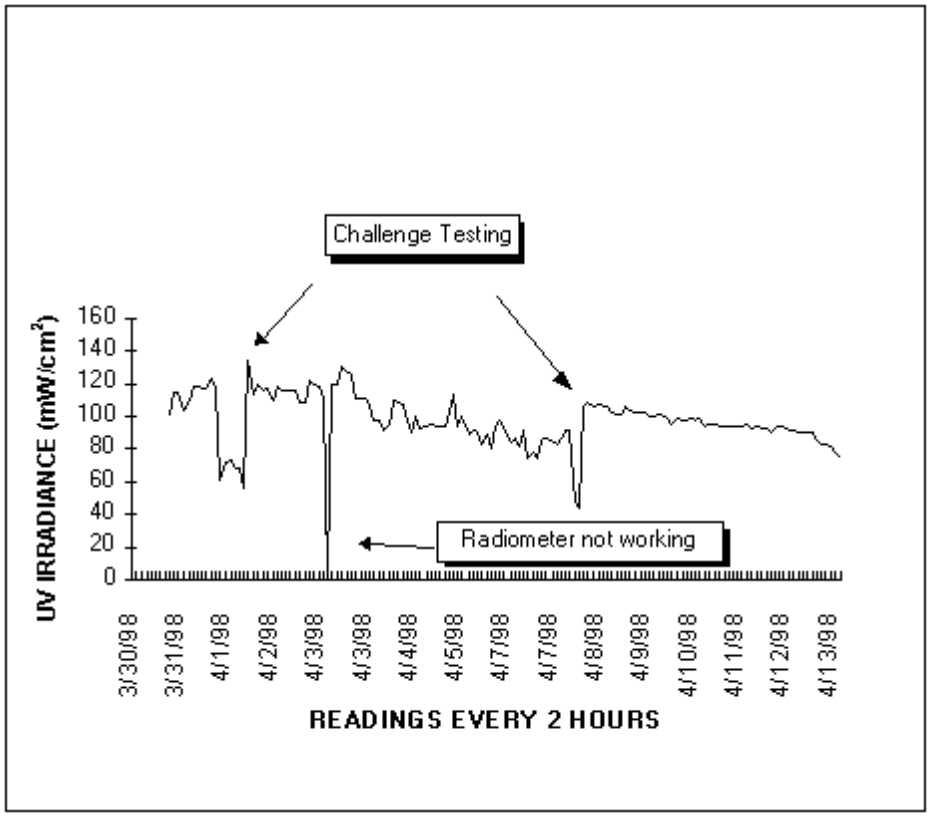

Figure 4-1. Average of UV Irradiance Over Time

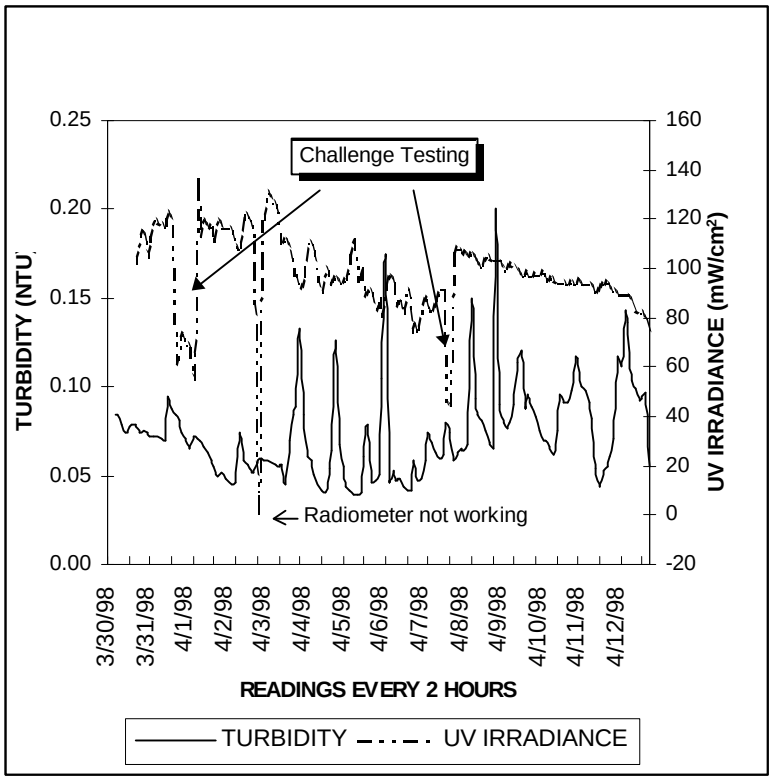

Figure 4-2. Turbidity vs. UV Irradiance

Turbidity alone does not correlate well with irradiance. Turbidity spikes appear to be related to filter backwash periods. The overall turbidity of the plant increased following the change in pretreatment chemistry on April 7 and following that change the filters were backwashed several times a day during the restoration period.

4.3 Microbiological Challenge Results

4.3.1 In vitro Viability Assays

Viability data obtained with vital dyes and *in vitro* excystation have been summarized in Table 4-4. In each assay, 100 oocysts were visualized in duplicate. For comparative purposes the process control viability values were normalized to 100% and the respective viability values for all remaining test samples were adjusted according to the normalization factor. These data have been presented in Table 4-5.

Table 4-4. Effects of UV Exposure on *Cryptosporidium parvum* Viability

		***Cryptosporidium parvum* viability** (n=3)	
Lab ID number	**Pilot testing parameters**	**Vital dyes**	**Excystation**
98090-7	**Trip control 1**	82.0 ± 4.0	81.4 ± 8.1
98090-6	**Process control 1**	71.7 ± 15.4	29.7 ± 1.1
		61.7 ± 4.9*	45 ± 7*
98091-2	**Trip control 2**	90.4 ± 1.2	79.8 ± 4.3
98091-1	UV dose (High)	4.9 ± 4.5	13.7 ± 3.1
98092-2	**Trip control 3**	88.7 ± 1.0	56 ± 9.8
			89 ± 2.7*
98092-1	UV dose (Medium)	73.6 ± 4.1	72.7 ± 2.3
98093-9	**Trip control 4**	76.6 ± 4.4	80.4 ± 1.7
98093-8	UV dose (High)	8.5 ± 1.4	12.1 ± 1.5
98094-13	**Process control 2**	45.3 ± 16.8	49.3 ± 4.0
98094-14	UV dose (High)	25 ± 8.9	34.3 ± 4.0
98099-8	**Trip control 5**	79.7 ± 5.1	77.3 ± 4.2
98099-7	UV dose (Low)	75.3 ± 6.8	47 ± 7.8
			72.7 ± 1.5*

*Repeat analysis on an aliquot taken from same concentrate.

4.3.2 Neonatal Mouse Infectivity Assays

Mouse infectivity assays with high and medium UV doses demonstrated no infection in neonatal mice despite oral inoculation of up to $1x10^5$ oocysts (Table 4-6). The oocysts which had been exposed to a low UV dose resulted in 4.5% infection (1 of 22 mice) with an inoculum of $1x10^5$ UV exposed oocysts per mouse; however, no mice were infected when inocula of either $1x10^4$ or $1x10^3$ UV exposed oocysts were administered into a total of 36 mice (Table 4-6).

Table 4-5. Normalized (Percent) oocyst/cyst Inactivation Using the Sentinel™ System and *in vitro* Viability Assays

	Cryptosporidium parvum viability	
UV Dose (mW-s/cm^2)	**Vital Dyes**	**Excystation**
Process control	**100**	**100**
20	104.7 ± 9.5	160 ± 3.3
69	102.3± 5.7	160 ± 5.1
137	34.8± 12.4	75.5 ± 8.8
152	11.8 ± 1.9	26.6 ± 3.3
167	6.8 ± 6.3	30.1 ± 6.8

Note: values over 100% should be considered to be 100%.

Table 4-6. Effects of UV Exposure on *Cryptosporidium parvum* oocyst Infectivity

Lab ID number	Pilot scale testing parameters	*Cryptosporidium parvum* infectivity		
		Inoculum 1	**Inoculum 2**	**Inoculum 3**
98090-7	**Trip control 1**			
	Oocysts per mouse	25	75	150
	# of total mice	38	40	27
	# of mice infected	2	14	15
	% infectivity	5.3%	35%	55.6%
98090-6	**Process control 1**			
	Oocysts per mouse	50	500	5000
	# of total mice	25	20	23
	# of mice infected	11	20	23
	% infectivity	44%	100%	100%
98091-1	**UV dose (High)**			
	Oocysts per mouse	1000	10,000	100,000
	# of total mice	24	12†	24
	# of mice infected	0	0	0
	% infectivity	0%	0%	0%
98092-1	**UV dose (Medium)**			
	Oocysts per mouse	1000	10,000	100,000
	# of total mice	22	26	25
	# of mice infected	0	0	0
	% infectivity	0%	0%	0%
98099-7	**UV dose (Low)**			
	Oocysts per mouse	1000	10,000	100,000
	# of total mice	18	18	22
	# of mice infected	0	0	1
	% infectivity	0%	0%	4.5%

†Data from one of two cages of 12 mice was invalid due to laboratory accident.

4.3.3 Dose Response Infectivity Calculations

The assay procedure and "Logit Dose Response Calculation" are presented in detail in Section 3.3.7. The initial analysis of the dose response data yielded the following equation which describes the dose response of fresh oocysts in neonatal CD-1 mice:

$$\text{Response Logit} = -6.752 + 3.611\text{Log}_{10}\text{Dose}$$

This equation enables the estimation of the number of infective oocysts in a dose administered to the mice based on the proportion of mice infected and eliminates the need to construct dose-response curves for each level of disinfection to be studied.

The linear regression equation of the model (e.g. response logit = $-6.752 + 3.611\log_{10}$dose) is a mathematical representation of a straight line of the type $y = b + mx$. Here, response logit (y) is calculated from the expression ln(P/1-P) where P is the proportion of animals infected. The intercept (b,-6.752) and the slope (m,3.611) are provided by linear regression analysis whereas the dose of fresh oocysts (x) is a known quantity. When the proportion of infected animals is known for a given dose of oocysts, solving for the number of infectious organisms in a given dose of oocysts becomes quite easy. Determining the number of infective oocysts in a given dose involves calculating the response logit [ln(P/1-P)] from the proportion of infected animals and solving the model equation for $\log_{10}$ dose. Taking the antilog provides the number of infectious oocysts in the administered dose. For example, of 20 mice administered 300 oocysts, 14 became infected and 6 did not. To determine the number of infective oocysts administered to the mice and the log reduction in oocyst infectivity use the model: [Response logit = $-6.752 + 3.611\ \text{Log}_{10}$ Dose] as illustrated below.

1. Determine the proportion of mice infected: 14/20 = 0.7
2. Calculate the response logit: ln [P/(1-P)] = ln [0.7/(1-0.7)] = ln 2.333 = 0.8473
3. Substitute into the model: $0.8473 = -6.752 + 3.611\ \text{Log}_{10}$ Dose
4. Solve for Log dose: Log Dose = [(0.8473 + 6.752)/3.611] = 2.1045
5. Find the antilog: antilog 2.1045 = 127 This is the number of infective oocysts present in the dose of 300 oocysts administered to the 20 mice.

The final infectivity $\log_{10}$ inactivation calculations are based on the LOGIT dose response model:
Response LOGIT = $-6.752 + 3.611\ \text{Log}_{10}$Dose
Where:
Response LOGIT = LN [proportion of mice infected ÷ (1 - proportion of mice infected)]

The $\log_{10}$ inactivation of *C. parvum* upon exposure to UV is given by the following calculations for treated oocysts (low dose).

Proportion of mice infected = 0.045; 97,500 oocysts administered.

Response LOGIT = LN[0.045 / (1-0.045)] = -3.055

Substituting into the model equation yields the number of infective oocysts in the administered dose:

$-3.055 = -6.752 + 3.611\ Log_{10}Dose$

$Log_{10}Dose = 3.697 / 3.611 = 1.024$
Calculated Infective Dose = 10.6 oocysts

Log Change of Infectivity = Log(infective dose / administered dose)
Log Decrease of Infectivity = Log(10.6 / 97,500) = -4.0 Log Change (decrease).

Thus, the low dose has a 4 log decrease in oocyst infectivity.

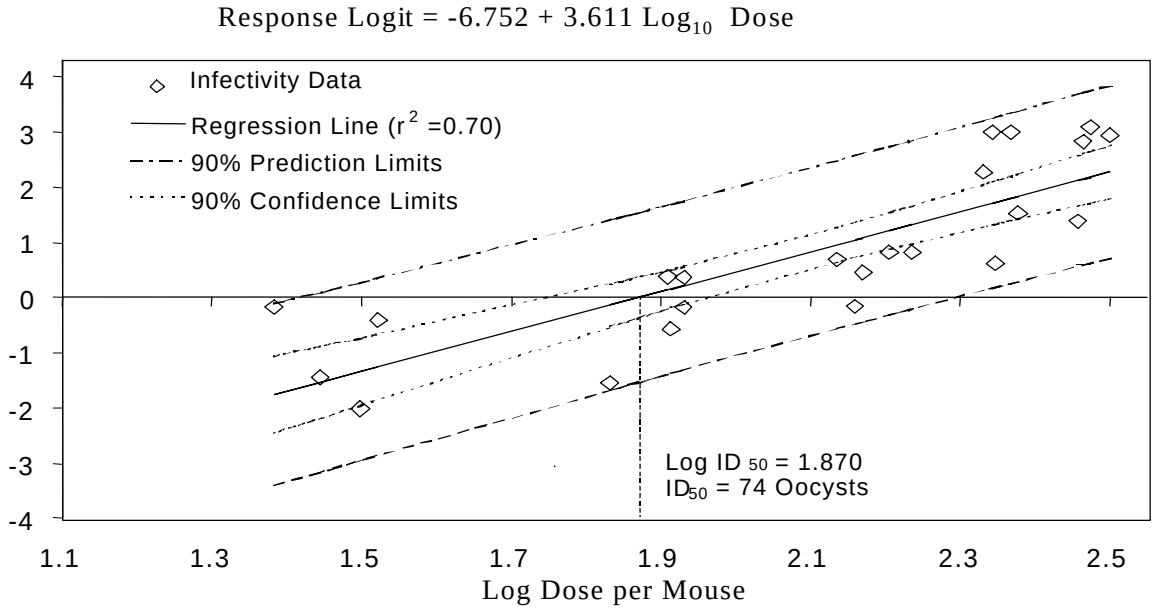

Figure 4-3. UV Dose Response Curve for *C. parvum* oocyst Infectivity

4.3.4 Comparison of Inactivation Methods

For comparative purposes the log reduction in oocyst viability was compared with the log reduction in oocyst using *in vitro* methods (Table 4-7). These results indicated that exposure of oocysts to the highest UV failed to reveal greater than 0.4 log inactivation with *in vitro* excystation. While the vital dyes assay (using DAPI/PI) indicated marginally higher levels of inactivation following oocyst exposure to the high UV doses (1.2 log reduction), mouse infectivity indicated 3.9 log reduction at the lowest UV dose examined. At the medium and high UV doses, mouse infectivity indicated between 4 and 5 log inactivation (Table 4-7).

Nonetheless measuring oocyst inactivation at the high, medium and low UV doses indicated that the *in vitro* methods demonstrated marginal reductions in oocyst viability when compared to the process control. In a comparison between the vital dyes and *in vitro* excystation, data indicated that the vital dyes assay provided a greater decline in oocyst viability than *in vitro* excystation. For example, a UV dose of 152 mW-s/cm^2 resulted in a normalized viability value of 11.8%, which decreased to 6.8% as the UV dose was increased to 167 mW-s/cm^2. However, at these respective UV doses, *in vitro* excystation indicated a normalized viability value of 26.6%, which increased to 30.1%.

Table 4-7. Log Inactivation of *Cryptosporidium parvum* Following Exposure to UV Light: Comparison of *in vitro* Methods with Mouse Infectivity Assays

		Cryptosporidium parvum		
UV Dose (mW-s/cm^2)	**Lab ID Number**	**Vital dyes assay (DAPI/PI)**	***In vitro* excystation**	**Mouse infectivity**
Process control (No UV)	98090-6	0	0	0
20 (Low)	98099-7	0	0	3.9
69 (Medium)	98092-1	0	0	>4
137 (High)	98094-14	0.5	0.2	Not Done
152 (High)	98093-8	0.9	0.4	Not Done
167 (High)	98091-1	1.2	0.4	>4

The demonstration study samples contained large amounts of contaminating debris/particulates that were derived from filtration of large volumes of finished water. It is well documented that *in vitro* excystation has limited application in environmental samples, due to the ease with which oocysts can be masked by contaminating debris. Masking of oocysts clearly creates a scenario where increased errors are likely to occur in ascertaining oocyst population viability. This may be a possible reason for greater variability with *in vitro* excystation than with the vital dyes. Despite this, these data indicated that both *in vitro* assays failed to demonstrate in excess of 1.2 log inactivation at the three UV doses that were examined. However, when aliquots of oocysts derived from the same concentrates were subjected to mouse infectivity assays, > 4 log inactivation was noted (Figure 4-4) with oocysts that were exposed to the high and medium UV doses, whereas 3.9 log inactivation occurred with the oocysts which were exposed to the low UV dose (Table 4-7).

These results demonstrate that *in vitro* methods for *C. parvum* oocysts (vital dyes or *in vitro* excystation) significantly under-estimate oocyst inactivation of UV exposed oocysts when compared to the mouse infectivity assays. Previously, it has been suggested that the sensitivity of the mouse infectivity assays was attributable to their capacity for enabling analysis of large numbers of oocysts than was feasible with the *in vitro* assays. However, data from recent studies suggest that *in vitro* methods may be sensitive to the mechanisms of oocyst inactivation and in turn less reliable than mouse infectivity assays for determining oocyst inactivation (Clancy et al.,

1998). Belosevic et al. (1997) noted previously that excystation did not correlate with animal infectivity using this same CD-1 mouse model.

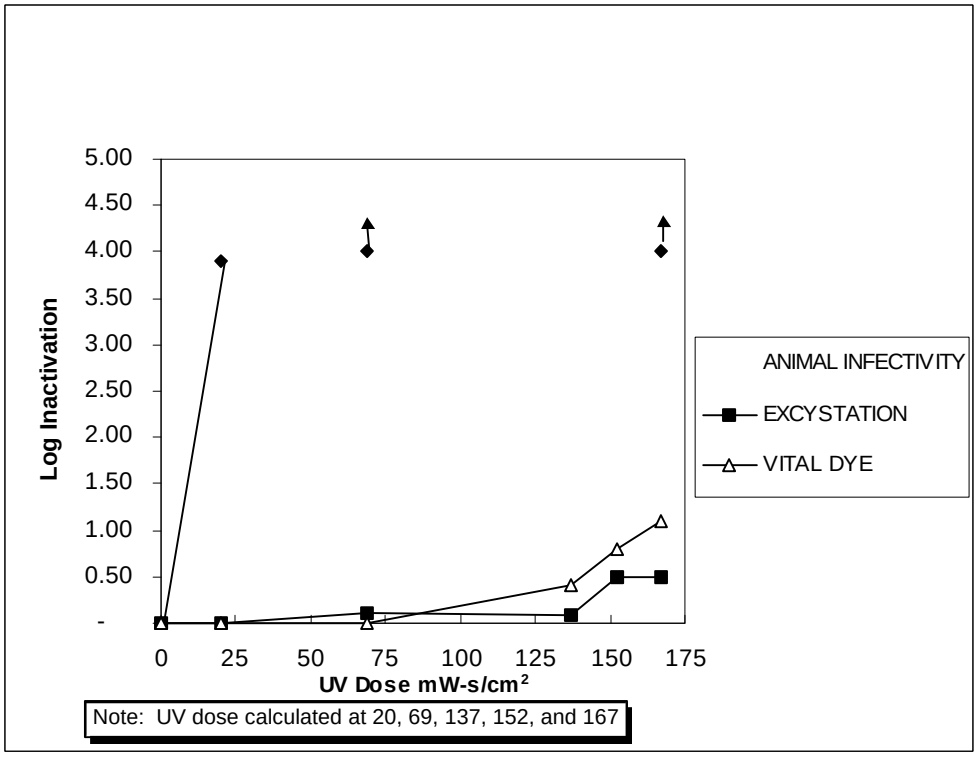

Figure 4-4. *Cryptosporidium parvum* Log Inactivation Ratio vs. UV Dose

A recent study comparing four viability assays (DAPI/PI, excystation, cell culture, and animal infectivity) showed a 4.6 log inactivation of *C. parvum* using the animal infectivity model (Slifko, 1998). The results of the cell culture most probable number (MPN) analysis showed a 4.07 log inactivation of *C. parvum*.

4.3.5 Affect of oocyst Trip Controls, Holding Time and Temperature on Results

The critical excystation rate, expected to be 80% or higher (as noted in the test procedures), is that of the oocysts when assayed prior to delivery into the field. The excystation rate of the trip and process controls after they returned from the field varied, and may be (and were) lower than 80% due to the rigors of the travel (trip control) and experimentation (process control).

However, this does not mean that the testing is invalid because the excystation rates were lower than 80%. For example, if the excystation rates for trip or process controls were extremely low (<50% viable when they began at 80+%), even normalizing the data would present problems. A 50% excystation rate means that the oocyst preparation were half dead (consequently half were alive). The excystation rates in this study were all within the 80% range (when considering standard deviation (SD)) except for the Sample 98094-13 Process Control 2 which was 49.3% (Table 4-4).

The effect of the process control on the log decrease is as follows:

Proportion of mice infected = 0.44; 51.9 oocysts administered.
Response LOGIT = LN[0.44/(1-0.44)] = -0.241

-0.241 = -6.752 + 3.611 Log_{10}Dose
Log_{10}Dose = 6.511 / 3.611 = 1.803
Infective Dose = 63.5 oocysts

Log Change of Infectivity = Log(63.5 / 51.9) = 0.09 Log Change (increase).

The effect of the trip control on the log decrease in oocyst infectivity is as follows:

Proportion of mice infected = 0.55; 158 oocysts administered.

Response LOGIT = LN[0.55/(1-0.55)] = 0.201

0.201 = -6.752 + 3.611 Log_{10}Dose
Log_{10}Dose = 6.953 / 3.611 = 1.925
Infective Dose = 84.2 oocysts

Log Change of Infectivity = Log(84.2 / 158) = -0.27 Log Change (decrease).

The overall effect of process and trip controls is negligible on the log decrease in oocyst infectivity. Hence, the log inactivation was assumed at the low dose to be 3.9 (-4.0 + 0.09 = -3.9). The trip control was not considered in the calculation.

4.4 Operations and Maintenance

To illustrate the application of the system for small drinking water systems, studies of operating conditions and power consumption were measured and evaluated. These records and a recapitulation of all measured operating parameters in the log are included on the spread sheets as Appendix G.

4.4.1 Ease of Operation

The duration of the test was too brief to make a full determination of the ease of operations and maintenance. Operator involvement would be related to the size of the community served and the reporting requirements, and to the degree of automation afforded the treatment plant. Prior studies have suggested that one of the advantages of UV disinfection is its relative ease of operation (USEPA, 1996).

The Sentinel™ UV System can contain a high level of sophisticated controls, suitable for attachment to Supervisory Control and Data Acquisition (SCADA) or other remote monitoring systems. It also has on-board fail safe controls that can be programmed to sound an alarm, shut down the system or both upon lamp failure. Additional controls to illuminate a back-up lamp can be added if desired.

Even without automated controls however, operator time is minimal: it will take approximately ten minutes per day (or per shift if required) to check the operation of the lamps, wipers, observe and note irradiance measurements, power consumption, lamp turn-on frequency, gallons processed and flow rate, all of which are automatically recorded and LED displayed by the system. Operator time may be somewhat longer if chemical testing is required (for example, parameters such as turbidity, pH and alkalinity). Continuous chart monitoring can readily be attached if necessary. The UV chamber has viewing ports to observe lamps and wipers.

Major repairs to the system, including the power supply and instrumentation, would necessarily be performed by qualified service technicians.

During the verification period, aspects of the operation were evaluated to determine insofar as is possible over a brief period, the degree of maintenance and "hands on" attention required. For this observation the equipment was run continuously and monitored 24 hours a day until the completion of a period of 27 days. During this time few problems were noted apart from those already enumerated above.

During the continuing operations stage following the challenges, the reactor operated with little intervention. It was noted at one time that the quartz cleaning brush was stopping in mid-travel, but that was an aberration which corrected itself. As the operators grew more confident in their understanding of the system, small anomalies became understood and accepted. The inspections of the lamps, after seeing the same patterns for several days in a row, were less of a concern; shadows and opaque areas were identified as normal and not as scaling intrusions or failures.

4.4.2 UV Sensor

Three of the contained irradiance sensors failed due to unexpected electronics problems. Consequently, the irradiance was hand measured with the portable radiometer at all six lamps during the entire verification test, and compared to the three in line irradiance instruments. The in-line data were not used in the UV Dose calculations but were registered to accommodate corrections to the on-board sensors.

4.4.3 Lamp Fouling/Cleaning

During the operations performance period, and more critically during the verification period, the automatic quartz sleeve wipers ceased operating for many reasons including a broken weld. Wiping was initially set at 15 minute cycles, and then increased to five minute cycles and then to one minute cycles (see Table 4-8). This frequency may have contributed to breakage. Following the wiper repair the frequency of cleaning was reduced from one minute, then to 150 seconds, and then to 500 seconds for the duration of the verification period.

On 4/2 a brush disconnected from the wiper rod. On 4/3, during the repair of the brush, a part of the mechanism fell on and cracked the quartz tube of lamp #1. (The lamps are numbered 1 through 6 from the bottom up, to correspond to the flow path of water.) Also on 4/3, the wiper

for lamp 5 stuck in the extended position. On 4/4 the #5 wiper was repaired, and the wipers on #6 and #3 failed. On 4/5 the #3 and #6 wipers were removed and repaired.

Table 4-8. Wiper Cycle Frequency

Date	Frequency
3-30	900 seconds
3-31	900 seconds
3-31	300 seconds
4-1	150 seconds
4-2	60 seconds
4-3	60 seconds
4-4	wiper failure
4-5	60 seconds
4-6	60 seconds
4-7	150 seconds
4-8	150 seconds
4-9	500 seconds
4-10	500 seconds
4-11	500 seconds
4-12	500 seconds
4-13	500 seconds

On 4/6 the wiper frequency changed to 150 seconds. On 4/7, the #5 wiper again failed and was replaced on 4/8. On 4/8 the frequency was changed to 500 seconds for the duration of the study. Following the last repair, no additional failure occurred. Later, wipers were noted to stop along the lamp, but they self corrected upon activation of the next cycle.

The wiper mechanism is being redesigned and will be the subject of a separate ETV evaluation. CCC determined that the cause of wiper failure was the impact force of the brush with the wiper stop at the end of the extended travel position.

Because the water flow was reduced during non-challenge periods to a rate far below the design flowrate (to 25 gpm instead of the design flow of 500 gpm), there was a greater likelihood of deposits on the quartz tubes (the lamps will have run hotter). During a reevaluation study it would be instructive to reduce the rate of wiping frequency until deposits appear on the quartz tubes, and then increase frequency until deposits do not form as a means of establishing wiper frequency under those conditions.

4.4.4 Lamp Hours and Power Consumption

Power was measured by a utility kilowatt-meter. The meter was installed on the power line that supplied the test unit on 3/31. The Valhalla Digital power meter originally planned for the test was not available.

The life of the lamps is guaranteed by CCC at 3,000 hours. Lamp life will vary with local conditions. Lamp life can degrade by fouling or by power losses. There is some depreciation as the lamps age as well.

Figure 4-5 below shows power consumption during the testing period. Because during the challenge period only at most two lamps were on, power consumption is not constant over time. During the maintenance period the power consumption was approximately 1.046±0.046 kW per lamp. Assuming daily operation of six lamps at full power, the power demand is estimated at 150.6 kW per day.

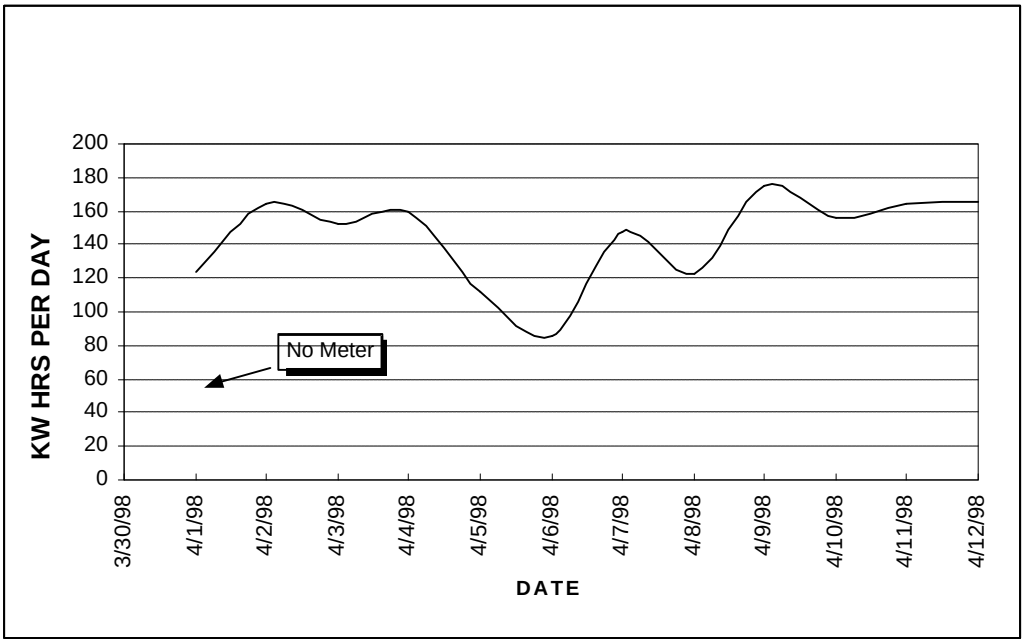

Figure 4-5. Power Used During Testing

Table 4-9 presents kW-h/1000 gal during challenge periods relating to UV dose, and the power consumption (as measured) during the balance of the period (regardless of flowrate).

Following the microorganism challenge periods, from midnight on 4/9/98 and through 2:00 am 4/14/98 (122 hours), the equipment was run continuously at 25 gpm with all six lamps on full power. During this period 840 kWh were used or 6.88 kW/hour.

Table 4-9. Power Consumed during Challenge Test Periods *C. parvum*

Date	Lamps	KWh*	gpm	Calc. mW-s/cm²	kW per 1000 gallons
3/31	2&5 High	2.0845	212	167	0.164
3/31	2&5 Reduced	0.984	214	69	0.077
4/6	2&5 High	2.095	200.4	152	0.174
4/7	2&5 High	2.109	213	159	0.165
4/8	5 Reduced	0.552	214	20	0.043

* - KWh was determined by multiplying voltage and amperage by 1000 for one hour (KVA)

Voltage and amperage readings, except during lamp off times, were stable throughout the period (Figures 4-6 and 4-7). Increased power demand following a reduced power period suggests that initial illumination requires a higher level of power.

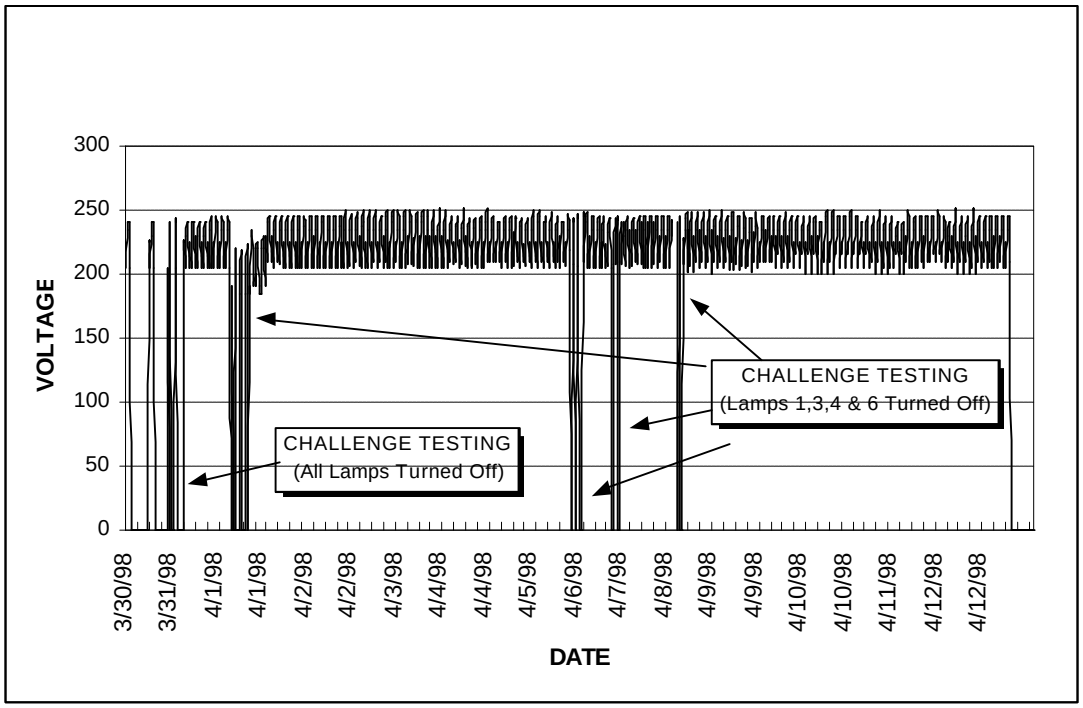

Figure 4-6. Voltage Used During Testing Period

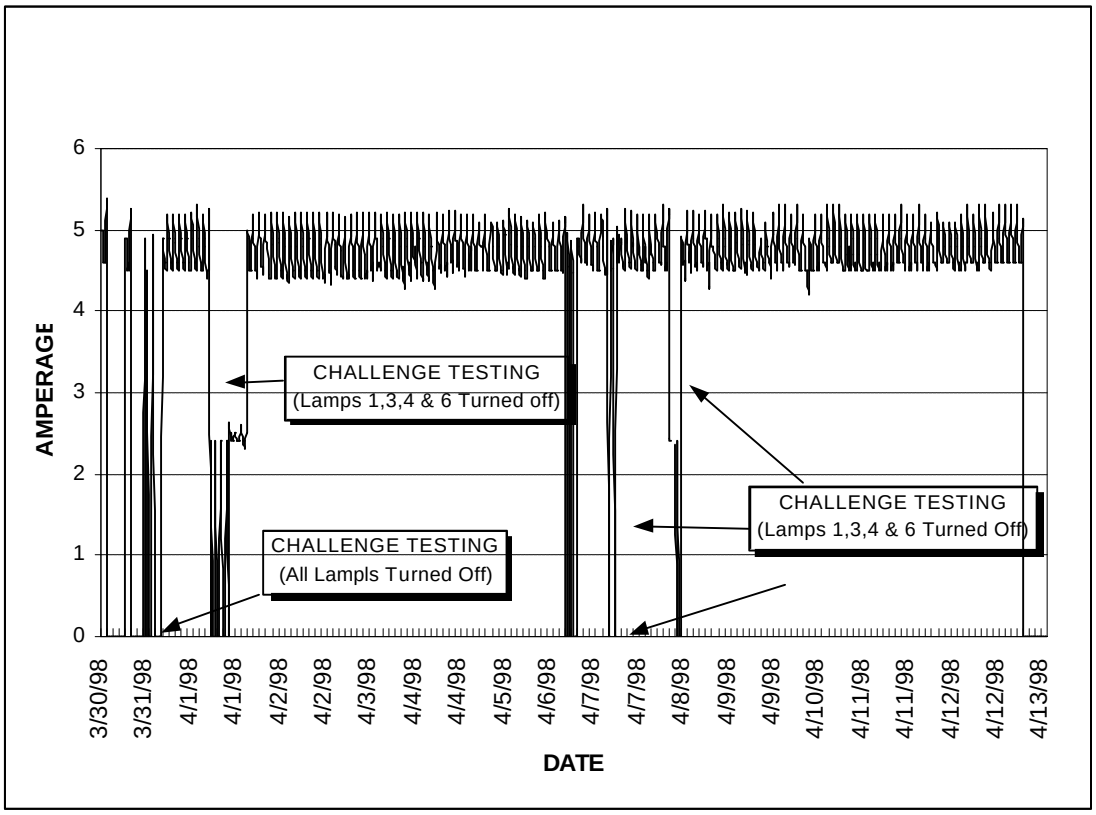

Figure 4-7. Amperage Used During Testing Period

4.4.5 O&M Manual

The Operations and Maintenance (O&M) manual supplied by the manufacturer was specific to this equipment and included all the components of the pilot plant. Drawings and illustrations showing the positions of the meters and controls are included along with explanations of control functions and step-by-step instructions for common maintenance functions, such as: replacement of lamps, quartz tube cleaning and reactor cleaning. Complete instructions for equipment start-up and shut-down procedures were listed in this guide. The control panel is thoroughly explained so that all programmable functions, including wiper cycles, lamp set-points for alarms and other PLC parameters are easily learned by even inexperienced personnel.

Safety measures included detailed instructions concerning high voltage, protection against UV irradiance, and the procedures for mercury spills in the event of lamp breakage. A trouble shooting guide was furnished that included the following potential problems.

- No power
- Emergency stop button engaged
- Transmittance controller not working
- Faulty solenoid

- Low air pressure
- Jammed cylinder
- Water leaks
- UV lamp not operating
- High temperature
- Low or no amp or voltmeter reading

Chapter 5
Limitations

With every drinking water treatment product evaluation, there are often limitations in the assessment methodology, the conditions of testing and the technology itself. The lack of consensus on evaluation methods and procedures or the application of a technology is a reflection of the uncertainties associated with emerging technologies, developing analytical techniques and engineering applications. The resolution of these uncertainties is within the purview of rigorous scientific research and not the ETV program. Rather the ETV Package Drinking Water Treatment Systems pilot verifies the performance of innovative water treatment systems using consensus methods and procedures. The following section describes the limitations of the methods and procedures that were followed in the verification of the performance of the CCC Sentinel^{TM} Ultraviolet radiation technology.

5.1 Method for Determining Viability and Inactivation

There is a need in the water treatment and microbiological communities to establish a consensus for determining *C. parvum* viability/infectivity and inactivation. While methodologies for determining viability of bacteria and other microbes have general acceptance, there is no consensus in the scientific community on *C. parvum* viability/infectivity methods. Research has not yet proven that infectivity in mice correlates to infectivity in humans; human studies to determine the infective dose of *C. parvum* are rare, but have been performed (DuPont et al., 1995). Water quality scientists do not agree that animal (mouse) infectivity is the irrefutable method for estimating. Most water quality scientists agree that the animal infectivity method is the best method presently available for estimating infectivity of the oocyst. The statistical guidance does not exist that allows interpretation of the test results in a manner that is irrefutable.

Water quality investigators, scientists and engineers are reluctant to use animal infectivity studies due to their expense. Additional tests of the performance of the Sentinel^{TM} would be very informative, and provide a more definitive dose response curve. For example, the experimental design had not anticipated that the lower UV dose was effective in inactivating *C. parvum*. Consequently, there was no UV dose response curve formed from the data. For a dose response curve to be meaningful, many additional data points would be required, and this is beyond the purpose of this study.

5.2 UV Dose Estimates and Measurements

There is a general lack of agreement among drinking water scientists and engineers as well as understanding as to the best ways to determine and report UV dosage. In drinking water, three approaches are used to determine the UV dose:

1. Determination of UV irradiance from sensor readings in mW/cm^2 and multiplication of irradiance by the residence time in seconds that is determined either theoretically or by tracer studies.
2. Determination of UV dose using a biological indicator such as *Bacillus subtilis* spores or MS-2 bacteriophage. The dose response curve is determined from bench-scale collimated

beam tests and then the full-scale unit is challenged with the biological indicator, inactivation determined and actual UV dose is calculated from the dose response curves established from the collimated beam tests.

3. Determination of dosage using a theoretical MPSS model first termed in the wastewater UV literature as the point-source summation model.

The work presented here uses a very sophisticated mathematical model similar to the point-source summation model, to calculate dosage. This model is undergoing peer review as part of its publication in a scientific journal. However, the model results are limited by a lack of verification data from more reliable electronic radiometer and actual velocity measurements or from biological indicator results. Any comparison of the UV dose estimated in this study by the MPSS method to the UV dose measured or estimated by another method is neither intended nor recommended.

5.3 Low Flow Rate Testing

The system was designed to handle up to 500 gpm. It was tested at approximately 215 gallons per minute (gpm) during the microbiological challenge testing and run at 25 gpm, during periods when the information on O&M was collected due the limitations of the test site. Unfortunately, the effects on the ability of the system to inactivate (oo)cysts as well as lamp operation, sensor life, cleaning frequency and other O&M parameters at the higher flow rate of 500 gpm were not collected in this study.

5.4 Feed Water Conditions

The verification testing was performed on a finished water source whose turbidity was ≤0.11 NTU, True Color was 5 TCU and whose UV_{254} absorption coefficient was between 0.02 and 0.06 cm^{-1} during microbiological challenge testing. System performance is highly dependent on feed water quality characteristics. UV irradiance in water may be limited to waters of low turbidity, and may have additional restraints determined by water chemistry, for example, pH, temperature, UV absorption, nitrates, TOC and True Color.

5.5 Exclusion of Giardia Data

CCC elected to evaluate the performance of the Sentinel™ in inactivating *G. muris* by using the excystation method. Although the *C. parvum* results demonstrate inactivation via animal infectivity results, the same conclusion cannot be drawn for *G. muris. G. muris* may not necessarily fully represent the human pathogen, *Giardia lamblia*. However, if interested, the reader may review *G. muris* data in Appendix L.

Chapter 6
Conclusions

Through this testing it was established that at a process flow rate of 215 gpm the Calgon Carbon Corporation Sentinel™ UV Reactor could obtain an estimated 3.9 log inactivation of *C. parvum* oocysts as determined by animal infectivity results with one lamp illuminated (out of six) at reduced power (0.5 kW). Greater (> 4 log) inactivation was achieved at 215 gpm with higher UV doses, respectively, with two lamps at reduced power (0.5 kW each), and with two lamps at full power (1.0 kW each), again as determined by animal infectivity results.

Furthermore, the use of *in vitro* methods like the vital dyes and *in vitro* excystation significantly under-estimated oocyst inactivation when compared to neonatal mouse infectivity (Figure 4-3).

During the verification period, water quality parameters that influence UV absorbance were measured to assist in evaluating other waters for application of this UV system. During the challenge periods, UV_{254} absorption coefficient was between 0.02 and 0.06; turbidity was ≤0.11 NTU. No iron or manganese was detected in the sample water; nitrates were no greater than 3.7 mg/L and total organic carbon was no greater than 4.3 mg/L. Other water quality conditions would require short duration, site specific testing to establish performance.

Also of importance to this study was the operation of the equipment in the field. Several deficiencies were noted with wiper failures, irradiance sensor, and attenuation tubes.

CCC has informed COA and NSF that they are taking action to improve these portions of the system.

Deficiency	**Action Taken**
Wiper Failures	More intensive plant quality control over their manufacture.
Irradiance Sensor	A re-design of the sensor circuit board.
Attenuation Tubes	Changing the materials from Teflon to an aluminum mirror configuration.

These elements will be required to undergo additional and separate verification testing.

Chapter 7
Recommendations

Although the results of this study are very promising, they warrant additional research and independent confirmation by other investigators to insure their validity. For example, the threshold of UV dose at which there is a consistent $\log_{10}$ reduction of oocysts needs to be established to develop the appropriate safety factors for the field application of UV equipment. It is important to regulators and users that the effective threshold UV dose be established. The threshold UV dose can be developed from an ID_{50} curve (a curve that defines the UV dose at which fifty percent of the test animals become infected when fed treated oocysts). The development of the ID_{50} curve need only be performed under controlled laboratory conditions.

Consensus is needed on the use of the neonatal mouse infectivity method to represent the inactivation of oocysts. The relationship between various viability methods, the study of which is already in progress, is necessary for deciding upon a final method for assessing the inactivation of cysts and oocysts. Once the scientific community can agree upon a method, then NSF and the EPA can modify the ETV Test Plan accordingly and develop a standardized methodology. The cost of performing the method must be affordable as well accurate, precise and reproducible.

The variance associated with the predictions of the existing animal infectivity logistical dose response model (LOGIT) needs to be addressed with additional laboratory studies. Of particular concern is when the LOGIT model extrapolates the decrease in oocyst infectivity outside the initial calibration range of the model.

The estimation of UV dose in the field needs additional research and refinement. The MPSS model needs verification using bioassay methods or radiometers that are not attenuated. NSF recommends that the UV dose produced by the Sentinel™ with the number of lamps ranging from one to six be, at a minimum, estimated using a bioassay technique.

Since flow rate affects UV dose, all UV equipment should be verified at its maximum design flow rate. In addition, the flow rate can affect the build-up of scale and other UV inhibiting substances on the quartz sleeve of the UV lamps. For the verification of operation and maintenance parameters, UV equipment should be tested under the minimum, median and maximum flow rates. NSF will recommend these modifications to the ETV test plan for Microbiological Inactivation by UV Technologies.

This ETV test focused on the inactivation of *C. parvum* and did not address other microbial pathogens such as bacteria or viruses that might be present. Site specific testing would also be suggested in determining applicability to other microbes.

Chapter 8
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