September 2003
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Environmental Technology Verification Report

UV Disinfection For Reuse Applications

Aquionics, Inc. bersonInLine® 4250 UV System

Prepared by

NSF International

Under a Cooperative Agreement with
U.S. Environmental Protection Agency

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency **NSF International**

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**ULTRAVIOLET DISINFECTION**	
APPLICATION:	**DISINFECTION OF GRANULAR OR FABRIC FILTERED EFFLUENT AND MEMBRANE FILTERED EFFLUENT FOR WATER REUSE**	
TECHNOLOGY NAME:	**bersonInLine® 4250 UV System**	
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NSF International (NSF) operates the Water Quality Protection Center (WQPC) under the U.S. Environmental Protection Agency's (EPA) Environmental Technology Verification (ETV) Program. The WQPC evaluated the performance of the Aquionics, Inc. bersonInLine® 4250 UV System (bersonInLine® System) for two water reuse applications: (1) disinfection of granular or fabric filtered secondary wastewater effluent, and (2) membrane filtered secondary wastewater effluent. HydroQual, Inc. (HydroQual) performed the verification test.

The EPA created the ETV Program to facilitate deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high quality, peer reviewed data on technology performance to those involved in the design, distribution, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations, stakeholder groups consisting of buyers, vendor organizations, and permitters, and the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and verifiable quality are generated and that the results are defensible.

Technology Description

The following description of the technology is provided by the vendor and does not represent verified information.

The bersonInLine® System uses high-output, medium-pressure, mercury lamps that are oriented horizontally and perpendicular to the direction of flow. Each lamp has an ultraviolet (UV) output rating of approximately 120 watts (W) at 254 nm and a total power draw of 3,500 W. The lamps have an effective arc length of 350 mm. Each lamp is housed in a quartz sleeve with a wall thickness of 1.26 mm, resulting in a UV transmittance of approximately 90%. The sleeves penetrate both end plates of the reactor module and are secured with watertight seals. The reactor module, which provides a straight-through flow pattern, is a round, flanged, stainless steel unit that has an inside diameter of 350 mm and is 755 mm long. Intersecting this housing is a cylinder with the same diameter and end plates, which houses the lamp connections and drive mechanism of the cleaning system.

The test system consisted of two, full-scale bersonInLine® System modules in series with six lamps per module, mounted in a staggered array with centerline spacing of 75 mm. Each module was connected to an independent power supply cabinet with an ECtronic control unit and was supplied with 480 Volt (V) delta power at 60 amps. Each cabinet had three power supplies; each of which drove two lamps. The control panel allowed for direct lamp power manipulation in three, finite increments: 100%, 125%, and 140% of design power. The control panel contained information that allowed the operator to interpret the status of the system, including: an on/off indicator for each lamp, an alarm indicator that would detect overheating of the module housing, and an hour counter that displayed the hours that the lamps had been in operation. Each reactor had a UVector detector located on the top of the reactor housing that monitored the intensity of the top lamp. The output from the detector was displayed as a bar graph with UV intensity values of 100%, 90%, 80%, and 70% (the alarm set point).

Each reactor housing was equipped with an automatic sleeve cleaning system, consisting of teflon wipers that were driven the full length of the quartz sleeve with a motor and lead-screw drive. The wipers were not operational during the verification testing, as there was no validation test planned for this equipment. However, the wipers were operated for one cycle during lamp warm-up to remove any debris or residue, and to ensure the cleaning system was returned to the idle position.

The influent water was introduced at the first module's inlet flange. This flange contained a flow modifier insert that, in effect, extended the pipe length inside the reactor and kept the flow focused toward the lamp array. The flow modifier minimized the effect of the dead spaces, such as the access hatch, that were present upstream of the lamp array. The flow modifier did not change the operating flow range in the UV unit.

Verification Test Description

Test Site

The test site was located at the Parsippany-Troy Hills (PTRH) Wastewater Treatment Plant in Parsippany, New Jersey. The test site had two, 80,000-liter tanks for preparation of challenge water, and two, 71 hp centrifugal pumps to provide challenge water at flow rates up to 13,000 L/min or recirculation flow rates of 1,100 L/min for mixing the tanks. Influent flow was metered with a magnetic flow meter, which was calibrated by the tank drawdown method before testing began.

Methods and Procedures

All methods and procedures followed the *ETV Verification Protocol for Secondary Effluent and Water Reuse Disinfection Application* (protocol) dated October 2002. The bersonInLine® System was tested

under Element 1 of the protocol, Dose Delivery Verification for Reuse Applications. Testing was conducted for granular or fabric filtered effluent at a nominal transmittance of 55%, and for membrane filtered effluent at a nominal transmittance of 65%.

Before dose delivery verification testing began, the lamps were aged for 100 hours to allow the lamp intensity to stabilize. During the burn-in period, the lamps were not turned off or restarted. There were no lamp failures during the burn-in period.

Power consumption for the two-reactor train, inclusive of all lamps and circuitry, was monitored during the startup, characterization, and bioassay flow tests. The 480 V, three-phase power was monitored at the main disconnect panel with a power datalogger. During the startup phase, the power consumption was measured at all three power settings.

Headloss measurements for five flow rates were determined by monitoring the pressure drop across the reactor train with a manometer system. The hydraulic characterization included the measurement of velocity profiles at the inlet (first module) and outlet (second module) flanges. A pitot tube system, mounted at the flanges, provided nine monitoring positions for each location. The 720 pressure drop measurements were converted to velocity using calibration data for the pitot tube assemblies.

The microorganism MS2, an F-specific RNA bacteriophage, was used for all bioassay tests. The dose-response calibration of the MS2 stock batch and seeded influent samples was achieved using a collimated beam apparatus.

Before each flow test series, the modules were manually cleaned and inspected. The sleeve cleaning system was operated for one cycle, water flow was started, and the lamps were turned on to verify all lamps were operating.

A batch of challenge water was prepared immediately before each flow test series by filling the tank with potable water (65 percent transmittance (65%T)) or filtered secondary effluent (55%T), and adding sodium thiosulfate to remove residual chlorine. Once onsite testing verified the absence of residual chlorine, instant coffee was progressively added to reduce the transmittance to the target level. Finally, MS2 bacteriophage was added to the tank to achieve the target level of 10^5 to 10^7 pfu/mL, and the tank was mixed for 30 minutes. Five flow conditions (1,052, 2,101, 3,941, 7,355, and 10,510 L/min) were replicated at least four times for each transmittance.

Influent and effluent samples were collected simultaneously and in triplicate, resulting in six samples for each flow test. The concentration of viable MS2 bacteriophage in flow test and dose-response samples was enumerated, using a microbiological technique based on ISO 10705-1. Transmittance of the challenge waters was measured on every influent sample and on the seeded influent samples used for dose-response analysis. Quality assurance/quality control (QA/QC) requirements included field duplicates, laboratory duplicates, and spiked samples, as well as appropriate equipment/instrumentation calibration procedures. Details on all field procedures, analytical methods, and QA/QC procedures are provided in the full verification report.

Verification Performance

Power Consumption and Headloss Results

The power consumption for the two-module system, which included power use by the auxiliary circuitry in the control panels, was 34 kilowatts (kW) at the beginning of lamp life setting or 2.8 kW per lamp. The highest power setting available showed a power consumption of 45 kW.

Headloss though the lamp modules exists at any non-negligible flow rate, due to the hydraulic resistance from obstacles such as lamps and mounting hardware. In ideal, turbulent systems, the headloss increases as a function of the square of flow velocity. The headloss (cm) as a function of flow (L/min) for the two-module bersonInLine® System used in this test is approximated by the relation:

$$headloss\ (cm) = 3.14 \times 10^{-8}\ (flow)^2 + 1.18 \times 10^{-3}\ (flow) + 2.72$$

The headlosses are measured for the flow rates used in this verification test and are dependent on the flow modifier used at the inlet flange. In order to extend the results of this verification test to a commercial installation, the commercial units must contain an identical flow modifier.

The protocol required the influent flow velocities to be between 0.8 and 1.2 of the theoretical value. For the influent data, the minimum and maximum of the velocity/theoretical ratios were all within the 0.8 to 1.2 range. Based on this analysis, the influent piping to the system provided appropriate control of inlet hydraulic conditions. For the effluent data, the minimum and maximum of the measured velocity to theoretical velocity ratio showed a greater range of variability than for the influent data. The effluent velocities exceeded the target value of 1.2 for the ratio of the measured velocity to the theoretical value at the highest flow rate.

Dose Response Calibration Curve

Thirteen, valid, dose-response tests were conducted during this verification test. The delivered doses were corrected for 2.5% reflectance at the surface of the sample. The calibration curve for the MS2 bacteriophage stock, using a second-order polynomial equation, is:

$$Dose = 2.071(survival)^2 - 12.57(survival) + 2.191$$

$$Survival = Log_{10}\left(\frac{N}{N_0}\right)$$

$$N_0 = \text{MS2 concentration in undosed sample}$$

$$N = \text{MS2 concentration in dosed sample}$$

The calibration curve was validated using QC criteria for the acceptance of the dose-response data that was based on statistical analysis of MS2 dose-response data from several independent labs. The dose-response data generated for this verification test met the established criteria.

Dose-Flow Assays

Demonstrating the effective delivered dose for a specific UV system's reactor is the technical objective of the protocol. The delivered dose for a specific UV system is the UV dose that provides the equivalent degree of inactivation of a target pathogen, as measured with a collimated-beam apparatus. The collimated beam apparatus can accurately monitor the UV intensity reaching the fluid and the exposure time to an organism.

Therefore, the MS2 bacteriophage log survival ratios measured on samples from the field test unit and presented in the final report for the bersonInLine® System are converted to an effective delivered dose using the calibration curve from the dose-response data. MS2 bacteriophage is used for the testing because it has a high tolerance for UV light, typically requires a larger delivered dose for inactivation than most bacterial and viral organisms, and has a consistent dose-response over repeated applications. This allows development of dose-response and delivered dose relationships that encompass dose levels required for most disinfection applications. The calculated, effective, delivered dose is used to design a

UV reactor for a specific application, based on site-specific criteria for inactivation of a target microorganism.

As described in the protocol, the final analysis of the flow test data is based on the lower 75% confidence interval (C.I.) results. The results for the two-module test system are shown in Figure 1, where they are fitted with a power function. For comparison, the average dose delivery curves are also shown, which track closely with the lower 75% C.I. curve.

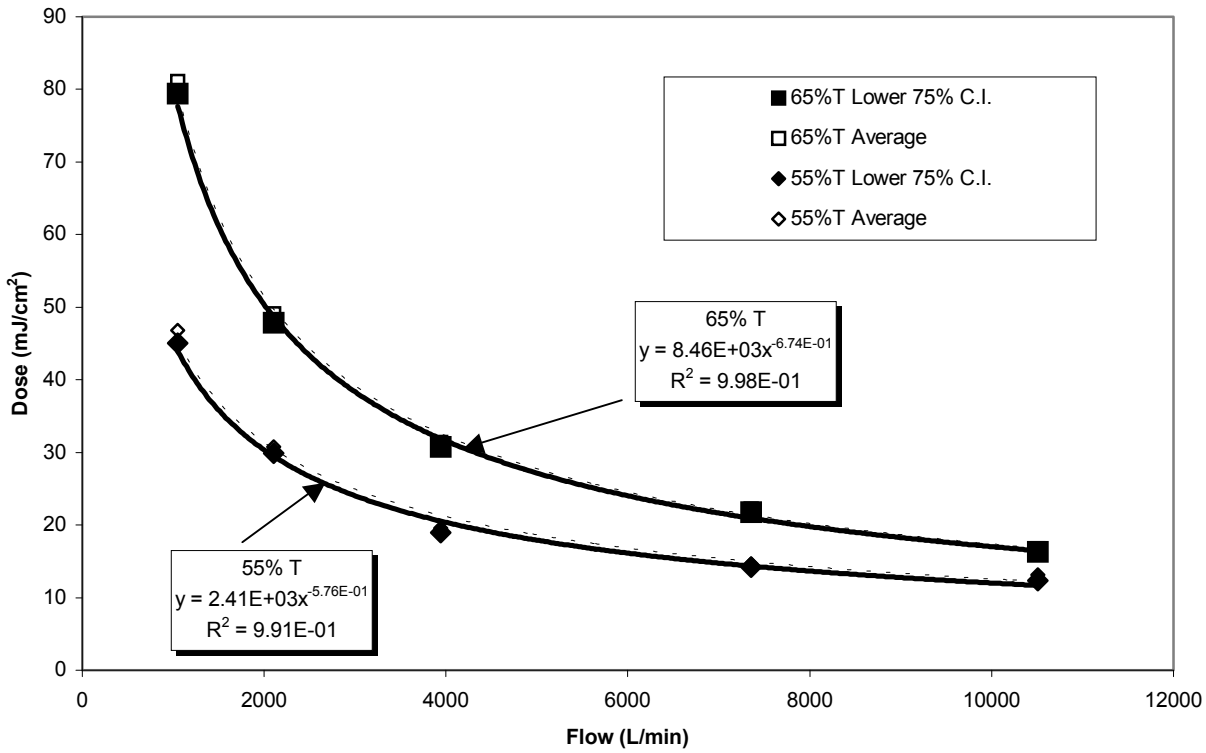

Figure 1. Dose delivery curves based on lower 75% C.I. for granular or fabric filtered effluent (55%T) and membrane filtered effluent (65%T).

Scalability

The protocol identified the elements of UV system design that are critical for designing larger systems, based on the data obtained from the verification. The appropriate data for these design elements were obtained during the verification.

The bersonInLine® modules used in the test were full-scale reactors sold commercially. Therefore, verification test data can be applied directly to systems using these modules with the same flow rates and flow modifier insert. The verification report provides a detailed discussion on application of the data for larger flow systems.

Quality Assurance/Quality Control

NSF performed QA/QC audits of the test site at PTRH and HydroQual laboratory during testing. These audits included: (a) a technical systems audit to assure the testing was in compliance with the test plan, (b) a performance evaluation audit to assure that the measurement systems used by HydroQual were

adequate to produce reliable data, and (c) a data quality audit of at least 10% of the test data to assure that the reported data represented the data generated during the testing. In addition to quality assurance audits performed by NSF, EPA QA personnel conducted a quality systems audit of NSF's QA Management Program and accompanied NSF during audits of the HydroQual facilities.

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United States Environmental Protection Agency			

NOTICE: Verifications are based on an evaluation of technology performance under specific, predetermined criteria and the appropriate quality assurance procedures. EPA and NSF make no expressed or implied warranties as to the performance of the technology and do not certify that a technology will always operate as verified. The end user is solely responsible for complying with any and all applicable federal, state, and local requirements. Mention of corporate names, trade names, or commercial products does not constitute endorsement or recommendation for use of specific products. This report in no way constitutes an NSF Certification of the specific product mentioned herein.

Availability of Supporting Documents

Copies of the *ETV Verification Protocol for Secondary Effluent and Water Reuse Disinfection Application* (Protocol), dated October 2002, the Verification Statement, and the Verification Report are available from the following sources:

1. ETV Water Quality Protection Center Manager (order hard copy)
   NSF International
   P.O. Box 130140
   Ann Arbor, Michigan 48113-0140

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

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

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

Environmental Technology Verification Report

Verification of Ultraviolet (UV) Disinfection For Water Reuse Applications

Aquionics bersonInLine® 4250 UV System

Prepared for

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Prepared by

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Under a cooperative agreement with the U.S. Environmental Protection Agency

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Notice

The U.S. Environmental Protection Agency (EPA), through its Office of Research and Development, has financially supported and collaborated with NSF International (NSF) under a Cooperative Agreement. The Water Quality Protection Center, Source Water Protection area, operating under the Environmental Technology Verification (ETV) Program, supported this verification effort. This document has been peer reviewed and reviewed by NSF and EPA and is recommended for public release.

Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

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Acronyms and Abbreviations

A	Amperage
Ave.	Average
ANSI	American National Standards Institute
C	Celsius
CFD	Computational Fluid Dynamics
C.I.	Confidence Interval
cm	Centimeter (10^{-2} meters)
EOL	End-of-life
EPA	United States Environmental Protection Agency
ETV	Environmental Technology Verification
ft	Foot
G	Velocity Gradient
gal	Gallons
gpm	Gallons per minute
hp	Horsepower
HydroQual	HydroQual, Inc.
Hz	Hertz
I	Intensity
In	Inch
ISO	International Standards Organization
kg	Kilogram
kW	Kilowatt
L	Liter
L/min	Liters per minute
Ln	Natural logarithm
log	Base 10 logarithm
LPHO	Low pressure high output UV lamps
m	Meters
μm	Micron (10^{-6} meters)
mA	Milliamperage
MGD	Million gallons per day
mg/L	Milligrams per liter
min	Minutes
mJ	Millijoule
mJ/cm^2	Millijoule per square centimeter
mL	Milliliters
mm	Millimeter (10^{-6} meters)
mW	Milliwatt
mW/cm^2	Milliwatt per square centimeter
nm	Nanometers (10^{-9} meters)
NIST	National Institute of Standards and Technology
NRMRL	National Risk Management Research Laboratory
NSF	NSF International
NTU	Nephelometric Turbidity Units

NWRL	National Water Research Laboratory
O&M	Operation and maintenance
ORD	Office of Research and Development, EPA
OSHA	Occupational Safety and Health Administration
%T	Percent Transmittance
PDC	Power Distribution Center
pfu	Plaque forming units
pfu/mL	Plaque forming units per milliliter
PLC	Programmable Logic Center
ppm	Parts per million
PTRH	Parsippany-Troy Hills
PVC	Polyvinyl chloride
QA	Quality assurance
QAPP	Quality assurance project plan
QC	Quality control
QMP	Quality management plan
RPD	Relative percent difference
SAG	Stakeholders Advisory Group
sec	Second
SOP	Standard operating procedure
SWP	Source Water Protection Area, Water Quality Protection Center
T	Temperature
TO	Testing Organization
UV	Ultraviolet
UVC	Ultraviolet Radiation in the range of 230 nm to 280 nm
UVDIS	Software package with an independently developed mathematical model of the UV disinfection process recommended by EPA
UVT	Ultraviolet transmittance
V	Volt
VO	Verification Organization
VR	Verification Report
VTP	Verification Test Plan
W	Watts
WQPC	Water Quality Protection Center

Chapter 1
Introduction and Background

1.1 The ETV Program

1.1.1 Concept of the ETV Program

The ETV Program was created by the EPA to accelerate the development and commercialization of improved environmental technologies through third-party verification and performance reporting. The goal of the ETV Program is to verify performance characteristics of commercial-ready environmental technologies through the evaluation of objective and quality-assured data so that designers, potential buyers, and permitting authorities are provided with an independent and credible assessment of the technology that they wish to use.

The ETV Program is made up of six Centers, one of which is the Water Quality Protection Center (WQPC) that is administered by NSF. The goal of the WQPC is to verify technologies that protect the quality of ground and surface waters by preventing or reducing contamination. The technologies evaluated by the WQPC are subdivided into several categories, among which is the validation of disinfection technologies, including ultraviolet (UV) radiation.

A technology panel formed through NSF oversaw the development of the *Verification Protocol for Secondary Effluent and Water Reuse Disinfection Applications* (protocol) (NSF, 2002). The Stakeholder Advisory Group (SAG) consists of various academic, commercial, and consulting professionals with experience in disinfection technology. This protocol provided the framework for the development, approval, and implementation of the *Verification Test Plan for the Aquionics, Inc. UV Disinfection System for Reuse Applications* (see Appendix A) under which the present verification test was conducted.

1.1.2 The ETV Program for Water Reuse and Secondary Effluent Disinfection

The protocol for UV disinfection verification consists of three test elements from which a vendor may choose.

<u>Test Element 1: Dose Delivery Verification.</u> This series of bioassays with MS2 bacteriophage tests the dose delivery of the disinfection system under different combinations of source water and UV transmittance (UVT) at 254 nm. The test conditions for the secondary effluent applications differ slightly from the test conditions for the reuse application.

- Secondary Effluent test conditions:
  - 55% Transmittance (%T)
  - 65%T
  - 75%T
- Reuse Applications test conditions (National Water Research Institute and American Waste Water Association Research Foundation, 2000):
  - Granular or Fabric Filtered Effluent – 55%T
  - Membrane Filtered Effluent – 65%T
  - Reverse Osmosis Effluent – 90%T

Test Element 2: Dose Delivery Reliability Verification. This series of tests verifies the long-term reliability of the specific system's configuration.

- Quartz Surface Maintenance

  Assessment of the efficacy of a UV system's automatic cleaning device to consistently maintain the quartz surfaces in a clean state, efficiently transmitting the UV energy to the liquid.

- System Reliability

  Assessment of system response control and a qualitative assessment of UV system monitors, alarms, and/or indicators.

- Process Control

  Assessment of the ability of the UV system to automatically monitor and/or adjust UV doses to changing conditions.

Test Element 3: UV Design Factor Verification. This series of tests determines the change in performance as the system ages through regular use.

- Quartz Fouling

  Quantitative determination of the long-term attenuation factor for quartz transmittance losses.

- Lamp Age

  Quantitative determination of the relative UV output after continuous, normal operation for the vendor-prescribed effective life.

The technology vendor determines the test elements of the protocol to use for the technology verification, based on the applications of the technology. There is no requirement that the vendor test against all elements of the protocol. The verifications in Test Elements 2 and 3, which are oriented to operation and maintenance issues, are not mandatory.

1.1.3 The Aquionics, Inc. bersonInLine® 4250 UV System Verification Test

This verification test of the Aquionics, Inc. (Aquionics) bersonInLine® 4250 UV disinfection system (bersonInLine® System) focused on the dose delivery, which is the most critical operational behavior and is evaluated within Test Element 1. This verification test consisted of dose delivery verification for the reuse applications at 55% and 65% water transmittance. The test included using transmittance-adjusted potable water and media filtered secondary effluent for bioassay testing, headloss measurements, and velocity profile measurements.

1.2 Mechanism of UV Disinfection

UV light radiation is a widely accepted method for accomplishing disinfection of treated wastewaters. Its germicidal action is attributed to its ability to photochemically damage links in

the DNA molecules of a cell, which prevents the future replication of the cell, effectively "inactivating" the microorganism. UV radiation is most effective in the region of the electromagnetic spectrum between 230 nm and 280 nm (referred to as the UVC range); this corresponds to the UV absorbance spectrum of nucleic acids. The optimum germicidal wavelengths are in the range of 255-265 nm.

1.2.1 Practical Application of UV Disinfection

The dominant commercial source of UV light for germicidal applications is mercury vapor, electric discharge lamps. They are commercially available in "low-pressure" and "medium-pressure" configurations.

The conventional, low-pressure lamp operates at 0.007 mm of Hg, and is typically supplied in long lengths (0.75-1.5 m), with diameters between 1.5 and 2 cm. The major advantages of the low-pressure lamp are that its UV output is essentially monochromatic at a wavelength of 254 nm, and it is energy efficient, converting approximately 35-38% of its input energy to UV light at the 254 nm wavelength. The UV power output of a conventional, low-pressure lamp is relatively low, typically about 25 W at 254 nm for a 70-75 W, 1.47-m long lamp. Recent developments have produced low-pressure, high-output (LPHO) lamps (~0.76 mm of Hg) by using mercury in the form of an amalgam and/or higher current discharges. LPHO lamps are very similar in appearance to the conventional, low-pressure lamps, but have power outputs 1.5 to 5 times higher, reducing the required number of lamps for a given application. LPHO lamps have approximately the same efficiency of conventional, low-pressure lamps.

Medium-pressure lamps operate from 300-30,000 mm of Hg and can have many times the total UVC output of a low-pressure lamp. Medium-pressure lamps emit polychromatic light and convert from 10-20% of their input energy to germicidal UV radiation, resulting in lower efficiency. However, the sum of all the spectral lines in the UVC region for a medium-pressure lamp results in three to four times the germicidal output when compared to low-pressure lamps. Because of their very high UV output rates, fewer medium-pressure lamps are needed for a given application when compared to low-pressure lamps.

Both low- and medium-pressure germicidal lamps are sheathed in quartz sleeves, configured in geometric arrays, and placed directly in the wastewater stream. The lamp systems are typically modular in design, oriented horizontally or vertically, mounted parallel or perpendicular to the water flow, and assembled in single or multiple channels and/or reactors.

The key design consideration of UV systems is efficient delivery of the germicidal UV energy to the wastewater and to the organisms. The total germicidal effectiveness is quantified as the "UV dose," or the product of the UV radiation intensity (I, W/cm^2) and the exposure time (t, seconds) experienced by a population of organisms. The effective intensity of the radiation is a function of the lamp output and of the factors that attenuate the energy as it is deposited into the water. Such attenuating factors include: (a) simple, geometric dispersion of the energy as it moves away from the source, (b) absorbance of the energy by the quartz sleeve housing the lamp, and (c) the UV absorbance (UV demand) of the energy by constituents in the wastewater.

1.2.2 A Comparison of UV and Chemical Disinfection

UV disinfection uses electromagnetic energy as the germicidal agent, differing considerably from chemical disinfection agents such as chlorine or ozone. The lethal effect of UV radiation is manifested by the organism's inability to replicate, whereas chemical disinfection physically destroys the integrity of the organism via oxidation processes. Germicidal UV radiation does not produce significant residuals, whereas chemical disinfection results in residuals that may exist long after the required disinfection is complete. Chemical residuals, such as chlorine or chloramines, may have a detrimental effect on organisms in the natural water system to which the effluent is released. An additional, subsequent process, such as dechlorination, usually mediates this detrimental result. This residual effect does not exist for UV disinfection processes.

Chemical disinfection involves shipping, handling, and storing potentially dangerous chemicals. In contrast, dangers associated with UV disinfection are minimal. A UV disinfection system produces high-intensity UVC radiation, which can cause eye damage and skin burns upon exposure. However, these dangers are easily mediated with protective clothing and goggles and by properly enclosing or shielding the UV system. A minor hazard exists because the lamps contain very small amounts of liquid or amalgamated mercury, requiring that lamps be disposed of properly. The primary cost associated with operating UV disinfection systems is the continuous use of significant amounts of electrical power and routine maintenance, whereas chemical generation and use is the primary operating expense for chemical disinfection systems.

1.2.3 Complications of Determining Dose Delivery

In theory, the delivery of UV radiation to wastewater can be computed mathematically if the geometry and hydraulic behavior of the system are well characterized. Ideally, all elements entering the reactor should be exposed to all levels of radiation for the same amount of time; a condition described as turbulent, ideal, plug flow. In fact, non-ideal conditions exist; there is a distribution of residence times in the reactor due to advective dispersion and to mixing in the reactor. The degree to which the reactor strays from ideal plug flow directly impacts the efficiency of dose delivery in the system.

The hydraulic behavior of the system is the most difficult performance factor to compute accurately. Such problems are modeled numerically using a computational fluid dynamic (CFD) model. To be accurate, a CFD model must include all submerged components of a real reactor, such as quartz-sleeve mounting hardware, wiring, baffles, sensors, and cleaning systems, that influence the flow path of the water parcels. To make the problem solvable, simplifying assumptions are often used. Such calculations quickly become inaccurate at high doses where a small percentage of microorganisms that escape disinfection begin to dominate the effluent populations.

1.2.4 Summary of the Bioassay Method

Bioassay testing is a method for determining the germicidal dose delivery to wastewater by using an actual, calibrated, test organism. For these verification tests, the bacteriophage MS2 was used. The survival ratio of the organism is calibrated to a well-controlled UV dose in the

laboratory with a dose-response procedure. The same organism is then used to field-challenge the actual disinfection system under specified conditions. Field tests generate a survival ratio of the organism under specified test conditions that then can be converted into an effective delivered dose through the dose-response calibration curve.

The advantages of the bioassay method are: (1) The organism records the actual germicidal dose; (2) The organism can be produced in such large quantities that every milliliter of test solution contains a statistically significant number of organisms; and (3) There are no simplifying assumptions about the hydraulic behavior of the reactor.

It is important to remember that this bioassay method is not used to determine the effective germicidal UV dose for any specific pathogen. It is a method of quantifying germicidal dose delivery. The test organism (MS2 in this case) can be thought of as a device to record the germicidal UV exposure of all parcels of water with a high degree of spatial resolution.

Chapter 2
Roles And Responsibilities of Participants

2.1 NSF's Role

The WQPC's ETV is administered through a cooperative agreement between the EPA and NSF, its verification partner organization. NSF administered the program and selected a qualified TO, HydroQual, Inc. (HydroQual) to develop and implement the Verification Test Plan (VTP). NSF's other responsibilities included:

- Review and approval of the VTP;
- Oversight of quality assurance, including the performance of technical systems and data quality audits as prescribed in the Quality Management Plan for the ETV WQPC;
- Coordination of Verification Report peer reviews;
- Approval of the Verification Report; and
- Preparation and dissemination of the Verification Statement.

Key contacts at NSF relating to this VTP include:

Mr. Thomas Stevens, Program Director
Ms. Maren Roush, Project Coordinator
NSF International
789 Dixboro Road
Ann Arbor, MI 48105
(734) 769-5347
(734) 769-5195 (fax)
stevenst@nsf.org
mroush@nsf.org

2.2 EPA's Role

The EPA, Office of Research and Development, through the Urban Watershed Management Branch, Water Supply and Water Resources Division, National Risk Management Research Laboratory (NRMRL) provided administrative, technical, and quality assurance guidance and oversight on all WQPC activities. The EPA had review and approval responsibilities through various phases of the verification project, including:

- Verification Test Plan
- Verification Report
- Verification Statement

The key EPA contact for the WQPC is:

Mr. Ray Frederick
USEPA – NRMRL Urban Watershed Management Branch
2890 Woodbridge Avenue (MS-104)
Edison, NJ 08837-3679
(732) 321-6627
(732) 321-6640 (fax)
Frederick.ray@epa.gov

2.3 TO's Role

The selected TO, HydroQual, has a well-established, international reputation for expertise in the area of ultraviolet disinfection technologies.

Mr. O. Karl Scheible, Project Director, provided overall technical guidance for the verification test program. Dr. Egon T. Weber II, Ph.D., served as the Project Manager and was responsible for day-to-day operations, project administration, and laboratory setup and oversight. Mr. Michael C. Cushing was the lead field technician, responsible for system installation, startup, sampling, and record keeping. Mr. Prakash Patil and Ms. Tina McKay were the project microbiologists. Other HydroQual personnel with support roles during the verification project include Ms. Joy McGrath (QA/QC Officer) and Mr. Francisco Cardona (Field/Lab Support). HydroQual also used additional in-house staff as required.

HydroQual's responsibilities included:

- Developing the VTP in conformance with the protocol, including its revisions in response to comments made during the review period;
- Coordinating the VTP with the vendor and NSF, including documentation of equipment and facility information as well as specifications for the VTP;
- Contracting with sub-consultants and general contractors, as needed, to implement the VTP;
- Coordinating and contracting, as needed, with the host test facility and arranging the necessary logistics for activities at the plant site;
- Managing the communications, documentation, staffing, and scheduling activities to successfully and efficiently complete the verification;
- Overseeing and/or performing the verification testing per the approved VTP;
- Managing, evaluating, interpreting, and reporting the data generated during the verification testing; and
- Preparing the Draft Verification Report and responding to questions and comments arising from report reviews.

HydroQual's main office is:

HydroQual, Inc.
1200 MacArthur Blvd.
Mahwah, New Jersey 07430
(201) 529-5151
(201) 512-3825 (fax)
http://www.hydroqual.com

Dr. Weber, the primary contact person at HydroQual, can be reached at:

Telephone extension: 7401 or
Email: eweber@hydroqual.com

Mr. Scheible can be reached at:

Telephone extension: 7378
Email: kscheible@hydroqual.com

2.4 ETV Host Site's Role

The Parsippany-Troy Hills (PTRH) Wastewater Treatment Plant was the host facility for conducting this ETV. The host site's responsibilities included:

- Dedicating the required area(s) for test equipment and setup;
- Providing reasonable access to the facility for non-plant employees;
- Providing some logistical support, including personnel and/or equipment; and
- Reviewing, approving, and/or assisting with activities affecting the plant, such as electrical connections from the plant's main feed.

The primary contact person at the PTRH plant is:

Mr. Phil Bober, P.E., ETV liaison for PTRH
1139 Edwards Road
Parsippany, New Jersey 07054
(973) 428-7953

2.5 UV Technology Vendor's Role

Aquionics provided the UV system that was verified. It was the full-scale version of their bersonInLine® 4250 UV system. Aquionics' responsibilities included:

- Providing the test system for verification, along with all ancillary equipment, instrumentation, materials, and supplies necessary to operate, monitor, maintain, and repair the system;
- Providing documentation and calculations necessary to demonstrate the system's conformity to commercial systems, hydraulic scalability, and conformity to the requirements of the protocol;
- Providing descriptive details of the system, its operation and maintenance, its technical capabilities, and its intended function in secondary effluent applications;
- Providing technical support for the installation and operation of the UV system, including designation of a staff technical support person and an on-site technician for training and system startup;
- Certifying that installation and startup of the system is in accordance with the manufacturer's recommendations;
- Reviewing and approving the VTP; and
- Reviewing and commenting on the Verification Report and Verification Statement.

The primary contact person at Aquionics is:

Mr. Patrick Bollman
Aquionics, Inc.
21 Kenton Lands Road
Erlanger, Kentucky 41018
(859) 341-0710
(859) 341-0350 (fax)
Patrickb@aquionics.com

2.6 Support Organization's Role

Two other organizations provided support, as subcontractors to HydroQual, for activities that could not be provided by NSF, EPA, HydroQual, or Aquionics.

International Light, Inc. provided calibration services for the UV intensity sensors used for the verification test.

International Light, Inc.
17 Graf Road
Newburyport, MA 01950

Alden Research Laboratory, Inc. was a subcontractor to HydroQual and provided velocity measurements for the velocity profile portion of the verification test.

Alden Research Laboratory, Inc.
30 Shrewsbury Street
Holden, MA 01520

2.7 Technology Panel's Role

The ETV Technology Panel on Secondary Effluent and Water Reuse Disinfection Applications was available as a technical and professional resource during all phases of the verification.

Chapter 3
Technology Description

3.1 bersonInLine® System

Aquionics supplied two UV reactors for the verification test, which were setup in series. The operations and maintenance for the bersonInLine® System is described in the Users Manual (See Appendix B).

3.1.1 Lamps and Sleeves

The bersonInLine® System supplied by Aquionics used high-output, medium-pressure lamps (B35353H) that were oriented horizontally and perpendicular to the direction of flow. Each lamp had a UV output rating of approximately 120 watts (W) at 254 nm and a total power draw of 3,500 W. The lamps had an effective arc length of 350 mm.

The quartz sleeves around the lamps were straight-through tubes with an outer diameter of 33 mm. The sleeves were composed of clear, fused quartz with a wall thickness of 1.50 mm. They allowed a UV transmittance of approximately 90%. Figure 3-1 shows a diagram of the reactor assembly; Figure 3-2 shows the lamp configuration.

3.1.2 Lamp Aging

Aquionics conducted a lamp-aging test at the Ulrich Water Treatment Plant in Austin, Texas. The disinfection system was operated with clean water (87-93%T) from August 2000 to August 2001, just over one year. The UV output readout was set at 100% at the beginning of the test.

The lamps were allowed to operate continuously throughout the test period. At 7,200 hours, the UV output had decreased to 70%, so the power level was increased to the P2, medium, level (see Figure 3-3). This allowed the lamps to operate above 70% UV output for another 1,600 hours. This test shows that the lamps in the bersonInLine® System can be used for over 8,000 hours.

It is important to note that this data was collected by the vendor outside this ETV and is not intended to represent verified data.

3.1.3 Lamp Intensity vs. Temperature

The medium-pressure lamps used in the bersonInLine® System operated at relatively high power levels compared to low-pressure lamps. The lamp operating temperature was approximately 600 ^{o}C. According to the vendor, the lamp temperature does not likely change significantly over the range of water temperatures encountered during typical disinfection applications.

3.1.4 Disinfection Reactors

Each bersonInLine® System's reactor (see Figure 3-1) had a round, flanged, 316 L stainless steel housing with a straight-through flow pattern. The housing had an inside diameter of 350 mm (13.8 in) and was 755 mm (29.7 in) long. Intersecting this housing at a right angle was another

cylinder with end plates that had the same inside diameter. The ends of this cylinder housed the lamp connections and drive mechanism for the cleaning system. The quartz lamp sleeves penetrated both end plates and were secured with watertight seals.

The housing contained an access hatch to allow inspection and cleaning of the lamp sleeves and the cleaning mechanism. The bottom of the housing included drains for removing water from the system. The tops of the housing and the access hatch each had small valves to allow the bleeding of trapped air from the system during startup.

Each reactor contained six lamps (B3535) mounted in a staggered, rectangular array with centerline spacing of 75 mm. The lamps were horizontal and perpendicular to the direction of flow in two, parallel 1 x 3 rows (see Figure 3-2).

Each power supply cabinet contained three power supplies, each driving two lamps. There was a separate power supply cabinet for each reactor.

3.1.5 Sleeve Cleaning System

Each reactor housing was equipped with an automatic sleeve cleaning system consisting of Teflon® wipers that were driven the full length of the quartz sleeve with a motor and lead-screw drive. The wipers could either be manually activated or set to automatically activate anywhere from 10 min to 24 hours between cleaning cycles.

The wipers were not operational during the verification testing, as there was no validation test planned for this equipment. However, they were operated for one cycle during lamp warm-up to remove any debris or residue and to ensure the cleaning system was returned to the idle position.

3.1.6 Electrical Controls

Each reactor was connected to an independent power supply cabinet with an ECtronic control unit. Each cabinet was supplied with 480 V/60 A delta power input. The cabinets were fitted with a main switch, cabinet ventilators, an hour counter, and a display. The main switch turned the whole system on and off. The cabinet ventilators removed the heat produced by the lamp power supplies.

The lamps could be turned on automatically or manually. The control panel had three lamp power settings: power level 1 (P1, 100%), power level 2 (P2, 125%), and power level 3 (P3, 140%). The output from the detector was displayed as a bar graph with UV intensity values of 100%, 90%, 80%, and 70% (the alarm set point).

The control panels included other information that allowed the operator to interpret the status of the system. The operational status of each lamp was displayed with an on/off indicator to show lamp failure. An alarm indicator activated if the module housing overheated. A two-stage alarm indicated when the cabinet began to get hot and when it overheated. When either the module or the control panel overheated, the system shut off the lamps. An hour counter, which could not be reset, indicated the hours that the lamps had been in operation.

3.1.7 UV Detectors

Each reactor had a UVector detector located on the top of the reactor housing. It monitored the UV intensity of the top-most lamp (see Figure 3-2). The detector housing was located outside of the reactor and the UV light was carried through a quartz probe to the detector. The cleaning system included a wiper that would clean contamination from the quartz probe during each cleaning cycle.

The UVector detectors had an optical filter that set the acceptance angle at 8˚ at half-maximum (50%) sensitivity. A two-stage, reflective filter with a passband of 240-265 nm controlled the detectors' sensitivity adjustment. Greater than 95% of the lamp output was within the range of 220-320 nm.

The detectors' maximum range was 200 mW/cm^2. Typical operating conditions were 100 mW/cm^2 or lower. At typical operating conditions, the detectors' long-term stability was approximately 10% per year; its temperature stability was 0.1% per ˚C.

Under typical operational conditions, the UVector detectors' output signal to the ECtronic control unit is 4-20 mA. The output signal from a UVector detector is directly related to the transmittance of the water and to the lamp intensity.

The UVector detectors were calibrated after the lamps were burned in for 100 hours. This calibration setting depends on the application and the transmittance of the water when the calibration adjustment is made.

The operator sees the relative UV output on the control panel as a bar graph with UV intensity levels of 100%, 90%, 80%, and 70% (the alarm set point). After calibration, the readout on the control panel shows the approximate UV output of the test solution. After lamp burn-in, the readout is set to 100% at the nominal dose delivery conditions. It is important to note that this setting is based on a specific, maximum flow condition; this readout does not represent the dose delivered. To calculate dose delivery, both the readout value and the flow rate of the effluent would be required.

3.1.8 Design Operational Envelope

The bersonInLine® System is used for a variety of wastewater disinfection applications. It must be set up specifically for the application (e.g., transmittance, required dose delivery, and flow rates). The UV output readout (and its proper calibration) is the heart of proper dose delivery maintenance.

After installing the bersonInLine® System, the UV output monitors are set to 100% for the particular application and operating conditions. The UV output monitors will then denote a subsequent decrease in reactor performance, and an alarm will activate when the UV output drops to 70%. Three common factors can contribute to this low UV output: (a) lamp deterioration through aging, (b) quartz sleeve fouling, or (c) low transmittance conditions.

Low UV output can then be fixed by either periodic maintenance (e.g., sleeve cleaning) or by increasing the lamp power level to a higher setting, which increases the UV output to an

acceptable level (>70%). If the power supply is operating at the highest level (level P3) and the UV output is below 70% (with clean sleeves and adequate water transmittance), the lamps need to be replaced. This is illustrated in Figure 3-4. The end-of-life (EOL) lamp condition occurs when the UV output cannot be maintained above 70% of the UV output at the end of the 100-hour burn-in.

3.1.9 Design Flow Rates

The design flow rates for a UV disinfection system are a function of the water conditions and the desired dose delivery. A formula and table for determining the dose delivery conditions (e.g., the maximum deliverable flow rates) are presented in the bersonInLine® System Users Manual (see Appendix B). The two independent variables are the %T of the water and the desired dose. The table shows flow rates up to 28 MGD for 100%T water and a dose of 25 mJ/cm^2. Note that these conditions probably are not encountered and they exceed the hydraulic capability of the system. However, these flow rates and doses allowed a dose determination for the reuse applications in this test. Based on these calculations and the configuration of two disinfection reactors in series, the maximum flow rates encountered for a reuse application would be up to 4 MGD.

3.2 Aquionics System Specifications

3.2.1 Verification Test Reactor

The disinfection systems used for this reuse verification test were identical to the disinfection systems in full-scale commercial applications. This verification test was performed with two, bersonInLine® System reactors aligned in series.

The influent flange on the first reactor contained a flow modifier described in Figure 3-5. The flow modifier was installed at the influent end of the reactor to, in effect, extend the pipe length inside the reactor and keep the flow focused toward the lamp array. This minimized the effect of the dead spaces, such as the access hatch, that were present upstream of the lamp array. The flow modifier did not change the operating flow range in the UV system. It is important to note that to extend the results of this verification test to a commercial installation, the commercial systems must contain an identical flow modifier.

The two test reactors were configured with identical, automatic, sleeve cleaning systems and ECtronic control units.

3.2.2 Scaling Considerations

The system tested was a full-size bersonInLine® System. Scalability is based on the concept that higher disinfection-rate requirements would be implemented with identical, parallel reactors. The flow velocities used during this verification testing should be equivalent to the flow velocities that would be present in the plant installations.

Requirements that must be met to extend the results of this verification test to commercial systems are: the flow velocities must be in the range tested during this verification, and the

velocity profile across the influent and effluent flanges to the system must be similar to or better than that verified under this test. The latter can be achieved by measuring the velocity flow fields and by ensuring that the influent and effluent conditions (e.g., pipe lengths) are similar to those in this verification test.

3.3 Verification Test Claims

The overall objective of this verification test was to validate the disinfection performance of the two-reactor train bersonInLine® System for water reuse applications. The nominal transmittances of the test waters were adjusted to simulate conditions where the UV output of the system has been reduced to 70% by lamp aging and sleeve fouling. Within this goal, four specific objectives were fulfilled. The test:

1) Verified the flow-dose relationship for the system at a nominal UVT of 65% to simulate membrane filtered effluent. (Note: The actual UVT was 54 %.)

2) Verified the flow-dose relationship for the system at a nominal UVT of 55% to simulate granular or fabric filtered effluent. (Note: The actual transmittance was 41%.)

3) Verified the velocity profiles on the influent and effluent ends of the reactor assembly.

4) Verified the ability of the UVector detector and readout alarm to accurately represent the presence of low UV output conditions.

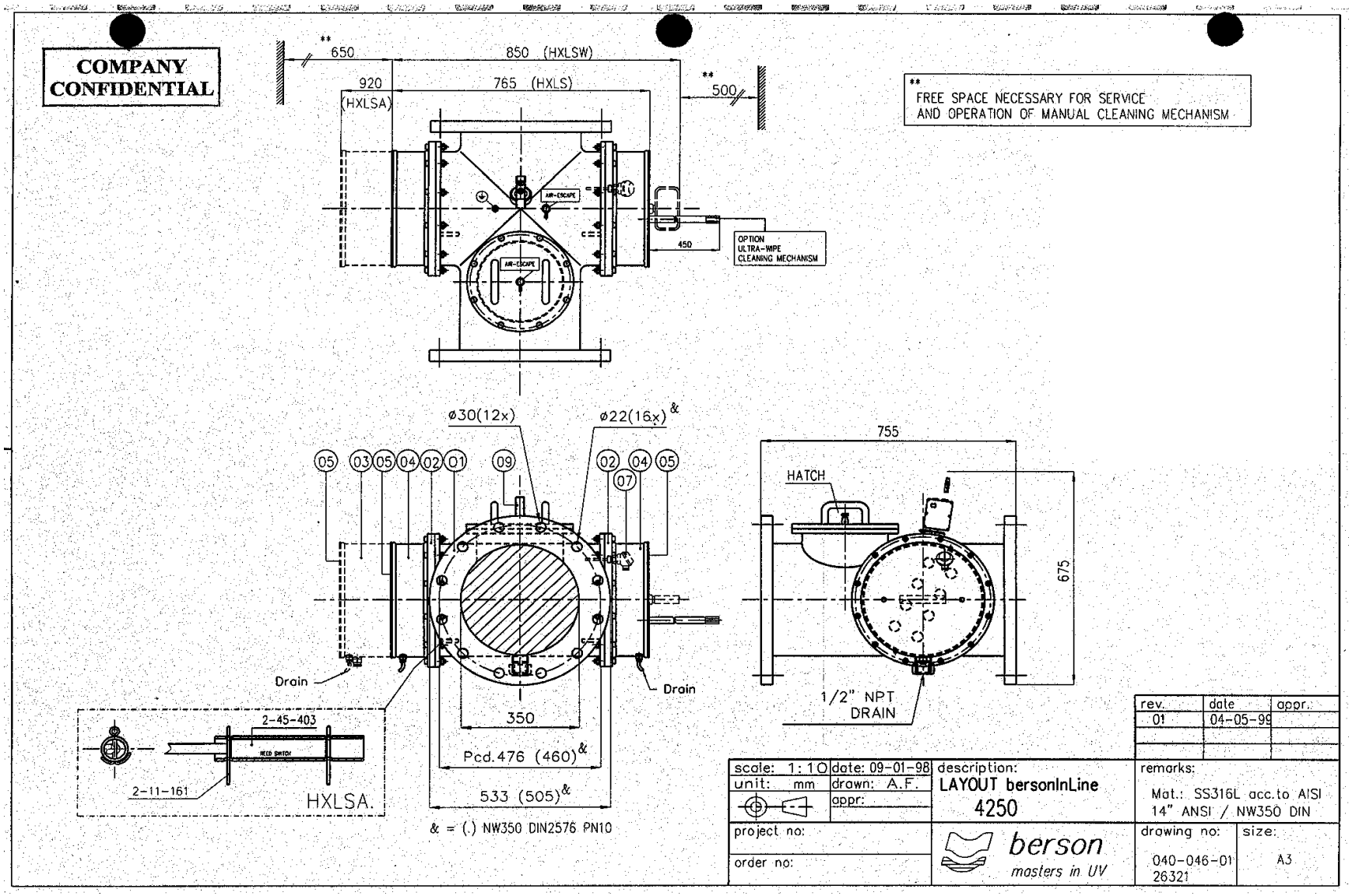

Figure 3-1. Diagram of reactor assembly used for the verification test.

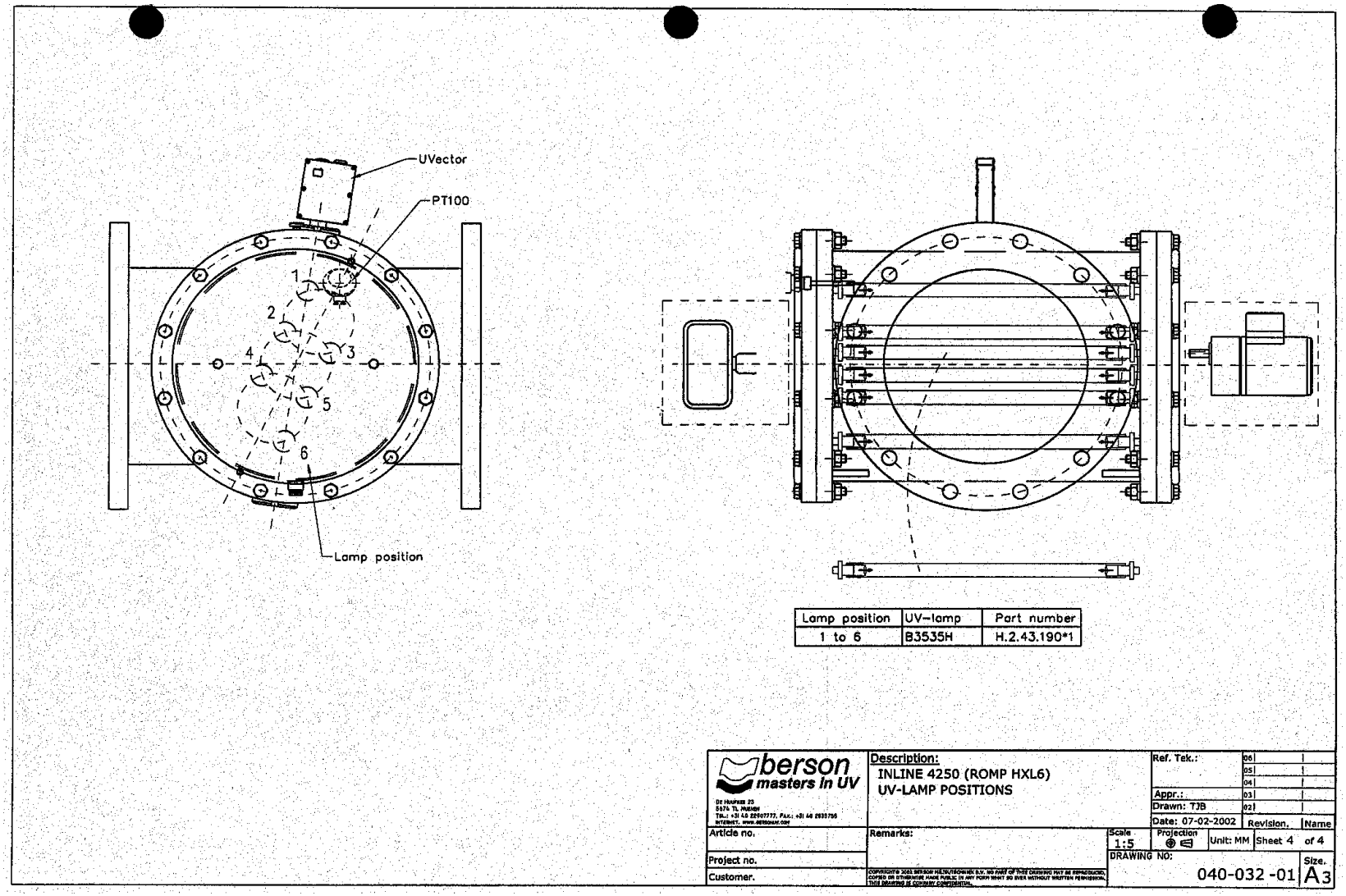

Figure 3-2. Diagram of lamp assembly used for the verification test.

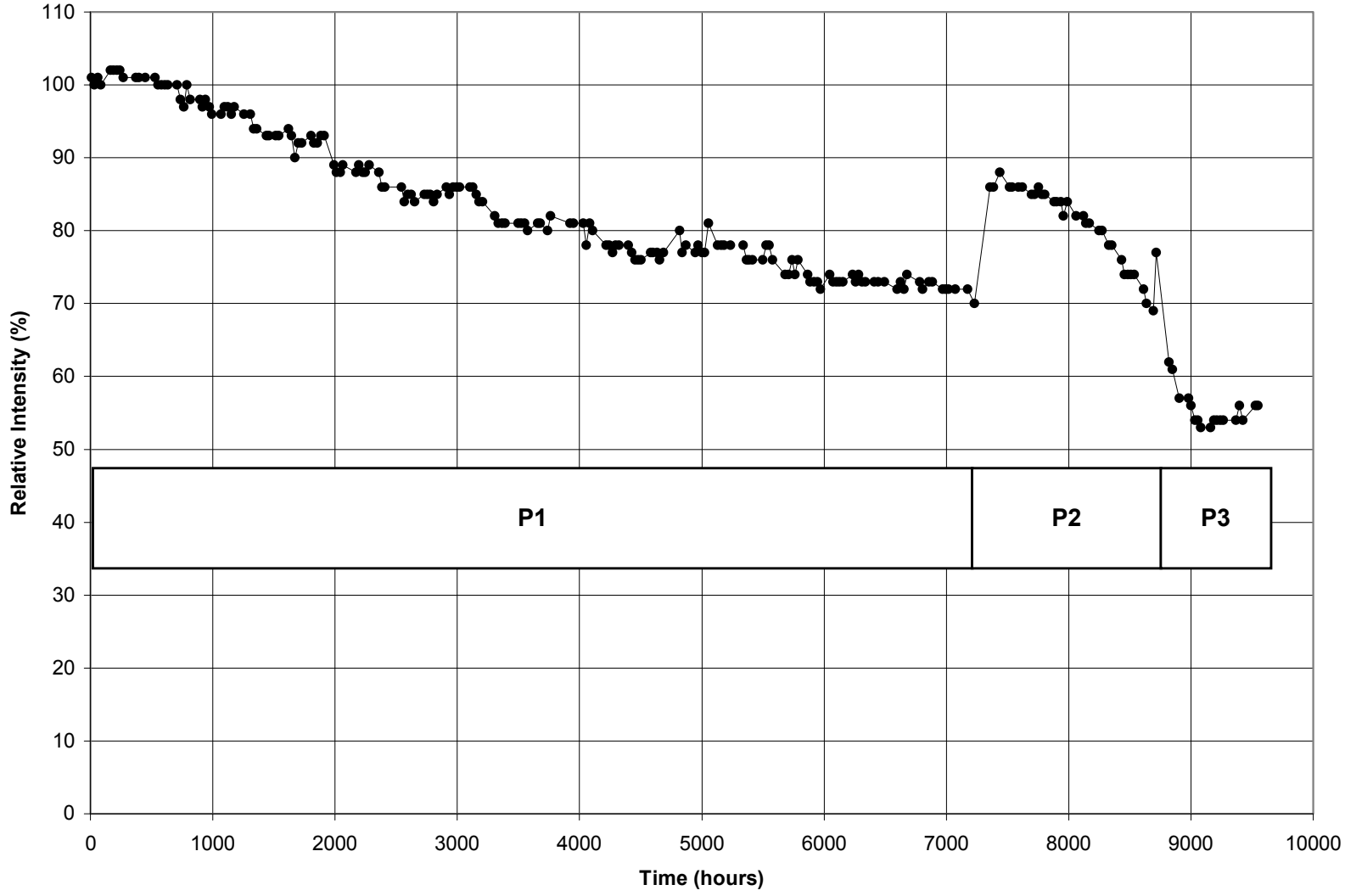

Figure 3-3. Data from lamp aging test.

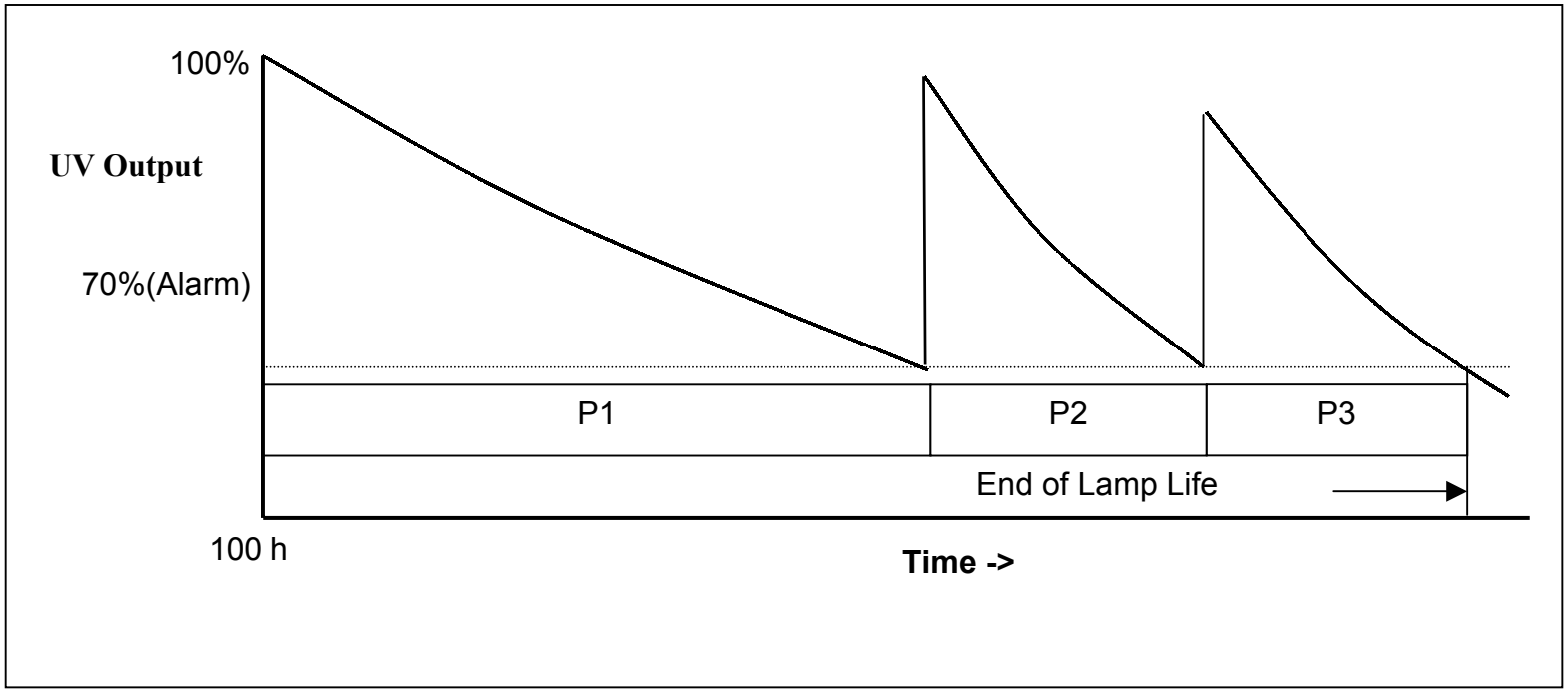

Figure 3-4. Schematic of lamp operational lifespan.

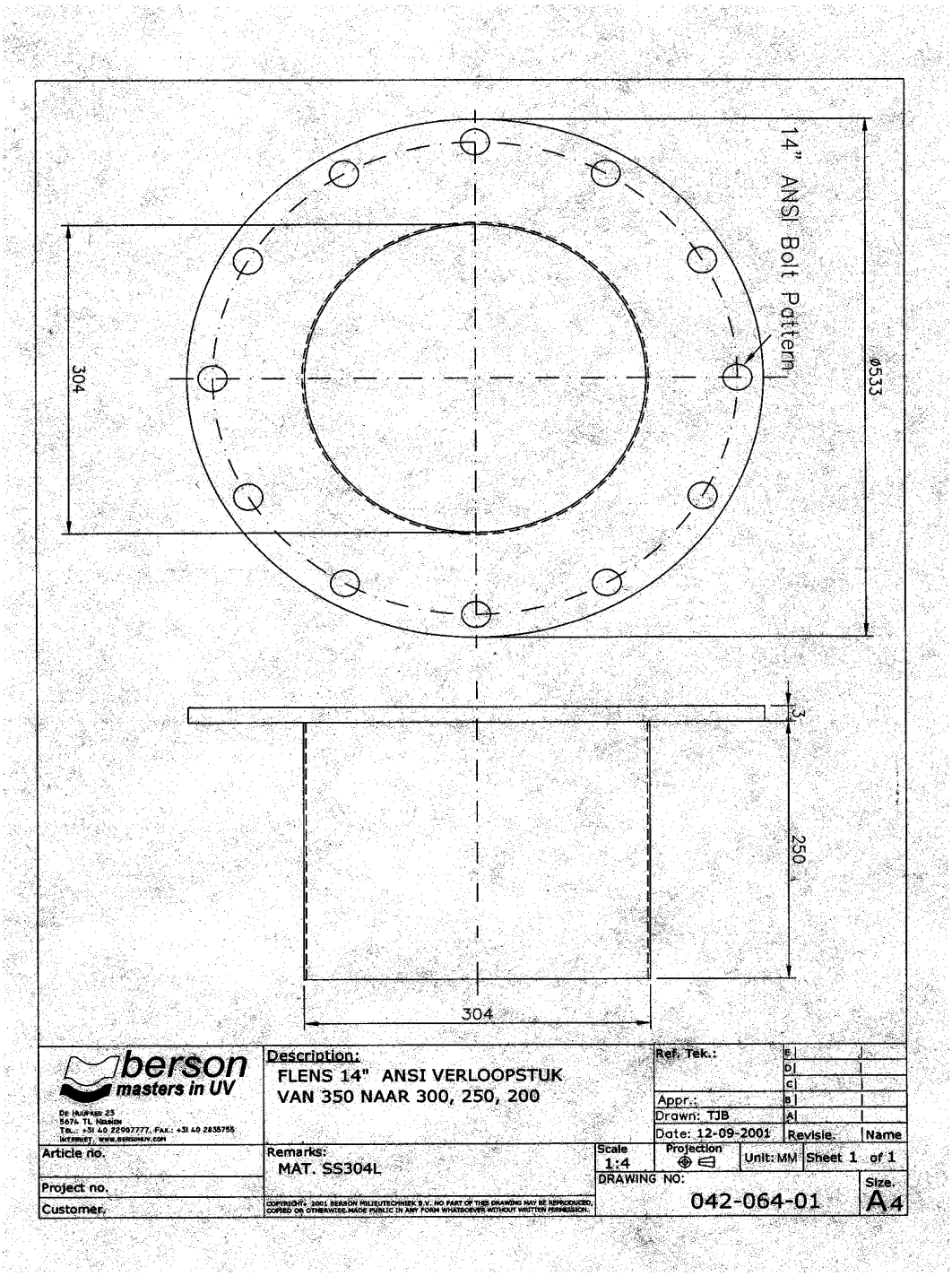

Figure 3-5. Drawing of influent flow modifier.

Chapter 4
Procedures And Methods

4.1 Test Site Setup

4.1.1 General Description

The test site for this verification test was the PTRH Wastewater Treatment Plant. This plant was built to process 16 MGD of sewage with secondary treatment and granular filtration. Sources of primary effluent, secondary effluent, granular filtered secondary effluent, and potable water were available at the test site.

The ETV installation occupied an area approximately 30 feet by 120 feet located between the main chlorine contact chamber and the primary clarifier for the old plant (see Figure 4-1). The south end of the test site was adjacent to an aeration tank, which was used to dispose of treated and untreated challenge waters. The test site included a semi-permanent structure for housing the test system and support equipment as well as an office trailer for housing analytical equipment, documentation, and fax and phone equipment.

Figure 4-2 shows a schematic of the test installation used for the bersonInLine® System. The test system was fed with challenge water prepared in a batch tank that was pumped to the influent side of the system's two-reactor train. The effluent was allowed to flow into the adjacent aeration tank. Power from the PTRH plant's electrical supply was used for the test system.

4.1.2 Water Sources

The first water source used for these bioassay tests was taken from a hydrant at the wastewater treatment plant, which delivered potable water at a rate of approximately 2,000 L/min. This water was piped into the top of the challenge water tanks to allow for the addition of modifying agents such as sodium thiosulfate, instant coffee, and MS2 bacteriophage. The discharge temperature of the water was in the range of 10.1-14.2 ºC, the UVT was in the range of 97.4-98.4%T at 254 nm, the pH was in the range of 7.42-7.62, and the turbidity was in the range of 0.18-0.73 Nephelometric Turbidity Units (NTU).

The second water source used for these bioassay tests was taken from the effluent side of the granular filtering process before entering the chlorine disinfection system. This filtered effluent was delivered to the test site via a submersible pump and 4-inch PVC plumbing at a rate of approximately 1,400 L/min. This water was piped into the top of the tanks for challenge water preparation and directly into the influent manifold for extended flow conditions such as lamp burn-in. The discharge temperature of the water was in the range of 10.9-15.2 ºC, the UVT was in the range of 74.0-74.5% at 254 nm, the pH was in the range of 7.17-7.25, and the turbidity was in the range of 0.70-1.5 NTU.

Daytime, outside, ambient air temperature ranged from -5 ºC to 10 ºC during the verification test.

4.1.3 Challenge Water Tanks

The test site contained two, 80,000-liter tanks supplied by Adler Tank Rental, Newark, New Jersey. The tanks were 11.5 m long, 2.4 m wide, and 3.1 m high (see Figure 4-1). Each tank had an eight-inch flanged outlet with a butterfly valve leading to the pump and a four-inch flanged outlet on the rear, which was used as a circulation loop. Access to the tank was via a manway on top, where modifying agents were added and potable water entered the tank (see Figure 4-2).

The tanks were supplied with a fresh coating of epoxy paint on the interior to minimize corrosion and chemical reaction with the water. A float-type level indicator was present on both tanks.

The eight-inch outlets of the tanks were in series with the pump influent connection. This allowed both tanks to be used simultaneously during conditions of high flow or large batches. A recirculation line was connected to the effluent side of the pump to return water at a rate of approximately 1,100 L/min to the rear of both tanks to provide for mixing. The tanks were valved so that they could be isolated or operated in tandem.

4.1.4 Pump

The test challenge waters were pumped to the test system or recirculated to the challenge water tanks with two, Godwin CD150M Dri-Prime Centrifugal Pumps from Bridgeport, New Jersey. The pumps were trailer mounted with jack stands for semi-permanent installation. They were equipped with a diesel-powered 71 hp motor to provide flow rates up to 13,000 L/min in the test configuration.

A ball valve on the discharge pipe of the pump was used as a sample port for the test challenge waters while the test batches were being mixed and prepared. Samples were drawn for total chlorine, pH, and UVT measurements (see Figure 4-2).

4.1.5 Other Equipment

A Fisher-Porter 10D1462 200 mm magnetic flow meter measured the flow rate to the test system. The flow meter's calibration was verified before testing using the tank drawdown method (see Section 6.1.1).

A critical measurement was the UV output of the system at 254 nm. This was measured by an International Light Model 1700 Research Radiometer using an SUD240 detector with a quartz wide-eye diffuser and an NS254 narrow band filter.

Another important measurement was the UVT of the test batch. A UV-Vis spectrophotometer (Shimadzu 1200) was kept on site for measuring the UVT of samples. Transmittance was verified at the lab with a Perkin-Elmer Lambda-6 spectrophotometer. Transmittance scans from 230 nm to 280 nm were also conducted.

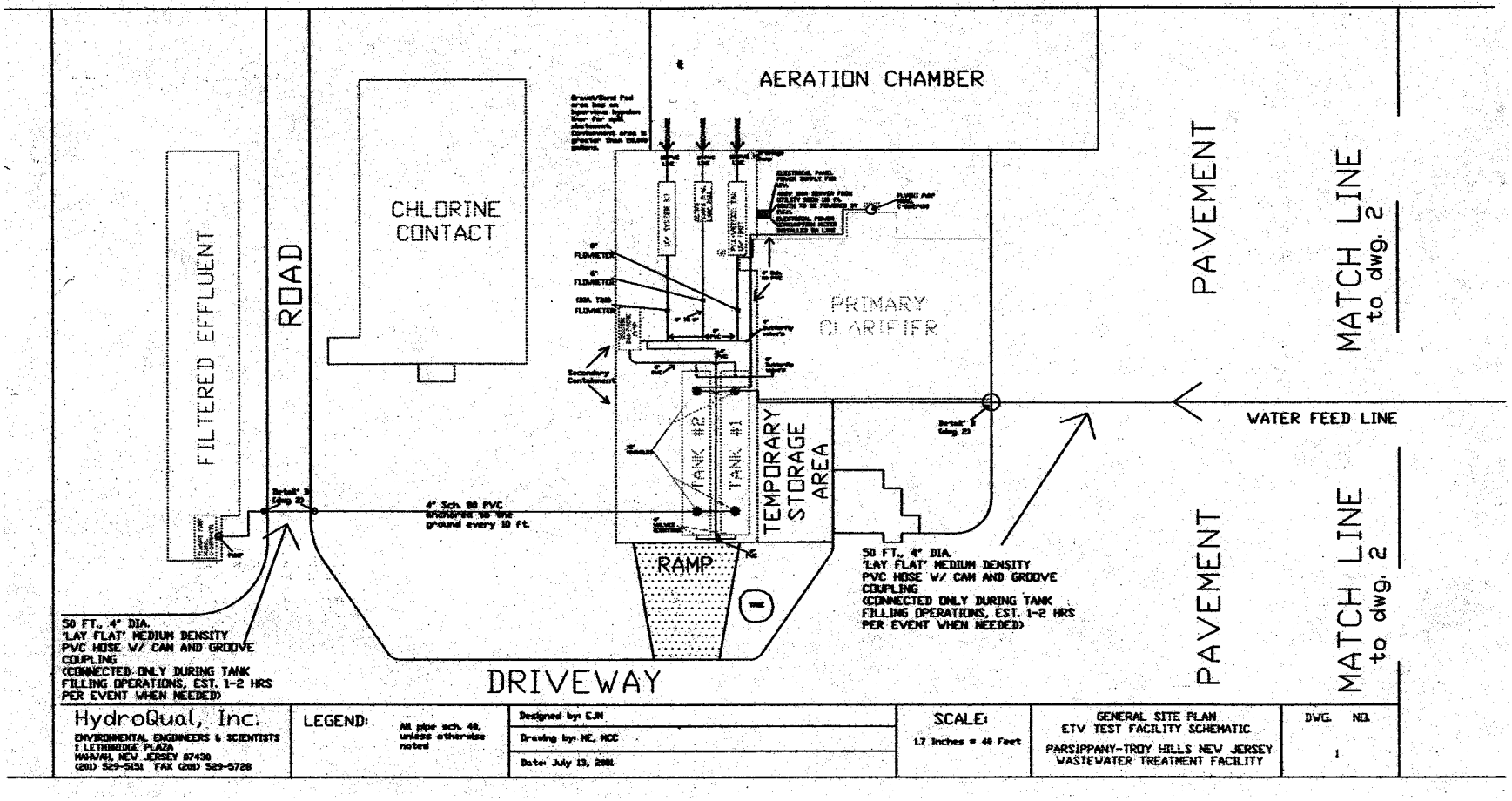

Figure 4-1. General site plan of the ETV test facility at the PTRH Wastewater Treatment Plant.

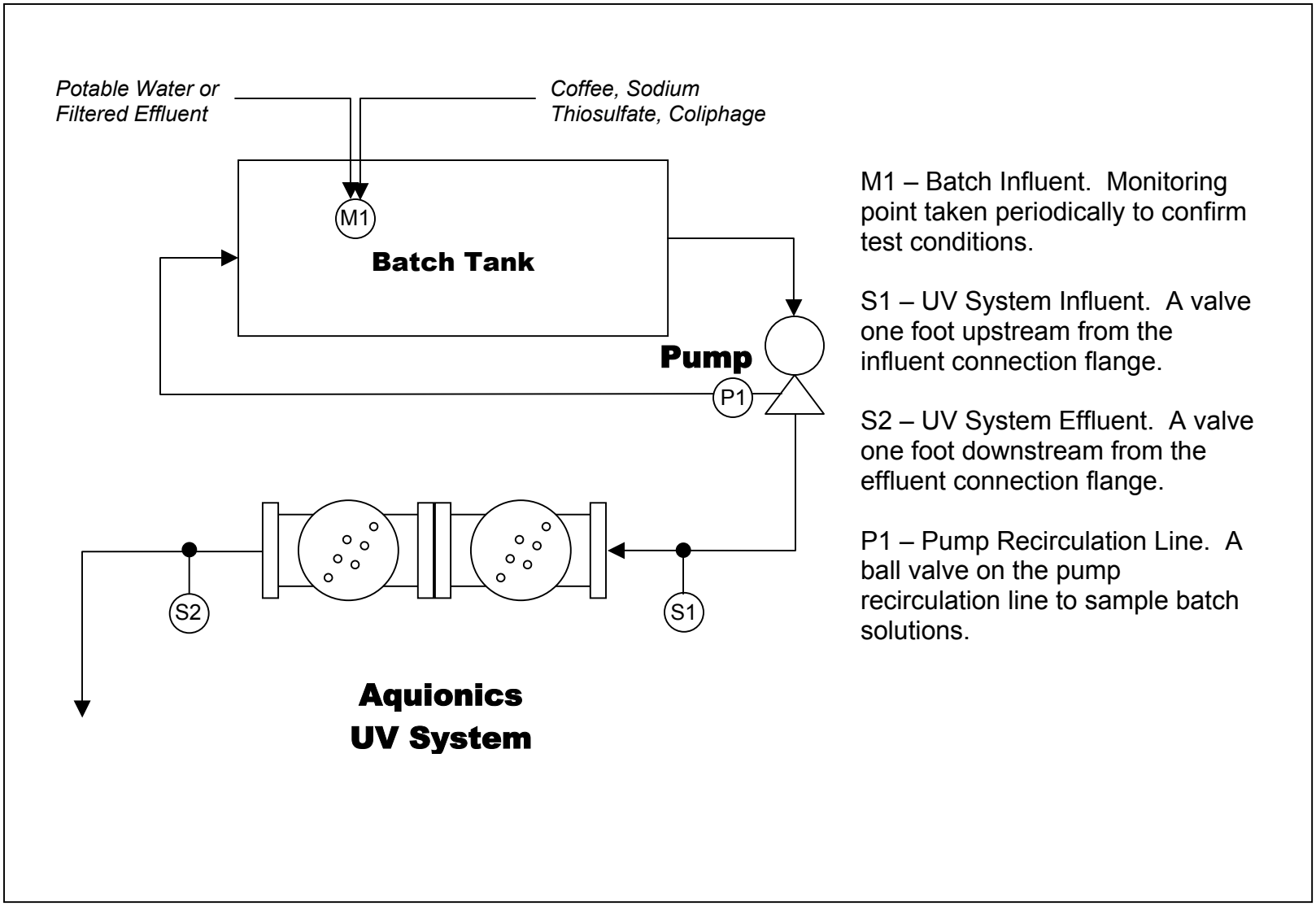

Figure 4-2. Flow schematic and sampling points.

4.2 Disinfection System Startup and Characterization

4.2.1 100-Hour Lamp Burn-In

Before dose delivery verification testing began, the lamps were aged for 100 hours to allow the lamp intensity to stabilize. Flow from the filtered effluent was introduced at a rate of 1,300 L/min and the lamps were turned on to a power setting of P1. Over the five-day burn-in period, HydroQual personnel monitored the process by checking the system status one to two times a day. The system was checked to verify that all lamps were operating. During the burn-in period, the lamps were not turned off or restarted and no lamps failed. Notes about the lamp burn-in process are in Appendix C.

4.2.2 Power Consumption and Intensity Stability Measurement

4.2.2.1 Power Consumption

The overall power consumption of the two-reactor train bersonInLine® System was monitored during the startup and characterization tests and during all of the subsequent bioassay flow tests. The 480 V, three-phase power supply was monitored at the main disconnect panel with a power datalogger. This measured the total power consumption of the system, inclusive of all lamps and control circuitry.

During the startup phase, the power consumption was measured at all three power settings.

4.2.2.2 Intensity Stability

With potable water flowing through the reactor train at approximately 1,100 L/min, the lamps were turned on to power level P1 from a cold start, and the intensity from the UVector detector, voltage, and current were logged at five-second intervals for 12 minutes.

4.2.3 Detector and Alarm Validation

4.2.3.1 Summary of Detector and Alarm Operation

The intensity monitoring and alarm system for the bersonInLine® System consists of essentially three parts: (a) The UVector detector receives UV irradiance from the lamp through a finite path of water. The output signal is then converted to 4-20 mA via the preamp in the UVector detector's housing. (b) The ECtronic control unit converts this 4-20 mA output signal to an adjustable voltage in the range of 4.0-6.3 V. (c) The UV output readout converts the ECtronic control unit's voltage into the relative output as a bar graph with UV intensity values of 100%, 90%, 80%, and 70% (the alarm set point). A schematic of this system is shown in Figure 4-3.

The system's operator, depending on the exact application, transmittance, and power setting, can set both the outputs of the UVector detector and the ECtronic control unit. When the relative intensity drops below a preset point, the alarm is activated and the operator must take action to remedy the potentially low-dose condition that is present.

4.2.3.2 UV Output Intensity Measurement

The UV output of the system was measured with built-in UVector detectors on each reactor. These were attached in the factory-installed position to monitor the uppermost lamp in each reactor. The intensity output of these detectors was a 4-20 mA signal, which was recorded with a datalogger during the startup and characterization phase as well as during the flow tests.

During the detector validation tests, the outputs of the UVector detectors were set via a small built-in potentiometer adjustment. Typically, the detector validation tests would start with the UVector detector's setting at the nominal output of 11.5 mA when the nominal transmittance water was present in the reactor. Due to the adjustable "zero" of the UVector detector, only relative readings were made.

The UV output intensity of the lamps in the downstream reactor was also measured with an International Light IL-1700 radiometer connected to an SUD 240 UV detector. The detector received a light signal through an optical fiber that was mounted at the effluent side of the reactor train and was oriented towards the flow of the water, essentially "looking" upstream. The light path to the nearest lamp was several centimeters long, so accurate measurements were made only with high transmittance water. In addition, only relative readings can be acquired with a detector mounted in such a position because of the geometry of the lamp's UV emission pattern and the input optic of the detector/fiber system.

The voltage outputs of the ECtronic control units were measured with 0-10 V datalogger channels during the detector validation phase. The readout status was recorded at each stage of the tests. The setting for the nominal condition was adjusted to 6.3 V, which resulted in a readout of 100% UV output.

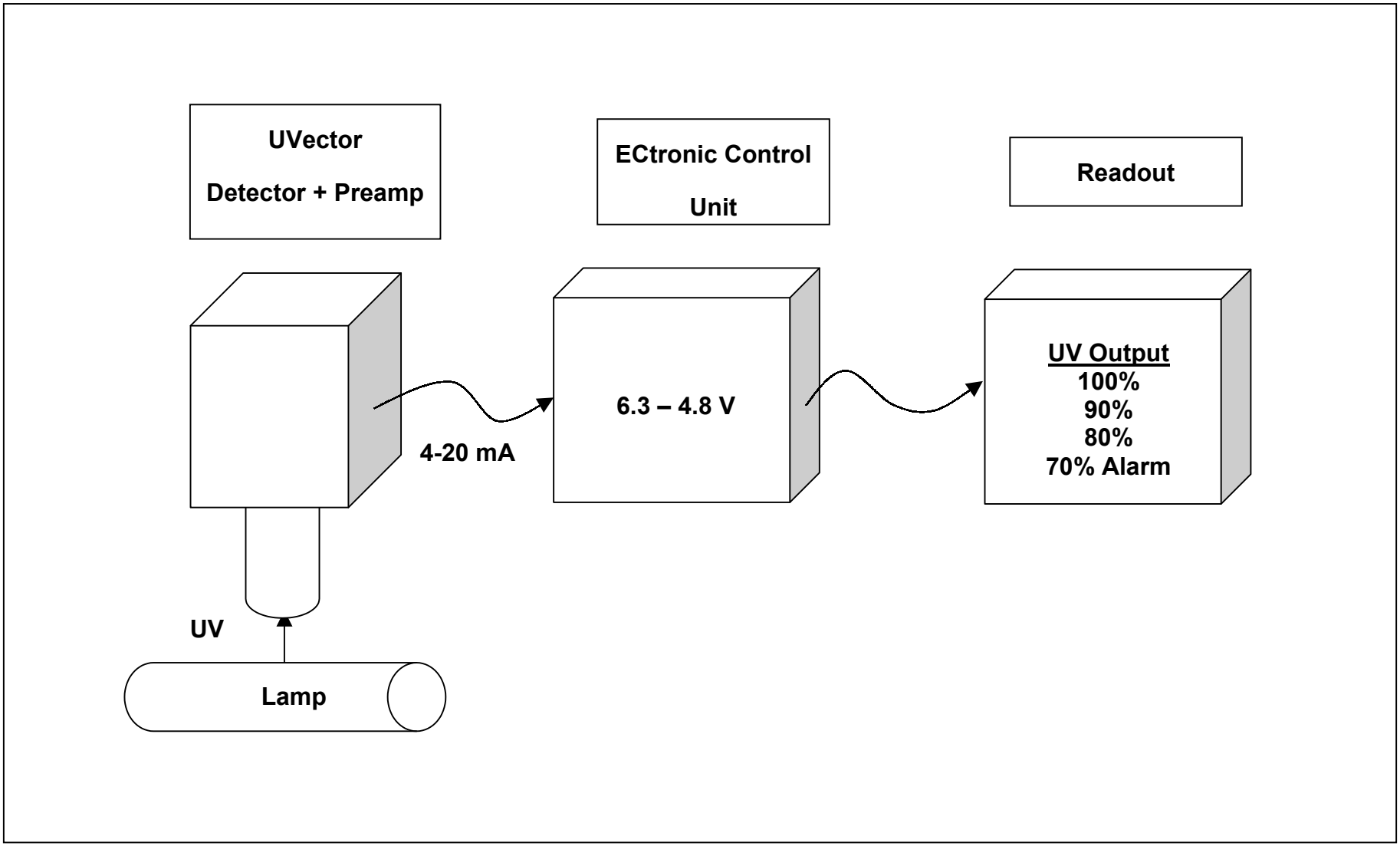

Figure 4-3. Schematic of signal path for Aquionics detector and alarm system.

4.2.3.3 Verification Test Summary

The detector and alarm validation tests were conducted to quantify the relationships between the various signals and to determine the conditions that would activate the low UV output alarm. To accomplish this, three tests were conducted:

(1) The nominal setting adjustments were made for the highest power level (P3) and with potable water with a transmittance of 98-99%T. The outputs were monitored as the system was stepped down and up through the three power levels. In this way, the system monitors and readouts could be compared to the IL-1700 measurements.

(2) The nominal setting adjustments were made for the P1 setting with 55%T water. Then the transmittance was stepped down until the UV alarm was activated.

(3) The nominal setting adjustments were made for the P1 setting with 65%T water. Then the transmittance was stepped down until the UV alarm was activated.

These tests were conducted with flow rates of approximately 1,140 L/min. In the case of test (2) and test (3), the transmittance was adjusted up and down to trip the alarm multiple times. Transmittance was adjusted by changing the mixture of the water taken from both tanks, which were adjusted and mixed with different transmittance waters.

4.2.4 Headloss Measurements

Headloss was measured by determining the pressure drop across the reactor train with a manometer system. Identical, static port tubing fittings were installed on the flanges attached to the influent and effluent sides of the reactor train. The fittings were connected to transparent tubing mounted on a vertical frame. The water level and water level differences were measured, using a graduated scale. The headloss measurements were acquired at all flow rates used in this verification test.

4.2.5 Hydraulic Flow Field Measurement

The velocity profiles in the influent and effluent sides of the reactor train were measured by Alden Research Laboratory, Holden, Massachusetts, with consultation of the HydroQual Project Manager. The report from Alden is in Appendix C, and the method is summarized here.

The setup to perform the velocity profile measurements is shown in Figure 4-4, where the influent side of the system is detailed. An identical system was installed on the effluent end of the system to allow simultaneous measurements. The setup included 2.5-cm thick PVC rings that fit in the initial and final flange connections of the reactor train. By inserting two pitot tubes, the pitot tube jigs allowed velocity field measurements in the pipe just before (~1.3 cm) the flange on the first reactor and just after (~1.3 cm) the flange on the second reactor. The inside diameters of the rings were matched to the inside diameter of the pipes connected to the reactor.

Fittings were located at 90º intervals (evenly spaced) around the circumference of the flange. This allowed the insertion of pitot-tube velocity sensors in a watertight fashion. Figure 4-4 shows a pitot tube installed in the 0º position (on the top); the 90º position would be in the lower right, just out view in the figure.

The pitot tubes could be inserted into each fitting at three positions, as delineated on the pitot tube supports. The positions were, from the center, 0.0 cm, 5.0 cm, and 10.7 cm. Figure 4-4 shows the pitot tube installed 10.7 cm from the center, the other two radial positions required deeper insertion of the pitot tube.

Measurements were taken simultaneously in the upstream and downstream positions at one location on each ring (i.e. 2 pitot tube jigs were used during the test). As a result of the three radial positions and the four circumferential positions, there were a total of nine measurement positions in each flow field, and the center position was measured in quadruplicate. This multiple measurement of the central position was also to assure the repeatability of flow conditions between each setup.

The pitot tubes had one, dynamic, pressure port and two, static, pressure ports, as shown in Figure 4-4. The two, static, pressure ports were connected together for the static pressure reading. The differences between the static and dynamic pressures were measured with a differential pressure transducer connected to a PC. At each position, the pressure differential was measured at a rate of 12 Hz for one minute. This resulted in 720 measurements, which were averaged for the pressure drop at each position.

The pressure drop from the pitot tube at each position was then converted to an actual velocity with calibration data generated at Alden Research Laboratory. This data is included in Appendix C.

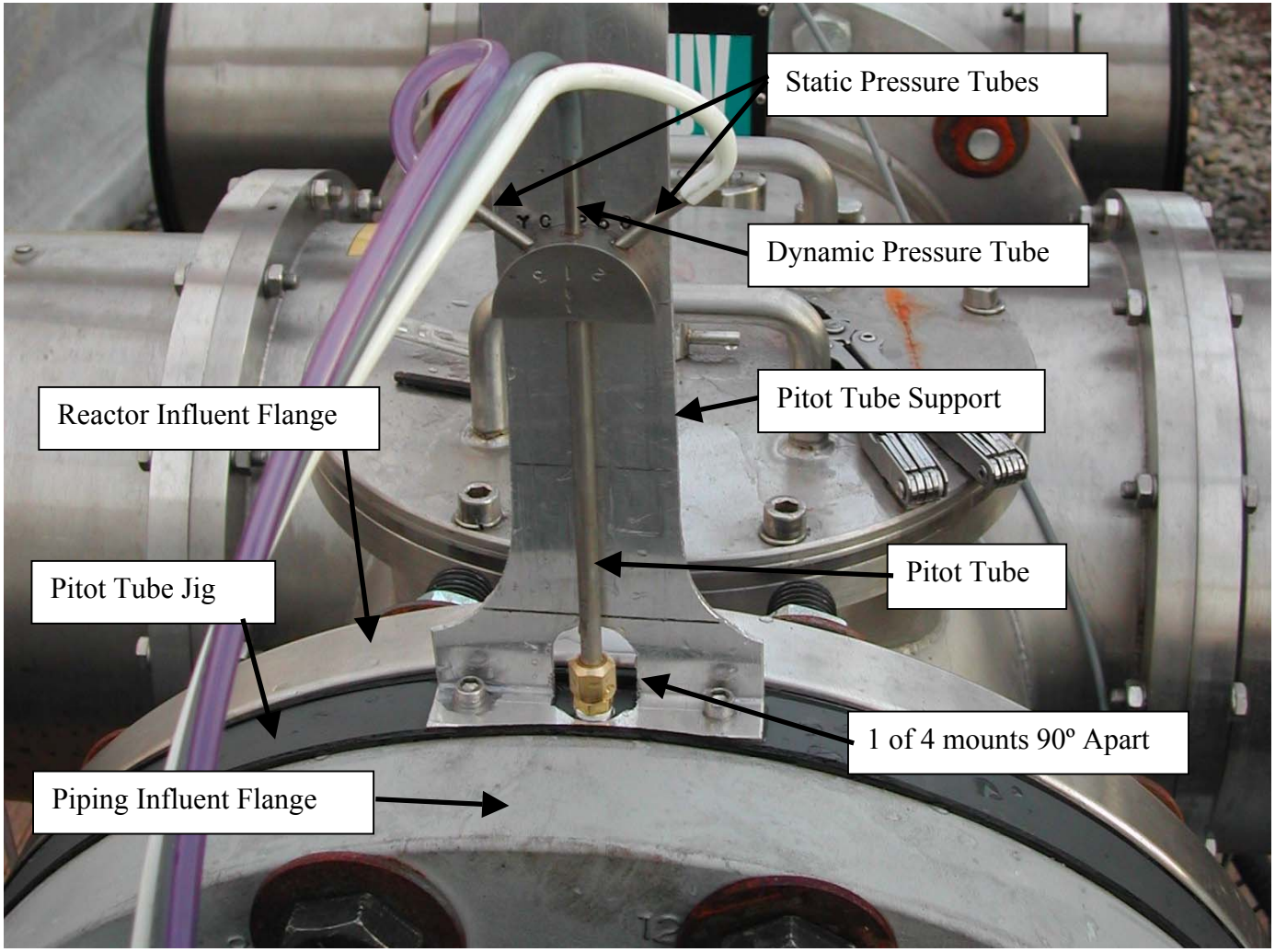

Figure 4-4. Pitot tube insertion scheme.

4.2.6 Shakedown Flows

Shakedown flows were unnecessary for the verification testing. Since flow testing and calibration were conducted for Aquionics at the test site prior to the verification test, the operators and technicians were familiar with all processes.

4.3 MS2 Production and Calibration

4.3.1 MS2 Propagation

The microorganism MS2 is an F-specific RNA bacteriophage (bacterial virus) consisting of a simple capsid of icosahedral symmetry, is 21-30 nm (0.021–0.030 μm) in diameter, and contains single-stranded RNA as the genome. MS2 is classified into the family Leviviridae, for which it is the type species. This bacteriophage is infectious for bacteria that possess the F- or sex plasmid originally detected in *Escherichia coli* (*E. coli*) K-12; it infects by adsorption to the F-pilli coded by this plasmid. MS2 only infects certain strains of *E. coli* that express the F-pilus, which is only present above 35 °C. Because of these characteristics, MS2 is non-pathogenic to humans and cannot reproduce in the natural wastewater environment.

Before the start of this bioassay testing series, a 20-liter batch of MS2 bacteriophage solution was prepared with a titer of approximately $1x10^{11}$ pfu/mL. The MS2 was ATCC 15597-B1 and the host *E. coli* strain was ATCC 23631. The propagation procedure was based on an ISO method (ISO, 1995), which was refined to produce the large volumes used in bioassay tests.

The host strain (*E. coli*) was grown at 37 °C in Trypticase yeast-extract glucose broth until the log-growth phase was reached. This time was determined by previously completing three growth curves of the same host-strain working culture. When the optimum log-growth phase was reached, the MS2 stock solution was pipetted into the bacterial growth culture to start the infection, which was allowed to continue overnight. During the following day, the culture media was filtered through 0.45 μm filters to remove cell lysate and to remove any other bacteria that may be present. Then the MS2 suspension was filtered through pre-sterilized 0.22 μm filters into pre-sterilized bottles to ensure complete removal of foreign microbes. This procedure improved the storage time for the solution. The solution was stored over chloroform at 4 °C. Daily sub-batches were typically prepared in 1.5 L volumes.

4.3.2 Dose-Response Calibration

The dose-response calibration of the MS2 stock batch and seeded influent samples was achieved using a collimated beam apparatus containing two, G64T5, low-pressure mercury lamps. The apparatus was constructed of an opaque, non-reflective material with a blower for ventilation and temperature control. The beam was collimated with a 10 cm diameter tube extending 40 cm below the lamps. The irradiance across the surface plane of the sample dish was mapped with a radially symmetric pattern containing 19 points. The average irradiance was integrated mathematically.

Dose-response samples consisted of: (a) laboratory dose-responses in 0.85% saline water, (b) field influent samples collected from the field-challenge batch solutions for flow tests, and (c) verification runs that were conducted on simulated challenge waters that used the site's potable water that was modified to mimic the field challenge waters (e.g., including sodium thiosulfate and instant coffee). The samples were exposed in a petri-type dish that had straight sides and a flat bottom. A stirring bar was used to gently agitate the solution during exposure. The dose delivery was controlled by the exposure time and determined by the following calculation:

Absorbance coefficient:

$$k = -2.3\log\left(\frac{\%T}{100}\right)$$

Depth averaged intensity I:

$$I = I_0\left(\frac{1-e^{(-kd)}}{kd}\right) \tag{4-1}$$

Necessary exposure time:

$$Time = Dose \times I$$

d = Sample Depth (cm)

$\%T$ = Percent Transmittance at 253.7nm

I_0 = Intensity at the surface of the sample solution (mW/cm^2)

I = Average Intensity (mW/cm^2)

k = Absorbance Coefficient (cm^{-1})

$Time$ = Exposure Time (seconds)

$Dose$ = Average Dose for the sample (mW - s/cm^2)

Each dose-response run was completed with two control samples that had no exposure to the germicidal radiation. The viable MS2 in each sample (the virus survivors) were then enumerated with a procedure described in Section 4.4.5.

For this verification test, 16 dose-response runs were conducted. Two were in 8.5% saline solution, eight were conducted with seeded influent solution, and six were conducted with simulated influent solution.

4.4 Dose flow Assays

4.4.1 Lamp Sleeve Preparation

Before each daily flow test session, the access hatches to both reactors were removed and the lamp sleeves were cleaned and inspected. The lamp sleeves were scrubbed with soft sponges

and an acidic cleaning solution (e.g., Lime Away). The hatches were reattached to the reactor housings and the system was flushed with potable water. The wipers were operated through one cleaning cycle to remove any debris and to ensure that the cleaning system was returned to the idle position before flow testing began.

4.4.2 Challenge Water Batch Preparation

The bioassay flow tests were conducted on a mixture of potable water or granular filtered effluent, instant spray-dried coffee, sodium thiosulfate, and MS2 bacteriophage. A 160,000 L batch of challenge water was prepared immediately before each flow-test series.

First, the tanks were filled approximately three-fourths full with potable water or filtered effluent, the total chlorine was checked, and 3 kg of sodium thiosulfate was added (for potable water); this was approximately 6 times the amount required for neutralization of the chlorine. The pumps were configured in a recirculation loop and run at approximately 3,000 L/min during batch preparation. After filling, the total chlorine was measured with a field test kit (Hach method 8167, detection limit of 0.05 mg/L) to verify that all chlorine had been removed. The instant coffee was progressively added to reduce the transmittance to the target level (41% or 54%), with frequent transmittance checks made. Finally, 2 L of MS2 bacteriophage were added and allowed to circulate for at least 30 minutes to mix fully.

4.4.3 Flow Testing

Before flow testing commenced, challenge waters were allowed to flow through the reactors at approximately 1,100 L/min. The reactors were turned on to power level P1 and the lamps were allowed to warm up for at least 10 min.

Flow testing was conducted by pumping the water through the channel at the specified flow rates with the power level set at the P1 setting. Enough time was allowed for at least five volume changeovers in the reactor train, the flow rate was checked again, and sampling commenced. Water that had passed through the test system was discharged to the wastewater treatment plant.

Samples were collected from valves in the upstream and downstream plumbing to the reactor (see Figure 4-2). After allowing the valves to purge for several seconds, both influent and effluent samples were collected in sterile, 120 mL, single-use specimen cups. The influent and effluent samples were collected simultaneously and in triplicate, resulting in six samples for each flow test. The samples were placed on ice in a closed (therefore, dark) cooler and transported to the lab.

Each flow condition (e.g., transmittance, flow) was duplicated at least four times, and four, no-dose flow tests were completed for a total of 48 valid flow tests conducted during eight different flow series.

4.4.4 Challenge Water Transmittance

4.4.4.1 Bioassay Transmittances

The dose flow assays used simulated wastewaters with two different UV transmittances at 254 nm. The nominal target was 55% for the granular or fabric filtered water and 65% for the membrane filtered water (simulated by dechlorinated potable water).

An important aspect of the reuse verification test was to simulate the EOL conditions that should be present when lamps and sleeves have deteriorated and have reduced the delivery of UV energy to the wastewater. For many UV disinfection systems, assumptions have to be made about the fouling of quartz sleeves and the aging of the lamps to determine these degraded EOL conditions. The protocol (NSF, 2002) requires an assumption that the quartz sleeves, at EOL conditions, will transmit 80% of the germicidal energy. The required lamp degradation factor can be 50% or above, but must be verified independently.

The bersonInLine® System and its control panel were designed to operate somewhat differently. As described in Section 3, the built-in detectors sense the deterioration of the lamps and sleeves and the operator is alerted by an alarm at the 70% UV output level. To simulate the EOL conditions with this system, the transmittance was reduced to mimic this 30% reduction in UV output that would be present under the UV output alarm conditions. Thus, a transmittance was determined at which the dose delivery was reduced by 30%.

Determining this reduction in dose delivery from the 100-hour nominal conditions was achieved with a mathematical model (the UVDIS point-source summation model) that calculated the average intensity in the disinfection system. The calculation involved determining the intensity at each point in a cross-sectional plane of the disinfection system, which consisted of a finely spaced grid. The intensity at each point was calculated as a summation of the energy from each lamp and the attenuation of the energy with the Beer-Lambert law as the radiation moves through the UV absorbing water. The average intensity of the radiation field was then calculated for a range of transmittances, resulting in the relationship shown in Figure 4-5.

The calculations were based on a model using lamps with an arc length of 35 cm, a lamp power of 160 W at 254 nm, and quartz sleeves with a radius of 1.65 mm. The lamps were arranged as in Figure 3-2–in a circular reactor with an inside diameter of 35.6 cm. Average intensities were determined for a range of transmittances between 40% and 65%.

The above calculation results were empirically fitted with a third-order polynomial that quantifies the relationship:

$$I_{AVE} = 5.813\times10^{-4}(\%T)^3 - 7.003\times10^{-2}(\%T)^2 + 3.73(\%T) - 4.185\times10^{1} \qquad (4\text{-}2)$$

The average intensity was calculated for the nominal %T (e.g., 65%) and then multiplied by the 0.70 EOL factor. Then a reduced %T was determined, which achieved the reduced average intensity. The results are shown in Table 4-1.

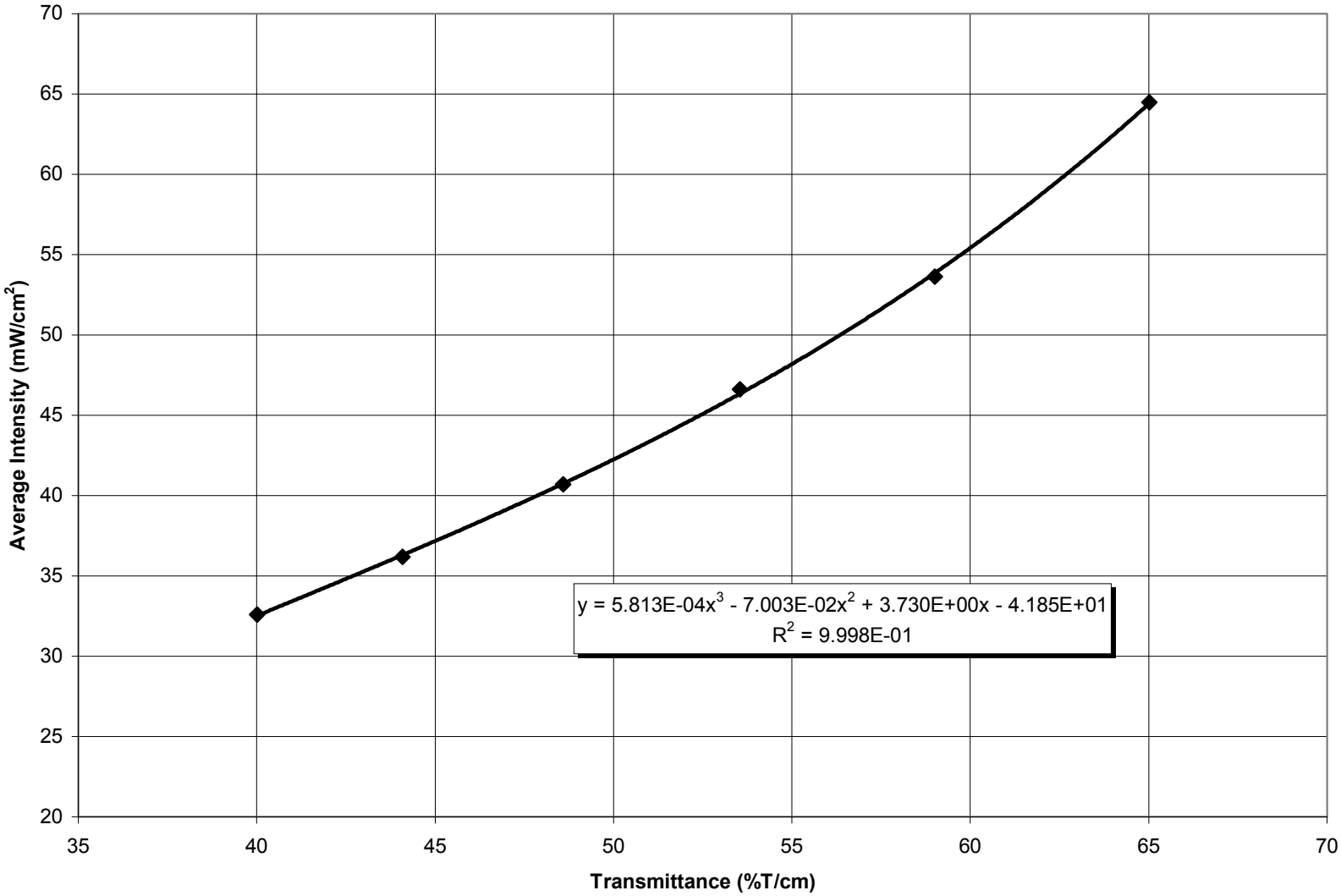

Figure 4-5. Average intensity in the bersonInLine® System as a function of transmittance.

Table 4-1. Transmittance Reduction Calculation Results

Transmittance (%T/cm)	I_{AVE} (mW/cm^2)	x 0.70
65.0	64.4	46.3
53.6	46.3	
55.0	48.2	33.7
41.3	33.7	

As determined by these calculations, the bioassay tests were performed at adjusted transmittances. For the 65%T nominal conditions, the actual transmittance was 54%T; for the 55%T nominal conditions, the actual transmittance was 41%T.

4.4.4.2 Transmittance Measurement

The transmittance of the challenge waters was measured on every influent sample and on the seeded influent samples used for dose-response analysis. The transmittance was measured in the laboratory, using a Perkin-Elmer Lambda-6 spectrophotometer, at 254 nm in quartz, 1 cm path-length cells. The zero reference was Grade 2 laboratory deionized water (ISO, 1987).

In addition, an influent sample from each challenge water batch was scanned for %T from 230-280 nm. Scans for the first two batches were conducted stepwise on a non-automated spectrophotometer that had to be zeroed at each 1 nm step.

4.4.5 MS2 Enumeration

The concentration of viable MS2 bacteriophage in flow test and dose-response samples was enumerated using a microbiological technique based on ISO 10705-1 (ISO, 1995).

The samples containing MS2 bacteriophage were serially diluted in peptone-saline dilution tubes to a dilution determined to be appropriate from experience or from shakedown runs. Then, 1 mL of this diluted sample was mixed with 1 mL of host *E. coli* and 2.5 mL semi-solid growth medium. This mixture was plated onto an agar plate and allowed to grow overnight (~16 hours) at 37 °C. This double-plating approach used trypticase, yeast-extract glucose broth as the growth medium.

Each sample was plated at two dilutions in triplicate, resulting in six plates for each sample. Only plates with 30-300 pfu were deemed valid for analysis. The acceptable data was then averaged geometrically and corrected for the dilution to determine the MS2 concentration (pfu/mL) in the test solution.

The survival ratio was then determined for the particular test conditions with the following relationship:

$$\text{Survival Ratio} = \log_{10}\left(\frac{N}{N_0}\right) \tag{4-3}$$

$$N_0 = \text{MS2 Concentration in Undosed Sample}$$

$$N = \text{MS2 Concentration in Dosed Sample}$$

4.4.6 Delivered Dose Determination

The dose-response calibration of the MS2 bacteriophage was quantified by fitting a second-order polynomial to all valid dose-response data, thereby generating a relationship where dose is a function of survival ratio (see Section 5.2). All flow test survival ratios were then converted to effective doses with the use of this relationship (see Section 5.3).

Chapter 5
Results and Discussion

5.1 Disinfection System Startup and Characterization

5.1.1 Power Consumption and Intensity Stability Characterization

5.1.1.1 Power Consumption

The power consumption of the two-reactor train was measured at all power level settings. The raw data are in Appendix C and data summaries with calculations are in spreadsheets in Appendix D. Table 5-1 shows the power and current data for the three power levels, averaged over a period of approximately 25 min.

Table 5-1. Power and Current Measurements for the Two-Reactor Train

Power Setting	Power (kW)	Power per lamp (kW)	Current (A per 480V leg)
P1	34.04	2.84	47.5
P2	39.61	3.30	53.8
P3	45.14	3.76	60.0

At the power level used at the beginning of lamp life (P1), the power consumption was 2.84 kW per lamp; at the highest power setting (P3), power consumption increased to 132% or 3.76 kW per lamp. It is important to note that these power readings are inclusive of all of the control circuitry. The current draw was balanced between the three 480 V legs to within 1 A; it ranged up to 60 A for the two-reactor train.

5.1.1.2 Lamp Output Stability

The lamp output stability was measured by turning the system to the P1 setting at a cold start and monitoring the two, built-in detectors for 12 minutes at five-second intervals. The 4-20 mA signal of the UVector detector's output was recorded with a datalogger. Figure 5-1 shows the relative output of the detectors as they approached the steady value of 10.5 mA.

After 3 minutes, the lamps exceeded 95% of the maximum output; they were at nearly 100% intensity at 10 min. Based on this result, the bioassay flow tests allowed a minimum of 10 minutes of lamp warm-up before flow testing commenced.

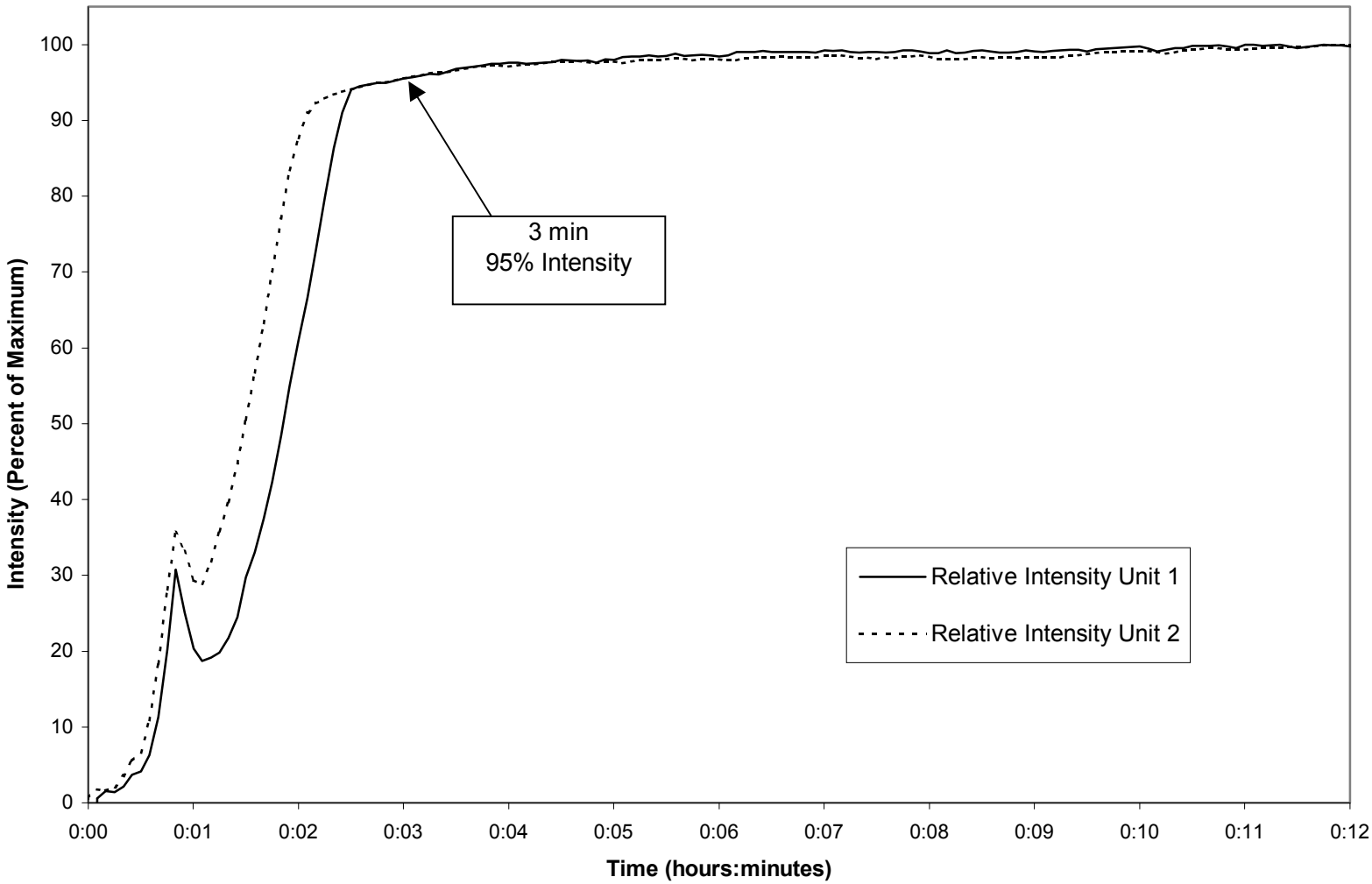

Figure 5-1. Lamp intensity warm-up curves.

5.1.2 Detector and Alarm Validation

5.1.2.1 UVector Detectors' Linearity Validation

The first step in validating the UVector detectors and alarm systems was to verify that the relative UV intensity signal from the UVector detectors agreed with the relative signal from an external UV detector. In this case, the external detector was the IL-1700/SUD 240 fiber-optic system described in Section 4.2.3.2. Raw data and notes are in Appendix C; they are summarized in Table 5-2.

The nominal condition was taken as the P3 intensity in potable water (98-99%T). After the lamps had warmed up at the P3 setting, the UVector detector outputs were set to 11.5 mA and the ECtronic control unit's voltage was set to 6.3 V. Then the power levels were taken down and up through all power level settings. The data for power levels P2 and P3 are averages of two, separate measurements taken through the up-down-up cycle.

A comparison of the relative intensities with reference to power level P3 is shown graphically in Figure 5-2. Note that the relative intensities are calculated with 4 mA subtracted from the UVector detector's signal, as is required with the 4-20 mA signal protocol. The relative intensity changes measured with UVector detector 1 and UVector detector 2 agree very closely. The data show a linear relationship, where the relative intensity changes indicated in the UVector detector output signals agree within approximately 5% with the relative intensity changes measured with the IL-1700.

This relationship verified the linear response of the UVector detectors. As such, the subsequent, lower transmittance verifications used only the UVector detectors' outputs to monitor relative intensity changes because the distance of the IL-1700 detector would not have allowed sufficient readings to be taken.

Table 5-2. Intensity Measurements at All Power Level Settings

Power Level	UVector 1 (mA)	UVector 2 (mA)	ECtronic 1 (V)	ECtronic 2 (V)	IL-1700 (V)	Readout (%)	IL (%)	UVector 1 (%)	UVector 2 (%)
P1	9.37	9.40	5.10	5.12	0.719	80	73.0	71.7	71.4
P2	10.43	10.46	5.69	5.70	0.861	90	87.4	85.9	85.6
P3	11.48	11.56	6.27	6.28	0.985	100	100	100	100

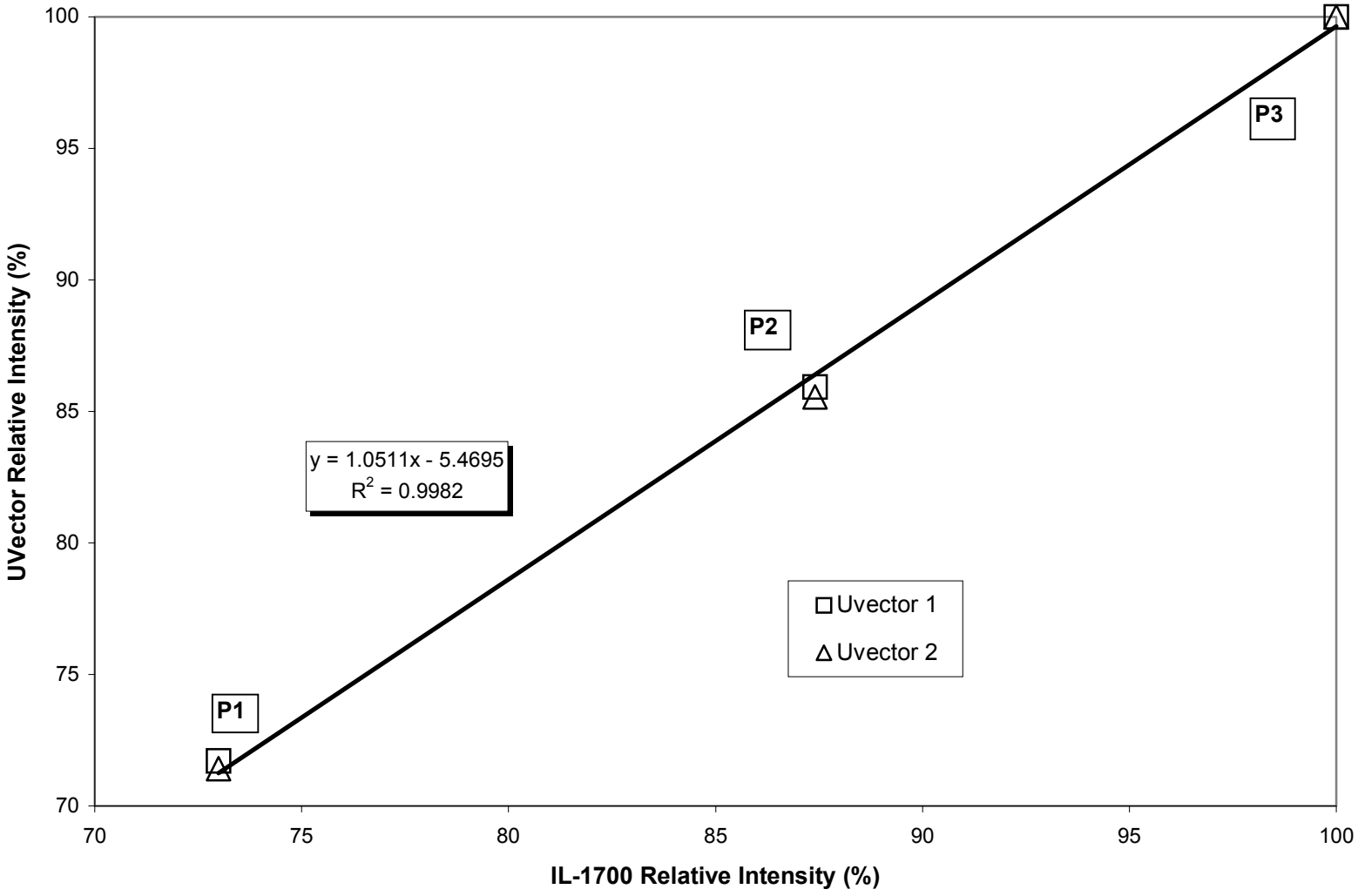

Figure 5-2. Comparison of UVector detectors and IL-1700 relative intensities.

5.1.2.2 UV Output Response to Changes in %T

Two verifications were conducted to determine the relative intensity at which the low UV alarm would activate and to determine the response of the UVector detectors' outputs to changes in transmittance. The first was conducted with the nominal condition as power level P1 and 65%T water. The second was conducted with the nominal condition as power level P1 and 55%T water. At the start of each test, the lamps were allowed to stabilize and then the UVector detectors' outputs were set to 11.5 mA, and the ECtronic control unit's voltage was set to 6.3 V. Raw data and notes are in Appendix C.

After stabilization at the nominal conditions, the transmittance of the water flowing through the reactor train was stepped down incrementally until the alarm activated (see Section 4.2.3.3). At several points in the series, a water sample was taken from the upstream reactor and measured for %T at 254 nm. The data are summarized in Table 5-3.

The response of the relative UVector detectors' output to the changes in transmittance is shown in Figure 5-3. The data showed some variability, reflecting the dynamic nature of the test. These data were fitted with power curves because of the exponential nature of the %T and power intensity relationship. These fits allow an analysis of the effective distance of the monitors. They also allow the derivation of an empirical relationship of the UVector detectors' behavior.

Table 5-3. Intensity and Alarm Response to Reduced Transmittance

%T (%T/cm)	UVector 1 (mA)	UVector 2 (mA)	ECtronic 1 (V)	ECtronic 2 (V)	UVector 1 (%)	UVector 2 (%)	Readout (%)
65.2	11.47	11.50	6.26	6.27	100.0	100.0	100
57.5	10.57	10.60	5.82	5.84	88.0	88.0	90
54.7	10.42	10.43	5.74	5.75	86.0	85.7	90
51.9	10.35	10.37	5.70	5.71	85.0	84.9	90
49.8	9.84	9.86	5.41	5.43	78.2	78.0	80
44.9	9.40	9.40	5.17	5.18	72.2	72.0	80
39.7	8.66	8.67	4.76	4.77	62.4	62.2	70
55.8	10.34	10.35	5.69	5.70	84.9	84.6	80
34.6	8.05	8.20	4.45	4.47	54.2	55.9	UV Alarm Activated
41.0	8.90	8.90	4.89	4.90	65.6	65.3	ALARM
45.4	9.73	9.47	5.27	5.30	76.8	72.9	80
51.2	10.23	10.18	5.62	5.63	83.4	82.4	80
NA	8.28	8.17	4.62	4.63	57.3	55.6	UV Alarm Activated
NA	8.26	8.27	4.53	4.54	57.0	56.8	ALARM
41.0	8.98	8.96	4.93	4.94	66.7	66.1	70
38.1	8.53	8.53	4.68	4.69	60.6	60.3	UV Alarm Activated
55.2	11.50	11.50	6.33	6.34	100.5	100.0	100
55.3	11.50	11.50	6.33	6.34	100.4	99.9	100
50.8	11.08	11.02	6.08	6.10	94.8	93.5	90
41.1	9.89	9.81	5.42	5.43	78.9	77.5	80
35.8	9.21	9.16	5.04	5.06	69.7	68.7	70
31.5	8.60	8.53	4.71	4.72	61.6	60.4	UV Alarm Activated
49.8	10.57	10.48	5.79	5.79	87.9	86.4	90
39.8	9.47	9.45	5.20	5.22	73.2	72.6	80
33.1	8.67	8.63	4.75	4.77	62.5	61.7	70
NA	8.50	8.48	4.67	4.67	60.2	59.7	UV Alarm Activated

This analysis is based on the Beer-Lambert law in transmittance form:

$$
\begin{aligned}
&I_{\%T} = I_0 e^{\ln(\%T)d} \\
&Where: \\
&I_{\%T} = \text{The measured intensity at some \%T.} \\
&I_0 = \text{The nominal intensity at 100\%T.} \\
&\%T = \text{The percent transmittance in decimal form.} \\
&d = \text{The distance of the monitor.}
\end{aligned}
\tag{5-1}
$$

A proportionality constant (C) must be included to account for the fact that the initial nominal intensity was not set at 100%T in the two tests:

$$I_{\%T} = I_0 C e^{\ln(\%T)d} \tag{5-2}$$

Now the intensity ratio must be isolated:

$$\frac{I_{\%T}}{I_0} = C e^{\ln(\%T)d} \tag{5-3}$$

Then the equation can be put in the form of the power functions shown in Figure 5-3, where the exponent (d) is the distance in cm:

$$
\begin{aligned}
\frac{I_{\%T}}{I_0} &= C\left(e^{\ln(\%T)}\right)^d \\
\frac{I_{\%T}}{I_0} &= C(\%T)^d
\end{aligned}
\tag{5-4}
$$

The relationships shown in Figure 5-3 show exponents to the power law relationship of 0.93 for the 65%T test and 0.88 for the 55%T test. This results in an effective UVector detector distance of approximately 0.9 cm. Based on this analysis, the intensity signal generated by the detector, if the detector was zeroed at 100%T, would be:

$$I_{\%T} = I_0 e^{\ln(\%T)0.9} \tag{5-5}$$

Using this relationship allows a prediction of the response of the detector to changes in transmittance and lamp intensity. The first step to setting up the bersonInLine® System is to setup the reactor and control panel to present an alarm when a potentially low dose condition arises during routine operation.

5.1.2.3 Low UV Output Alarm Validation

The final step in evaluating user feedback from the bersonInLine® System is to determine the relative UV intensity that activates the low UV alarm. This is evaluated with the data summarized in Table 5-3, where the readout/alarm condition is related to the relative intensity signal of the UVector detectors. This relationship is shown in Figure 5-4.

The data shown in Figure 5-4 is derived from both the 55%T and the 65%T tests. This figure shows the range of relative intensities that resulted in a given readout on the ECtronic control unit. For example, the ECtronic control unit read 80% UV output when the relative UVector detector output was in the range of approximately 72-84%.

The bersonInLine® System sounded a low UV alarm on the display panel and activated an internal relay for remote operation. Although the lowest readout indication is "70% Alarm," the alarm activated at slightly lower intensities. The ECtronic control unit required the alarm condition to be present for approximately 20 seconds before the alarm condition was indicated.

Figure 5-4 shows that the alarm condition activated below approximately 61% relative intensity. This differs somewhat from the 70% alarm condition used as the reference setting for this verification test and must be taken into account when a full-scale installation is set up. The low UV dose alarm setting is discussed further in Section 5.3.4.3.

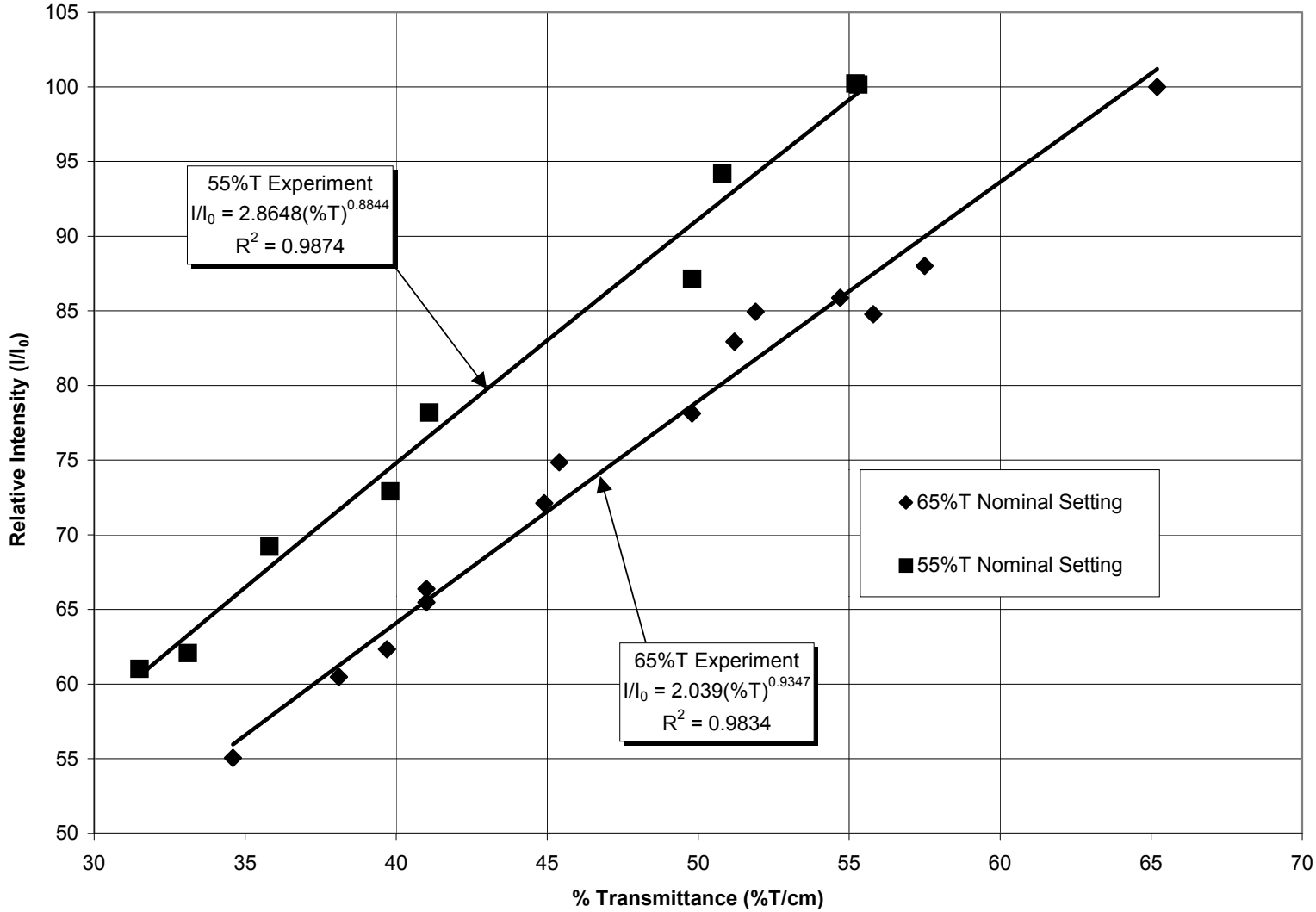

Figure 5-3. UVector detector intensity response to changes in transmittance.

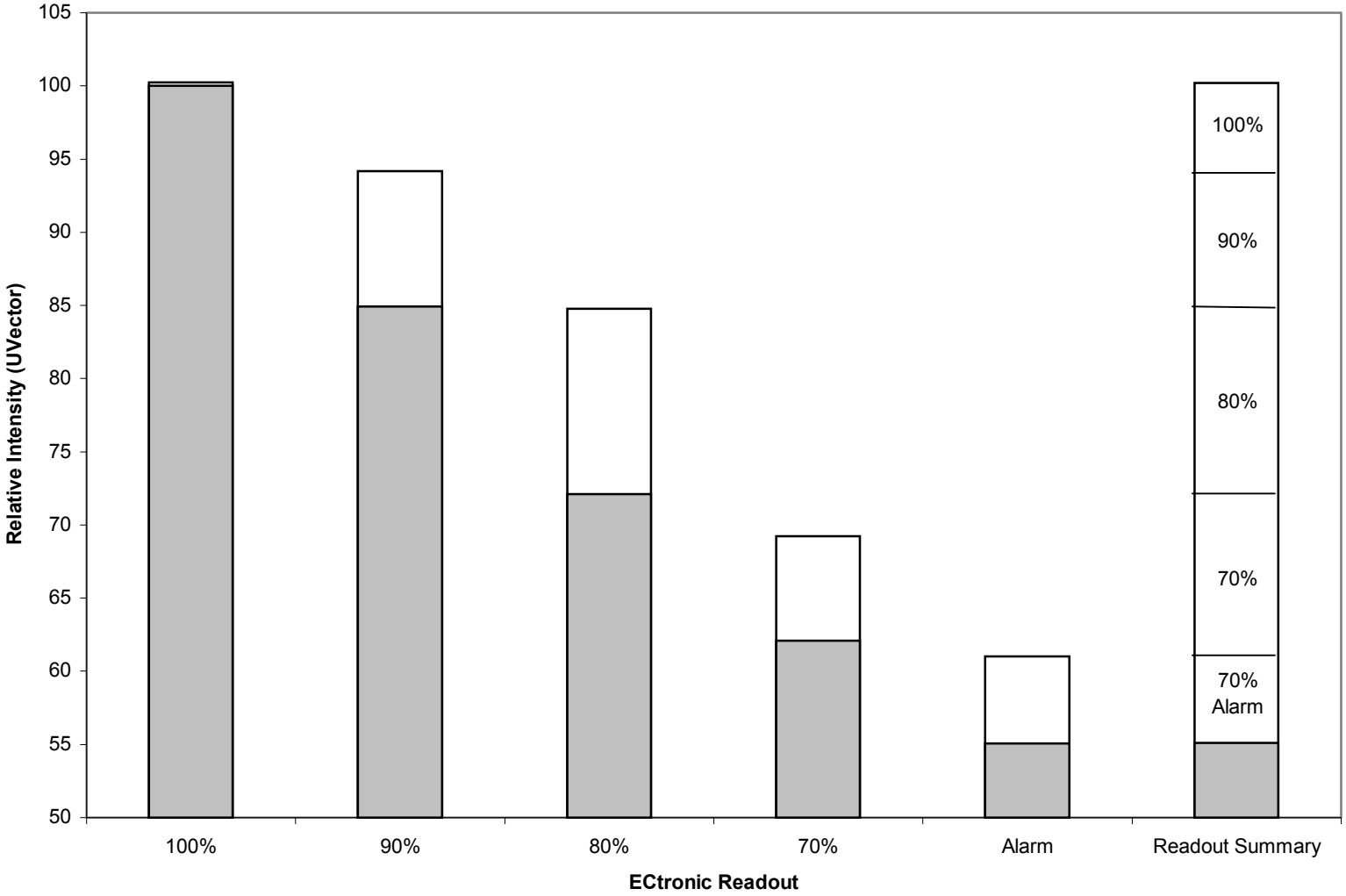

Figure 5-4. Relationship between ECtronic control unit readout and the relative intensity.

5.1.3 Headloss Measurements

The headloss measurements were determined with the method described in Section 4.2.4. Raw data and notes about them are included in Appendix C and summary data and supporting calculations are in Appendix D. The headloss data are summarized in Table 5-4 and are presented graphically in Figure 5-5.

Table 5-4. Headloss Data Summary

Flow (L/min)	Flow (gpm)	Flow (MGD)	Velocity[1] (cm/s)	Headloss (cm)
1,052	278	0.4	27.7	3.8
2,101	555	0.8	53.5	5.4
3,941	1,041	1.5	95.9	8.3
7,355	1,943	2.8	172	12.7
10,508	2,776	4.0	265	18.7

[1]Velocity from Table 5-6.

The headloss increased as a function of flow rate because of the flow resistance from the presence of the lamp sleeves and the irregular, internal geometry of the reactor train housings. The results in Figure 5-5 show a nearly linear relationship between flow and headloss. However, the data are better fitted with a second-order polynomial, which can be used to estimate the headloss (cm) for any flow in the range of 1,052 to 10,508 L/min.

$$headloss = 3.14\times10^{-8}(flow)^2 + 1.18\times10^{-3}(flow) + 2.72 \tag{5-6}$$

Headloss through a disinfection system should exist at any non-negligible flow rate, because of the hydraulic resistance due to viscous flow and the presence of obstacles such as lamps and mounting hardware. In ideal, turbulent systems, the headloss increases as a function of the square of the flow velocity, which is directly proportional to the flow rate. In theory, the data should fit the following relationship:

$$\frac{\Delta H}{L} = aV + b\rho V^2 \tag{5-7}$$

Where

$\frac{\Delta H}{L}$ = Headloss Over a Characteristic Length

V = Velocity

ρ = Fluid Density

a = Constant for Viscous Flow Term

b = Constant for Inertial (Turbulent) Flow Term

For the data in Figure 5-5, the constants *a* and *b* are positive, suggesting the presence of both viscous and turbulent components. The near linearity of the headloss relationship is reflected in the small value of *b*. It is likely that turbulent flow is present to a greater degree than suggested by the linear nature of the headloss relationship. This excess turbulent flow may be the result of the complex geometry and physical configuration of this two-reactor train. The y-intercept is non-zero, suggesting that the headloss at a flow of zero is 2.72 cm. Note that these data should not be extrapolated outside the range of the flow rates used in this verification test.

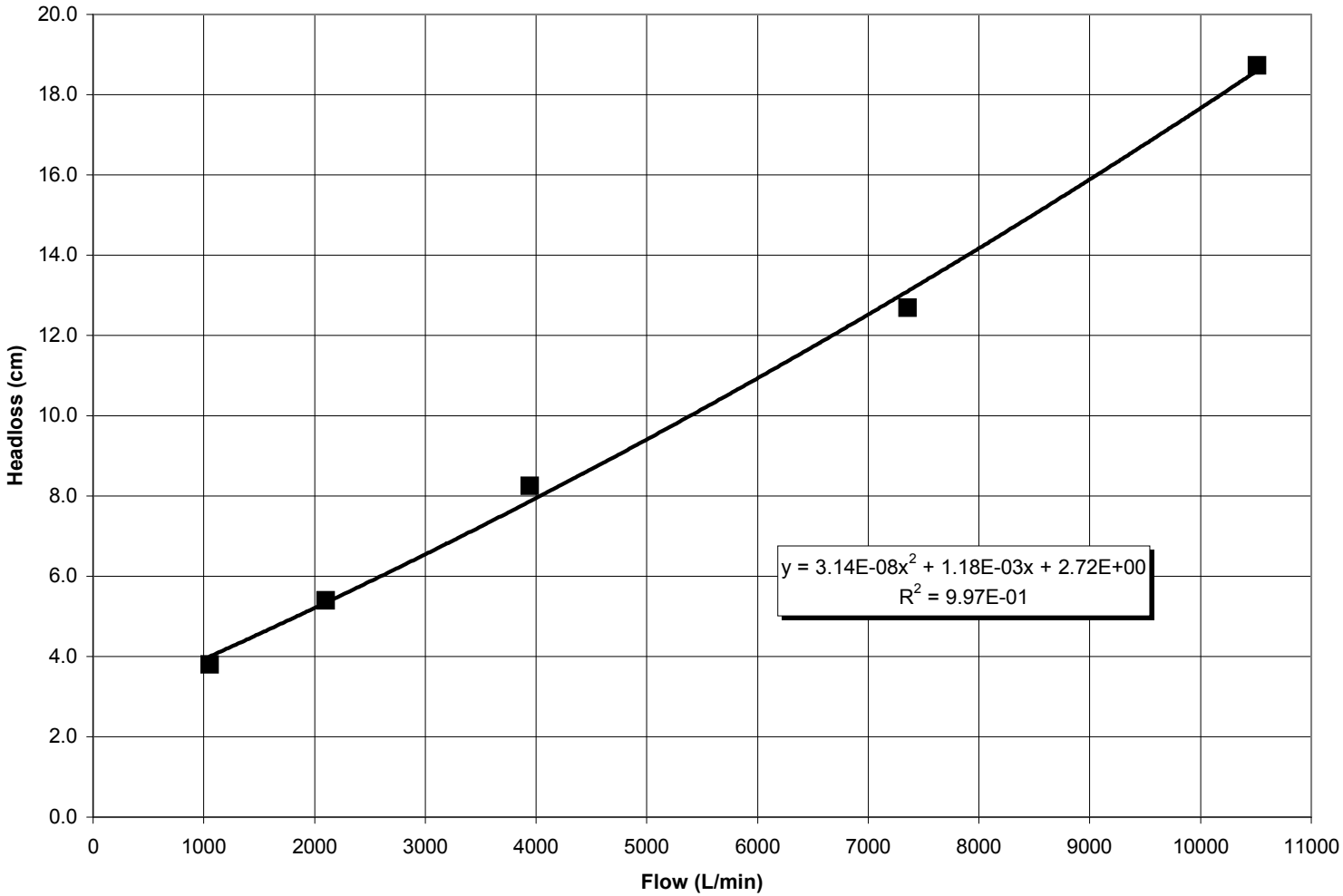

Figure 5-5. Headloss as a function of flow rate.

5.1.4 Hydraulic Flow Field Analysis

The data for the influent and effluent flow field measurements were acquired as described in Section 4.2.5. Raw data are in Appendix C; summary data and calculations are in Appendix D.

The flow velocities are compared to the cross-sectional average velocities at the influent and effluent positions. The cross-sectional average flow velocities were calculated based on the flow rate and the diameter of the pipe. Then $Q = VA$ was solved for the velocity. For the influent side of the system, the inside diameter of the influent flow modifier (see Figure 3-5) was used, which was approximately 1 cm downstream from the pitot tubes. This diameter was 29.9 cm. For the effluent side of the system, the inside diameter of the 14-inch pipe was used. This diameter was 31.5 cm.

Results of the cross-sectional average velocity calculations are in Table 5-5. Note the slight difference between the influent and effluent velocities as a result of the difference in diameters. Also included are the acceptable velocity ranges, which are 0.8 and 1.2 times the calculated velocities (National Water Research Institute and American Waste Water Association Research Foundation, 2000).

Table 5-5. Cross-Sectional Average Velocities

Flow (L/min)	**Flow** (gpm)	**Velocity** (cm/s)	**V x 1.2** (cm/s)	**V x 0.8** (cm/s)
Influent				
1,052	278	25.1	30.1	20.1
2,101	555	50.1	60.1	40.0
3,941	1,041	93.9	112.7	75.1
7,355	1,943	175.2	210.3	140.2
10,508	2,776	250.3	300.4	200.3
Effluent				
1,052	278	22.6	27.1	18.1
2,101	555	45.1	54.1	36.1
3,941	1,041	84.6	101.5	67.7
7,355	1,943	157.8	189.4	126.3
10,508	2,776	225.5	270.6	180.4

The flow velocity results are summarized in Table 5-6. For each flow condition, the velocity in the central position was measured four times on both the influent and effluent sides of the system. These data were averaged and that value was used as the velocity of the central position. These central velocity measurements also were evaluated statistically for variability using the standard deviation. With one exception, the repeatability of the measurements was within 3%; the effluent central velocity measurements for the lowest flow condition (1,052 L/min) varied

8.2%. Generally, the variability in these four central velocity measurements was greater at lower flows, and the variability was greater on the effluent measurements. Thus, the 8.2% value is the worst-case scenario.

The flow velocity data for the nine flow positions and all conditions are given in Table 5-6. The velocities are reported in cm/s and the average and ranges of the measurements are also reported. The actual velocities are normalized to the theoretical velocities presented in Table 5-6. This allows an evaluation of the adherence of the velocity fields to the allowable variation specified in "Ultraviolet Disinfection Guidelines for Drinking Water and Water Reuse" (National Water Research Institute and American Waste Water Association Research Foundation, 2000).

Table 5-6. Summary of Measured Flow Field Data

Flow (L/min)	Position CW from Vertical (º)	Distance From Center (cm)	Influent Velocity (cm/s)	Effluent Velocity (cm/s)	Influent Normalized Calculation	Effluent Normalized Calculation
1,052 (278 gpm)						
		0.0	27.6	23.1	1.10	1.02
	0	5.0	28.0	23.5	1.12	1.04
	0	10.7	27.4	24.4	1.09	1.08
	90	5.0	28.7	27.4	1.14	1.22
	90	10.7	27.1	22.6	1.08	1.00
	180	5.0	27.7	25.3	1.11	1.12
	180	10.7	27.7	21.6	1.11	0.96
	270	5.0	28.0	24.7	1.12	1.09
	270	10.7	27.1	17.7	1.08	0.78
		Average:	27.7	23.4	1.11	1.03
		Maximum:	28.7	27.4	1.14	1.22
		Minimum:	27.1	17.7	1.08	0.78
	0	0.0	28.0	22.9		
	90	0.0	28.3	25.3		
	180	0.0	26.5	20.7		
	270	0.0	27.4	23.5		
		Average:	27.6	23.1		
		Standard deviation:	0.8	1.9		
		%:	2.9	8.2		

Flow (L/min)	Position CW from Vertical (º)	Distance From Center (cm)	Influent Velocity (cm/s)	Effluent Velocity (cm/s)	Influent Normalized Calculation	Effluent Normalized Calculation
2,101 (555 gpm)						
		0.0	53.6	43.8	1.07	0.97
	0	5.0	54.6	48.5	1.09	1.07
	0	10.7	56.1	47.2	1.12	1.05
	90	5.0	57.3	47.9	1.14	1.06
	90	10.7	57.0	45.4	1.14	1.01
	180	5.0	52.1	50.0	1.04	1.11
	180	10.7	50.6	44.5	1.01	0.99
	270	5.0	50.9	47.9	1.02	1.06
	270	10.7	49.7	49.1	0.99	1.09
		Average:	53.5	47.1	1.07	1.05
		Maximum:	57.3	50.0	1.14	1.11
		Minimum:	49.7	43.8	0.99	0.97
	0	0.0	55.2	44.5		
	90	0.0	54.3	45.1		
	180	0.0	51.8	43.3		
	270	0.0	53.0	42.4		
		Average:	53.6	43.8		
		Standard deviation:	1.5	1.2		
		%:	2.7	2.8		

Flow (L/min)	Position CW from Vertical (º)	Distance From Center (cm)	Influent Velocity (cm/s)	Effluent Velocity (cm/s)	Influent Normalized Calculation	Effluent Normalized Calculation
3,941 (1,041 gpm)						
		0.0	98.0	86.6	1.04	1.02
	0	5.0	97.5	93.0	1.04	1.10
	0	10.7	95.1	89.9	1.01	1.06
	90	5.0	95.7	86.9	1.02	1.03
	90	10.7	91.7	70.1	0.98	0.83
	180	5.0	96.9	95.4	1.03	1.13
	180	10.7	93.9	76.5	1.00	0.90
	270	5.0	98.5	92.4	1.05	1.09
	270	10.7	96.0	80.8	1.02	0.96
		Average:	95.9	85.7	1.02	1.01
		Maximum:	98.5	95.4	1.05	1.13
		Minimum:	91.7	70.1	0.98	0.83
	0	0.0	98.5	88.4		
	90	0.0	97.2	85.6		
	180	0.0	98.1	86.3		
	270	0.0	98.1	86.3		
		Average:	98.0	86.6		
		Standard deviation:	0.5	1.2		
		%:	0.5	1.4		

Flow (L/min)	Position CW from Vertical (º)	Distance From Center (cm)	Influent Velocity (cm/s)	Effluent Velocity (cm/s)	Influent Normalized Calculation	Effluent Normalized Calculation
7,355 (1,943 gpm)						
		0.0	176.6	174.6	1.01	1.11
	0	5.0	170.1	195.4	0.97	1.24
	0	10.7	159.1	162.8	0.91	1.03
	90	5.0	176.2	174.7	1.01	1.11
	90	10.7	166.1	163.7	0.95	1.04
	180	5.0	179.5	188.7	1.02	1.20
	180	10.7	173.1	135.0	0.99	0.86
	270	5.0	177.7	173.1	1.01	1.10
	270	10.7	168.9	160.0	0.96	1.01
		Average:	171.9	169.8	0.98	1.08
		Maximum:	179.5	195.4	1.02	1.24
		Minimum:	159.1	135.0	0.91	0.86
	0	0.0	175.9	177.4		
	90	0.0	177.4	174.7		
	180	0.0	176.8	175.6		
	270	0.0	176.2	170.7		
		Average:	176.6	174.6		
		Standard deviation:	0.7	2.8		
		%:	0.4	1.6		

Flow (L/min)	Position CW from Vertical (º)	Distance From Center (cm)	Influent Velocity (cm/s)	Effluent Velocity (cm/s)	Influent Normalized Calculation	Effluent Normalized Calculation
10,508 (2,776 gpm)						
		0.0	273.0	305.6	1.09	1.36
	0	5.0	267.0	349.0	1.07	1.55
	0	10.7	259.1	300.2	1.03	1.33
	90	5.0	264.3	290.5	1.06	1.29
	90	10.7	250.9	260.3	1.00	1.15
	180	5.0	276.5	321.3	1.10	1.42
	180	10.7	267.6	207.3	1.07	0.92
	270	5.0	272.2	304.2	1.09	1.35
	270	10.7	257.6	262.4	1.03	1.16
		Average:	265.3	289.0	1.06	1.28
		Maximum:	276.5	349.0	1.10	1.55
		Minimum:	250.9	207.3	1.00	0.92
	0	0.0	272.8	305.7		
	90	0.0	272.8	306.3		
	180	0.0	273.4	303.3		
	270	0.0	273.1	307.2		
		Average:	273.0	305.6		
		Standard deviation:	0.3	1.7		
		%:	0.1	0.6		

CW - clockwise

Variations in both the influent and effluent flow velocity fields are evaluated by considering the range of the ratios of the actual velocity to theoretical velocity for each condition. For the influent data, the minimum and maximum of the actual velocity to theoretical velocity ratios are all within the 0.8-1.2 range. This indicates that the influent velocity fields are in compliance with the National Water Research Institute's requirements (National Water Research Institute and American Waste Water Association Research Foundation, 2000). Based on this analysis, the influent piping to the system is deemed acceptable.

For the effluent data, the minimum and maximum of the actual velocity to theoretical velocity ratios shows a greater range in variability than for the influent data. This variability likely is the result of a combination of turbulence and eddies behind the upstream obstructions (e.g., the lamp sleeves).

5.2 MS2 Dose-Response Calibration Curve

5.2.1 Dose-Response Results

A total of sixteen dose-response tests were conducted during this verification test. Seven were considered valid, six were used for QA/QC validation purposes, and the other three were excluded for the reasons discussed in Section 6.2.2. All raw data are included in Appendix C.

Data from the seven, valid, dose-response tests conducted on the seeded challenge waters used during this testing program are shown in Table 5-7. This valid data consists of three runs in 54%T challenge water (65%T nominal) and four runs in 41%T challenge water (55%T nominal).

At some doses, the survival ratios vary up to 0.5 log units. This variability is typical for such microbiological analyses and highlights the need for several dose-response data sets to enhance the statistical confidence of the dose-response calibration curve. See Section 6 for QA/QC discussion.

5.2.2 Dose-Response Calibration Curve

The dose-response calibration curve is presented in Figure 5-6, with the dose as a function of the survival ratio. This allows the computation of a calibration curve for the MS2 bacteriophage stock by empirically fitting a second-order polynomial. It also allows the determination of a dose at any survival ratio among those used to generate the curve.

$$Dose = 2.0713(Survival)^2 - 12.571(Survival) + 2.191 \tag{5-8}$$

Where:

$$\text{Survival} = \log_{10}\left(\frac{N}{N_0}\right)$$

N_0 = MS2 Concentration in Undosed Sample

N = MS2 Concentration in Dosed Sample

This equation is then applied to the survival ratios generated by the dose delivery of the test system to calculate an effective delivered dose.

It is important to note that the disinfection system used polychromatic light, whereas the dose-response data was generated with a monochromatic lamp. This may introduce a bias due to the multispectral nature of the lamps and the different action spectra of the test organism. However, the protocol (NSF, 2002) is designed to normalize the multispectral dose delivery to the monochromatic UV light used in the dose-response. This is one of the simplifying assumptions upon which this verification test is based.

Table 5-7. Valid Dose-Response Data for MS2

	Nominal Dose[1]:		10	20	30	40	50	60	80	100
	%T (%/cm)	Matrix	Dose, Survival	Dose, Survival	Dose, Survival	Dose, Survival	Dose, Survival	Dose, Survival	Dose, Survival	Dose, Survival
DRS1	41.4	(2)	10.0 / -0.35	20.0 / -1.16	--	40.2 / -2.27	--	60.5 / -3.08	--	100.7 / -4.41
DRS2	53.9	(3)	9.9 / -0.62	20.0 / -1.23	--	39.9 / -2.12	--	59.9 / -3.00	--	99.7 / -4.27
DRS3	40.0	(2)	--	20.3 / -1.27	--	--	--	60.7 / -2.97	--	101.2 / -4.41
DRS4	54.0	(3)	--	20.2 / -1.33	--	--	--	60.5 / -2.91	--	100.8 / -4.42
DRS6	53.8	(3)	--	20.3 / -1.31	--	40.6 / -2.14	--	61.1 / -3.03	81.4 / -3.90	--
DRS7	40.7	(2)	--	19.8 / -1.22	--	39.8 / -2.33	--	59.6 / -3.13	79.6 / -4.12	99.4 / -4.64
DRS8	40.8	(2)	--	19.9 / -1.14	--	--	--	60.0 / -3.13	--	100.0 / -4.48

(1) Dose in mJ/cm^2; Survival is log (N/N_0)

(2) Filtered effluent + Coffee;

(3) Potable water + Sodium thiosulfate + Coffee.

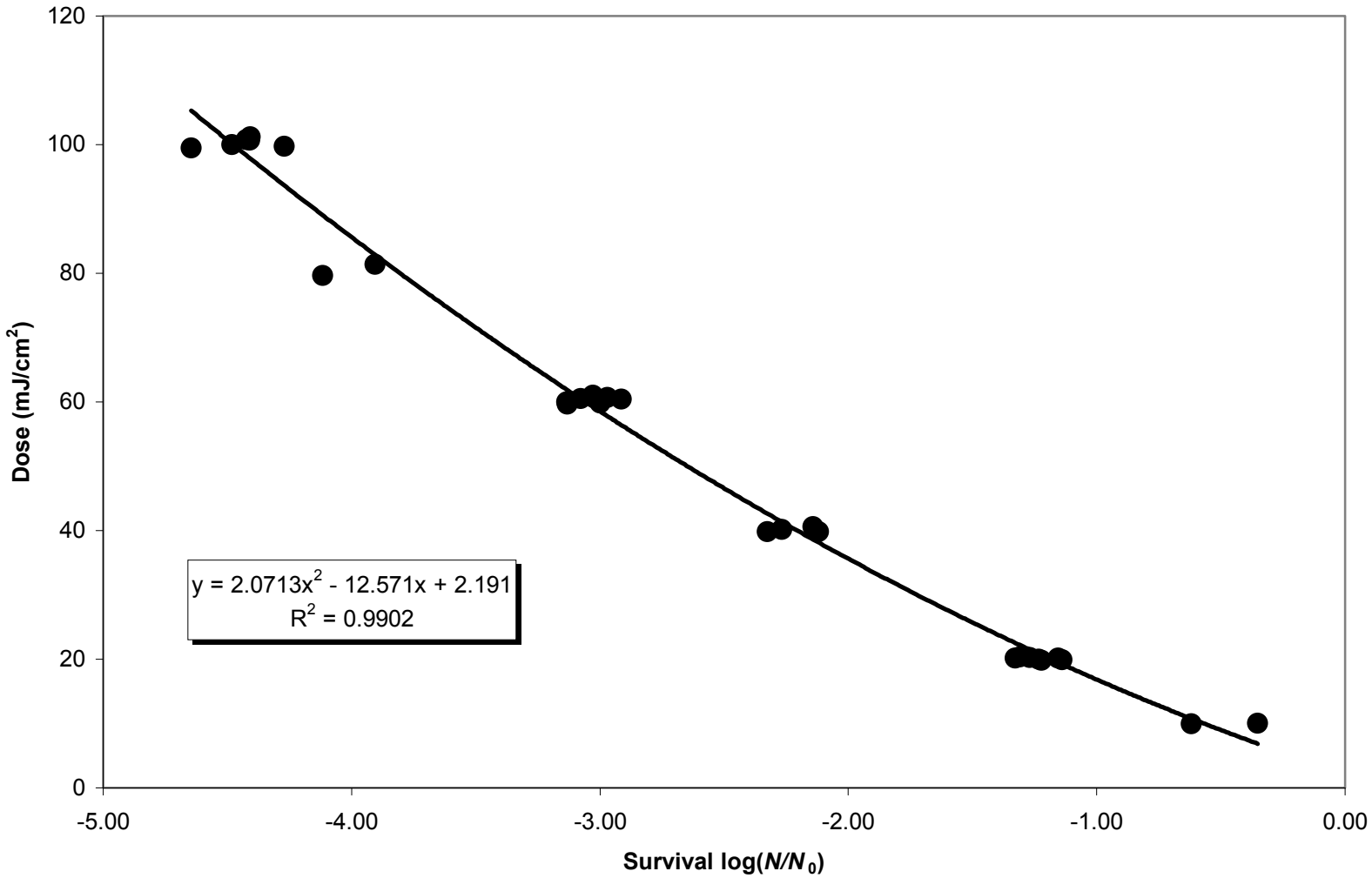

Figure 5-6. Dose-Response curve for the MS2 batch used for this verification.

5.3 Dose Flow Assays

5.3.1 Flow Test Summary

A total of 48 flow tests were conducted during this verification test. Forty-four valid flow tests were conducted over a period of 6 days and are summarized in Table 5-8. Four, no-dose flows were also conducted and are discussed in Section 6.3.2. All raw data and notes are included in Appendix C.

Table 5-8. Summary of Bioassay Flow Tests

Flow Series	Nominal % T (%T/cm)	Actual %T (%T/cm)	N_0 (pfu/mL)	Flows (L/min)
FLS1	65	53.9	6.1×10^5	1,052, 2,101, 3,941, 7,355, 10,508
FLS2	55	41.4	1.4×10^6	1,052, 2,101, 3,941, 7,355, 10,508
FLS3	55	40.0	8.0×10^5	1,052, 2,101, 3,941, 7,355, 10,508
FLS4	65	52.9	9.7×10^5	1,052, 1,052, 2,101, 2,101, 2,101, 3,941, 7,355, 10,508
FLS5	65	54.0	1.3×10^6	1,052, 3,941, 7,355
FLS6	65	53.8	7.0×10^5	2,101, 3,941, 7,355, 7,355,10,508, 10,508
FLS7	55	40.7	1.0×10^6	1,052, 2,101, 2,101, 3,941, 7,355, 10,508
FLS8	55	40.1	1.2×10^6	1,052, 2,101, 3,941, 7,355, 10,508, 7,355

5.3.2 Data Reduction and Results

Table 5-9 shows the flow test results for each set of flow and transmittance conditions. For each flow test, the titers of three influent samples were geometrically averaged to calculate the no-dose MS2 concentration (N_0). Then the titers of each of the three effluent samples (N) were used to calculate the survival ratio, log (N/N_0). Thus, each individual flow event resulted in the generation of three survival ratios. These survival ratios were then converted to a delivered dose, with the dose-response curve generated in Section 5.2.2.

Each flow condition resulted in 12-15 delivered dose estimates (see Table 5-9). The protocol (NSF, 2002) required that these data be analyzed statistically for a 75% confidence interval (C.I.), based on the two-tailed t-test for small samples. The C.I. High and the C.I. Low were then calculated with the following relation:

$$MEAN \pm t_{\alpha,\upsilon} \frac{\sigma}{\sqrt{n}}$$

$$Where:$$

$$\sigma = \text{Standard Deviation}$$

$$\alpha = 0.25$$

$$n = \text{Number of Measurements.}$$

$$\upsilon = n - 1$$

$$t = \text{Students } t\text{ - Test Distribution} \tag{5-9}$$

The individual doses are plotted, along with the 75% C.I., in Figures 5-7 and 5-8.

Table 5-9. Bioassay Flow-Test Delivered Dose Data and Statistics

Conditions	Series	Survival ($\log(N/N_0)$)	Dose (mJ/cm^2)	Dose Statistics (mJ/cm^2)	
1,052 L/min, 65% T (54% Actual)					
(278 gpm)	FLS1	-3.85	81.3	STDEV:	4.88
		-3.79	79.6	MEAN:	81.11
		-3.84	81.0	75%C.I.:	1.71
	FLS4a	-4.18	90.9	C.I. Hi:	82.82
		-3.96	84.5	C.I. Low:	79.40
		-4.04	86.8		
	FLS4b	-3.60	74.3		
		-3.75	78.5		
		-3.61	74.6		
	FLS5	-3.96	84.5		
		-3.74	78.2		
		-3.78	79.3		

Conditions	Series	Survival ($\log(N/N_{0})$)	Dose (mJ/cm^2)	Dose Statistics (mJ/cm^2)	
2,101 L/min, 65%T (54% T Actual)					
(555 gpm)	FLS1	-2.50	46.6	STDEV:	4.00
		-2.58	48.4	MEAN:	49.13
		-2.62	49.3	75%C.I.:	1.24
	FLS4a	-2.50	46.6	C.I. Hi:	50.37
		-2.59	48.6	C.I. Low:	47.90
		-2.63	49.6		
	FLS4b	-2.46	45.7		
		-2.52	47.0		
		-2.50	46.6		
	FLS4c	-2.57	48.2		
		-2.54	47.5		
		-2.40	44.3		
	FLS6	-2.87	55.3		
		-2.85	54.8		
		-3.00	58.5		
3,941 L/min, 65%T (54%T Actual)					
(1,041 gpm)	FLS1	-1.82	31.9	STDEV:	1.97
		-1.86	32.7	MEAN:	31.41
		-1.93	34.2	75%C.I.:	0.69
	FLS4	-1.64	28.4	C.I. Hi:	32.10
		-1.85	32.5	C.I. Low:	30.73
		-1.87	32.9		
	FLS5	-1.89	33.3		
		-1.82	31.9		
		-1.74	30.3		
	FLS6	-1.75	30.5		
		-1.74	30.3		
		-1.61	27.8		

Conditions	Series	Survival ($\log(N/N_{0})$)	Dose (mJ/cm^2)	Dose Statistics (mJ/cm^2)	
7,355 L/min, 65%T (54%T Actual)					
(1,943 gpm)	FLS1	-1.33	22.6	STDEV:	1.27
		-1.33	22.6	MEAN:	22.19
		-1.28	21.7	75%C.I.:	0.39
	FLS4	-1.11	18.7	C.I. Hi:	22.58
		-1.29	21.9	C.I. Low:	21.79
		-1.29	21.9		
	FLS5	-1.29	21.9		
		-1.40	23.9		
		-1.30	22.0		
	FLS6a	-1.36	23.1		
		-1.30	22.0		
		-1.38	23.5		
	FLS6b	-1.24	21.0		
		-1.32	22.4		
		-1.40	23.9		
10,508 L/min, 65%T (54%T Actual)					
(2,776 gpm)	Day 1	-1.00	16.8	STDEV:	1.13
		-1.03	17.3	MEAN:	16.74
		-0.96	16.2	75%C.I.:	0.40
	Day 3	-1.09	18.4	C.I. Hi:	17.14
		-1.02	17.2	C.I. Low:	16.35
		-1.06	17.8		
	Day 5	-0.92	15.5		
		-0.96	16.2		
		-0.95	16.0		
		-0.85	14.4		
		-1.05	17.7		
		-1.04	17.5		

Conditions	Series	Survival ($\log(N/N_0)$)	Dose (mJ/cm^2)	Dose Statistics (mJ/cm^2)	
1,052 L/min, 55%T (41%T Actual)					
(278 gpm)	FLS2	-2.52	47.0	STDEV:	4.90
		-2.15	38.8	MEAN:	46.80
		-2.34	42.9	75%C.I.:	1.72
	FLS3	-2.59	48.6	C.I. Hi:	48.52
		-2.64	49.8	C.I. Low:	45.08
		-2.63	49.6		
	FLS7	-2.87	55.3		
		-2.77	52.9		
		-2.55	47.7		
	FLS8	-2.23	40.5		
		-2.43	45.0		
		-2.36	43.4		
2,101 L/min, 55%T (41%T Actual)					
(555 gpm)	FLS2	-1.54	26.5	STDEV:	2.81
		-1.57	27.0	MEAN:	30.78
		-1.47	25.1	75%C.I.:	0.87
	FLS3	-1.82	31.9	C.I. Hi:	31.66
		-1.85	32.5	C.I. Low:	29.91
		-1.82	31.9		
	FLS7a	-1.98	35.2		
		-1.72	29.9		
		-1.77	30.9		
	FLS7b	-1.79	31.3		
		-1.73	30.1		
		-1.72	29.9		
	FLS8	-1.81	31.7		
		-1.93	34.2		
		-1.89	33.3		

Conditions	Series	Survival ($\log(N/N_{0})$)	Dose (mJ/cm^2)	Dose Statistics (mJ/cm^2)	
3,941 L/min, 55%T (41%T Actual)					
(1,041 gpm)	FLS2	-1.05	17.7	STDEV:	2.04
		-0.99	16.7	MEAN:	19.59
		-1.08	18.2	75%C.I.:	0.62
	FLS3	-1.22	20.6	C.I. Hi:	20.21
		-1.14	19.2	C.I. Low:	18.96
		-1.20	20.3		
	FLS7	-1.13	19.0		
		-1.04	17.5		
		-1.03	17.3		
	FLS8	-1.32	22.4		
		-1.31	22.2		
		-1.30	22.0		
7,355 L/min, 55%T (41%T Actual)					
(1, 943 gpm)	FLS2	-0.92	15.5	STDEV:	1.42
		-0.73	12.5	MEAN:	14.59
		-0.69	11.9	75%C.I.:	0.44
	FLS3	-0.89	15.0	C.I. Hi:	15.03
		-0.86	14.5	C.I. Low:	14.15
		-0.82	13.9		
	FLS7	-1.01	17.0		
		-0.86	14.5		
		-0.79	13.4		
	FLS8a	-0.78	13.3		
		-0.89	15.0		
		-0.88	14.9		
	FLS8b	-0.94	15.8		
		-0.90	15.2		
		-0.98	16.5		

Conditions	Series	Survival ($\log(N/N_{0})$)	Dose (mJ/cm^2)	Dose Statistics (mJ/cm^2)	
10,508 L/min, 55%T (41%T Actual)					
(2,776 gpm)	Day 1	-0.97	16.3	STDEV:	2.29
		-0.69	11.9	MEAN:	13.11
		-0.67	11.5	75%C.I.:	0.80
	Day 2	-0.90	15.2	C.I. Hi:	13.92
		-0.67	11.5	C.I. Low:	12.31
		-0.54	9.6		
	Day 5	-0.89	15.0		
		-0.87	14.7		
		-0.92	15.5		
	Day 6	-0.56	9.9		
		-0.71	12.2		
		-0.83	14.1		

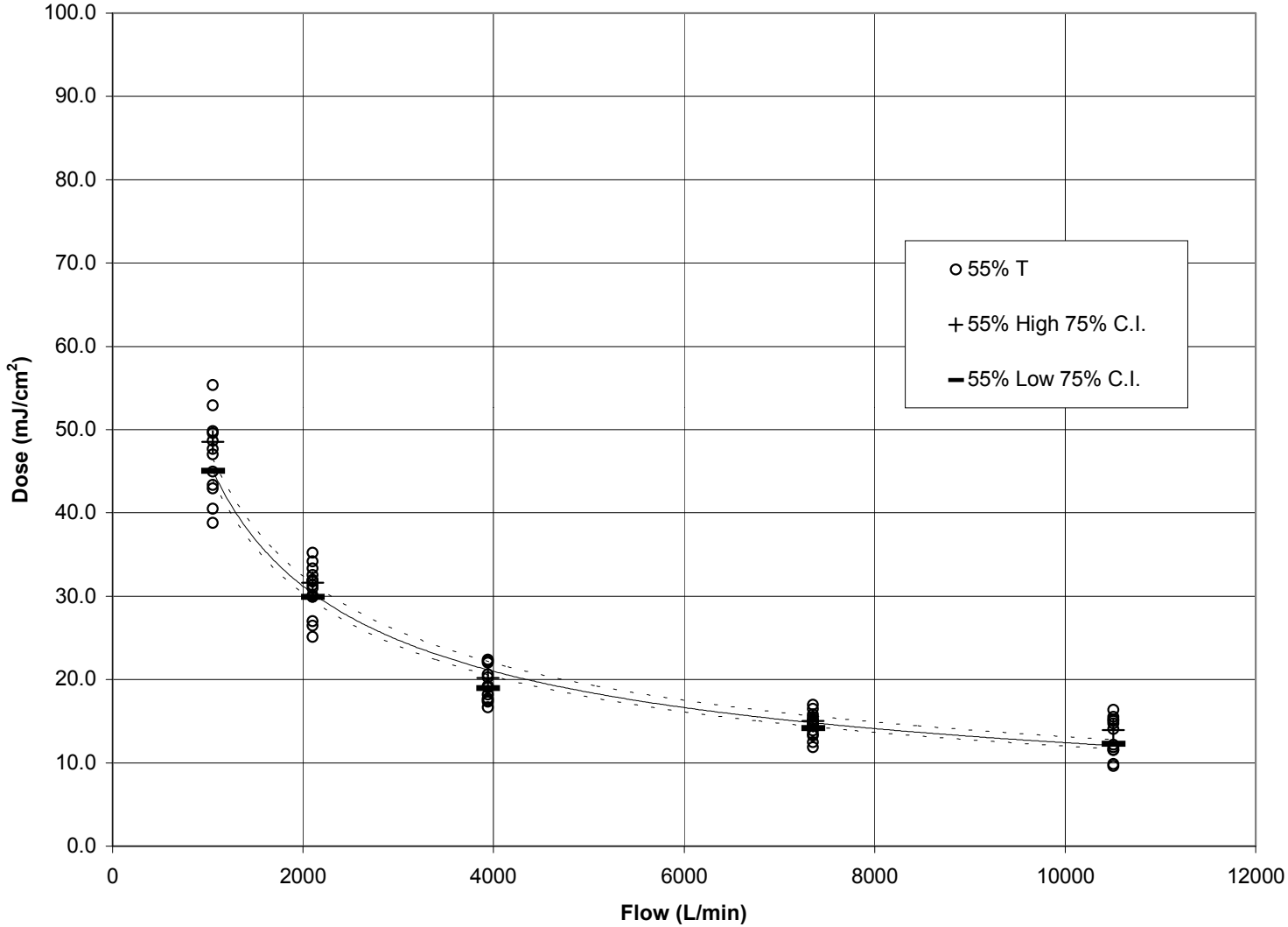

Figure 5-7. Dose Delivery as a function of flow rate for the 55%T nominal flows.

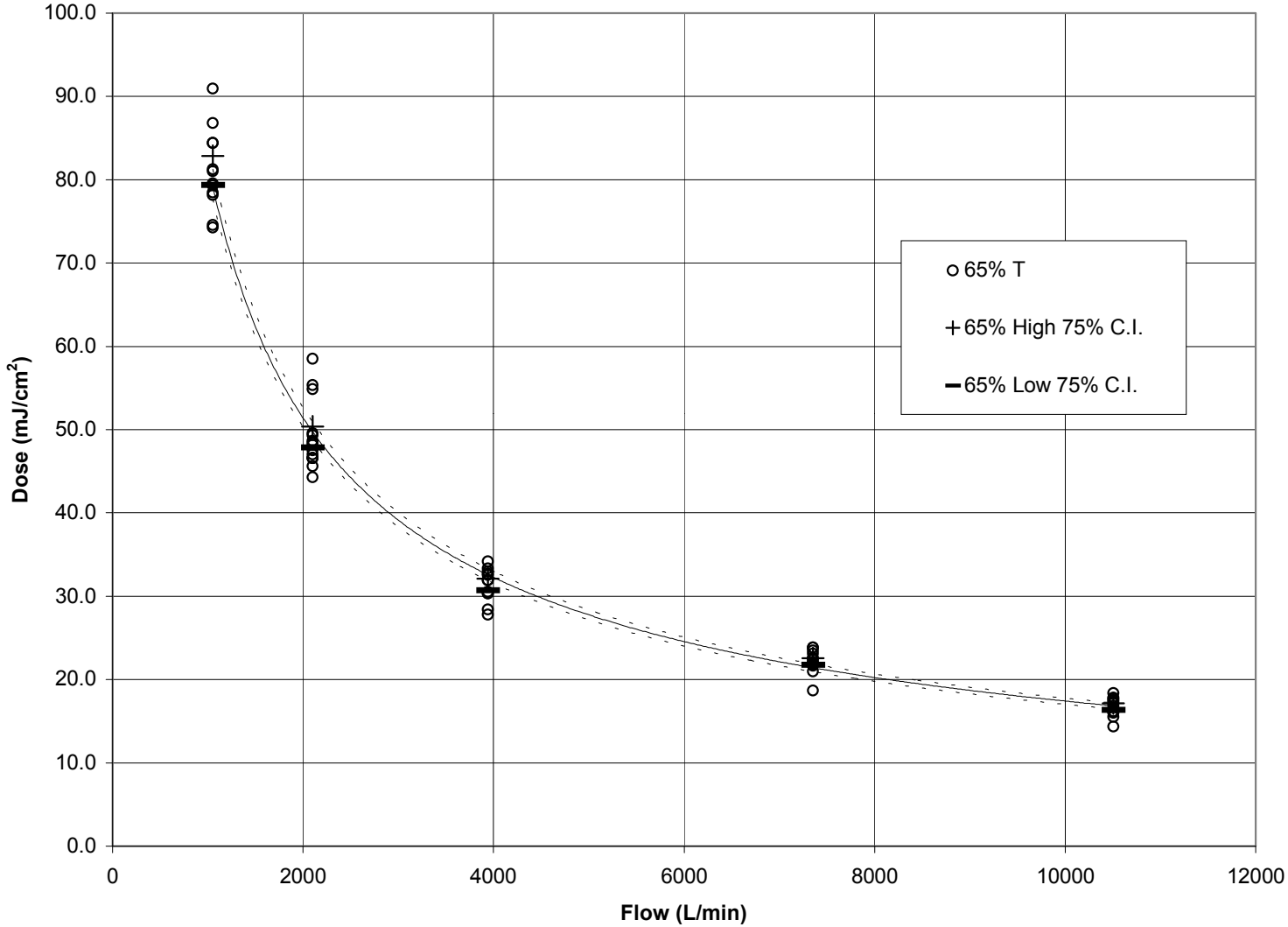

Figure 5-8. Dose Delivery as a function of flow rate for the 65%T nominal flows.

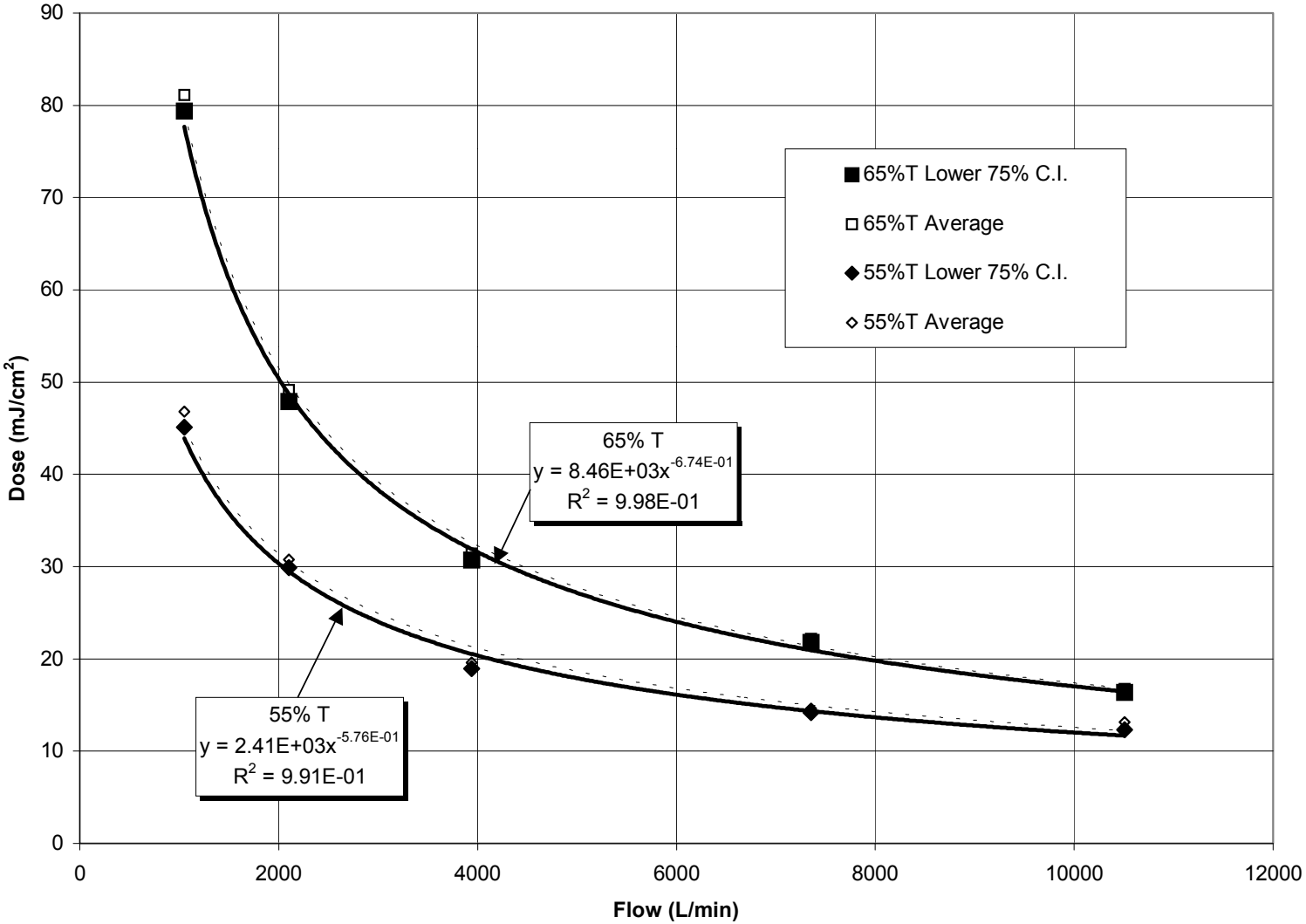

Figure 5-9. Dose Delivery as a function of flow rate for both 55%T and 65%T.

5.3.3 Flow Test Data Analysis

As described in the protocol (NSF, 2002), the final analysis of the flow test data is based on the lower 75% C.I. result for each flow condition (i.e., flow rate, %T). The results from the bersonInLine® System's tests (two reactors in series) are shown in Figure 5-9, where they are fitted with power functions. For comparison, the average dose delivery curve is also shown with a dotted line.

A UV disinfection system with ideal hydraulics should deliver a dose that is a function of 1/flow rate (Dose = k/(Flow Rate)), and the power function should have an exponent of -1. An actual, installed, UV disinfection system follows this relationship with an exponent that usually differs from -1 because of the complex fluid-dynamic behavior inside the reactors. The exponents for the power functions in Figure 5-9 are less than one and are consistent with the non-ideal behavior of the system. This non-ideal behavior is justification for conducting a bioassay test on an actual, installed system.

5.3.4 Extension of Verification Test Results to Commercial System Installations

This test resulted in the verification of a full-scale bersonInLine® System with two reactors in series (a train). Thus, the results of this verification test do not require any scale-up assumptions to be verified before these results are applied to an actual, commercially installed application. However, before these verification test results are extended to a commercially installed application, the following assumptions must be verified:

(1) The lamps, sleeves, and power supplies are identical to those of the bersonInLine® System used in this verification test.

(2) The number of lamps, lamp array geometry, and reactor housing design are identical to those of the bersonInLine® System used in this verification test.

(3) Two bersonInLine® System reactors are mounted flange-to-flange in series.

(4) The upstream reactor contains a flow modifier, as described in Section 3.2.1.

(5) The influent piping results in an influent flow-velocity field with all points within 0.9 to 1.1 of the velocities measured in this verification test.

Based on the validity of these assumptions, the results of this verification test can be extended to a commercially installed reactor train that is operated within the flow rates verified.

5.3.4.1 Dose Delivery per Two-Reactor Train

The results of this verification test are applied to the two-reactor train bersonInLine® System by using the lower 75% C.I. data, as specified in the protocol (NSF, 2002) and National Water Research Institute specifications (National Water Research Institute and American Waste Water Association Research Foundation, 2000). The relationships between dose and flow are from Figure 5-9:

For 65%T membrane filtered water:

$$D = 8460(Q_{train})^{-0.674} \tag{5-10}$$

For 55%T granular or fabric filtered water:

$$D = 2410(Q_{train})^{-0.576} \tag{5-11}$$

Where:

Q_{train} = Flow per two - unit bersonInLine 4250 train (L/min)

D = Dose delivery per train (mJ/cm^2)

5.3.4.2 Power Consumption

The power consumption of the reactor train is calculated, assuming that the lamps are at the EOL condition and the power level of the system has been turned up to the highest power level (P3). The calculation is then based on the results shown in Table 5-1, with the following expression for *Power* (kW):

$$Power = 45.14 \times N_T \tag{5-12}$$

Where:

N_T = Number of two - unit bersonInLine 4250 reactor trains

5.3.4.3 Low UV Dose Alarm Setting

The low UV dose alarm setting must be set to identify the conditions at which the lamp intensity or the transmittance decreases and causes a low-dose condition. To summarize, the signal to the ECtronic control unit's UV output display must fall to 61% to activate the low UV alarm. This condition should be present when the transmittance decreases to the nominal value (e.g., 65% for membrane filtered waters, 55% for granular or fabric filtered waters), and the lamp intensity decreases to 70% of its 100-hour burn-in intensity (see Section 5.1.2.3). The vendor specifies the setting of these alarm conditions.

5.4 Example of Application

The verification of the two-reactor train bersonInLine® System can be used to determine the design parameters of a commercial application. The assumptions presented in Section 5.3.4 must be verified. Each train must be operated within the flow rates verified in this test, which are 1,052 to 10,508 L/min (0.4 to 4.0 MGD).

5.4.1 Example Reuse Application for Two-Reactor Train bersonInLine® System

In this example, a two-reactor train bersonInLine® System will be used to disinfect a daily flow of 65%T water at 26,270 L/min (10.0 MGD) with a dose of 50 mJ/cm^2. The design parameters to be considered are summarized in Table 5-10.

Table 5-10. System Design Parameters

Peak Plant Flow Rate (MGD)	Q
Peak Flow Rate in Each Train	Q_{train}
Total Power Consumption	*Power*
Headloss	*HL*

(1) Flow per Train (Q_{train})

The flow per train is limited by the dose delivery per train. For a dose of 50 mJ/cm^2 and using equation 5-10, the maximum flow per train is 2,024 L/min:

$$D = 8460(Q_{train})^{-0.674}$$

$$50 mJ/cm^2 = 8460(2024\, L/\min)^{-0.674}$$

(2) Number of Trains (N_T)

The number of trains required is then calculated:

$$N_T = \frac{Q}{Q_{train}} \tag{5-13}$$

$$N_T = 13 = \frac{26270 L/\min}{2024 L/\min}$$

For this application, 13 trains of two-reactor bersonInLine® Systems would be required. The assumption that flow splitting is even must be verified.

(3) Power Consumption (*Power*)

The total EOL power requirement is then calculated using equation 5-12:

$$Power = 45.14 \times N_T$$

$$Power = 586.8kW = 45.14 \times 13$$

(4) Headloss

The headloss (cm) through each reactor train is then calculated, using the equation 5-6 from Section 5.1.3:

$$HL = 3.14 \times 10^{-8} (Q_{train})^2 + 1.18 \times 10^{-3} (Q_{train}) + 2.72$$

$$HL = 3.14 \times 10^{-8} (2024)^2 + 1.18 \times 10^{-3} (2024) + 2.72 = 5.24cm$$

Chapter 6
Quality Assurance/Quality Control

6.1 Calibrations

6.1.1 Flow Meter Calibration

The flow rate through the test system is a critical variable that controls the UV dose delivery. Therefore, before testing, the 8-inch magnetic flow meter was calibrated by measuring the drawdown in one of the tanks. The pump was set at the target flow rate, and, at constant intervals, the water level in the tank was measured with an electronic water level indicator with a resolution of 0.1 inches. During the calibration procedure, measured water levels were restricted to a range where the constant rectangular cross-section area of the tank could be used. This assumption was verified by examining the constancy of the drawdown for each time interval. Raw data is included in Appendix C.

This calibration procedure was repeated for flow rates from 1,052 L/min to 10,508 L/min (278 gpm to 2,776 gpm). Table 6-1 shows the results of the calibration procedure. Calibration of the flow meter by tank drawdown resulted in agreement between the reading on the magnetic flow meter and the flow rate calculated by drawdown. The average ratio of flow meter to drawdown flow rates was 98%, and no single flow deviated by more than 5%, verifying the accuracy of the flow meter.

Table 6-1. Flow Meter Calibration

Drawdown (L/min)	**Flowmeter** (L/min)	**Flowmeter** (gpm)	**Ratio Flow/Drawdown** (%)
1,071	1,052	278	98.2
3,933	3,941	1,041	100.2
7,684	7,335	1,943	95.5
10,675	10,508	2,776	98.4
		Average:	98.1

6.1.2 Radiometer Calibration

UV irradiances were measured during dose-response procedures using an International Light IL-1700 radiometer with two SED detectors that each had a quartz wide-eye diffuser and an NS254 filter. The first detector was calibrated on September 10, 2002, and on April 28, 2003, with a responsivity change of -8.4%. The second detector was calibrated on August 22, 2002, and on January 29, 2003, with a responsivity change of 0.53%.

6.2 Dose-response Data

All data for dose-response analyses are included in Appendix C and spreadsheets of the data, with calculations, are in Appendix D.

6.2.1 Quantitative QC Criteria

6.2.1.1 Field Intensity Mapping

The UV irradiance field, in which the dose-response samples were placed during UV dose deposition, was evaluated at the beginning and end of each dose-response series. For each mapping event, the intensity was measured with the UV detector in a radially symmetric pattern of 19 points. A total of 24 mapping events were completed during valid dose-responses.

The QC criteria requires that, for each intensity mapping event, 90% of the points shall be within 0.9 to 1.1 of the average intensity. In no case was an intensity measurement outside of the allowed deviation from the average. All intensity points have a ratio to the average between 0.90 and 1.06.

6.2.1.2 Initial and Final Control Similarity

Each dose-response series was bracketed at the beginning and the end with no-dose control samples. The geometric mean titer of these two samples is used as the N_0 value for the survival ratio calculations. In addition, the similarity of these two titers allows a quantitative evaluation of the plating procedure.

The titers are compared by calculating the similarity:

$$Similarity = \log\left(\frac{Inital\,Control(pfu/mL)}{Final\,Control(pfu/mL)}\right) \tag{6-1}$$

The similarities of the 13 valid dose-response series completed during this verification are shown in Figure 6-1. The similarities among the control titers are less than or equal to 0.15, which is well below the 0.32 acceptable value.

6.2.2 Excluded Data

Three dose-response series and five individual data points are excluded from the valid data for various QA/QC reasons. Table 6-2 lists the excluded data and the justification for their exclusion. All raw data are included in Appendix C.

Table 6-2. Excluded Dose-Response Data

Series	Doses	Justification
DR2	30	Counts < 30 pfu
DRV1	80, 100	Counts < 30 pfu
DRV2	All	Counts < 30 pfu
DRV3	All	Counts < 30 pfu
DRV4	100	Counts < 30 pfu
DRS5	All	Counts < 30 pfu
DRS6	100	Counts < 30 pfu

6.2.3 Compliance with QC Boundaries

The QC criteria for the acceptance of the dose-response data is described in the protocol (NSF, 2002), which defines linear boundaries for the data and requires greater than 80% of the data to fall between the lines. These QC criteria are based on the statistical analysis of MS2 dose-response data from several independent labs.

Figure 6-2 shows the linear QC boundaries and the valid dose-response data for this verification. Of the 28 data points from the seven valid dose-response tests, only one point lies outside specified QC boundary lines. Therefore, 96.4% of the data points lie within the accepted range, and the dose-response data generated for this test is accepted as valid for the MS2 bacteriophage.

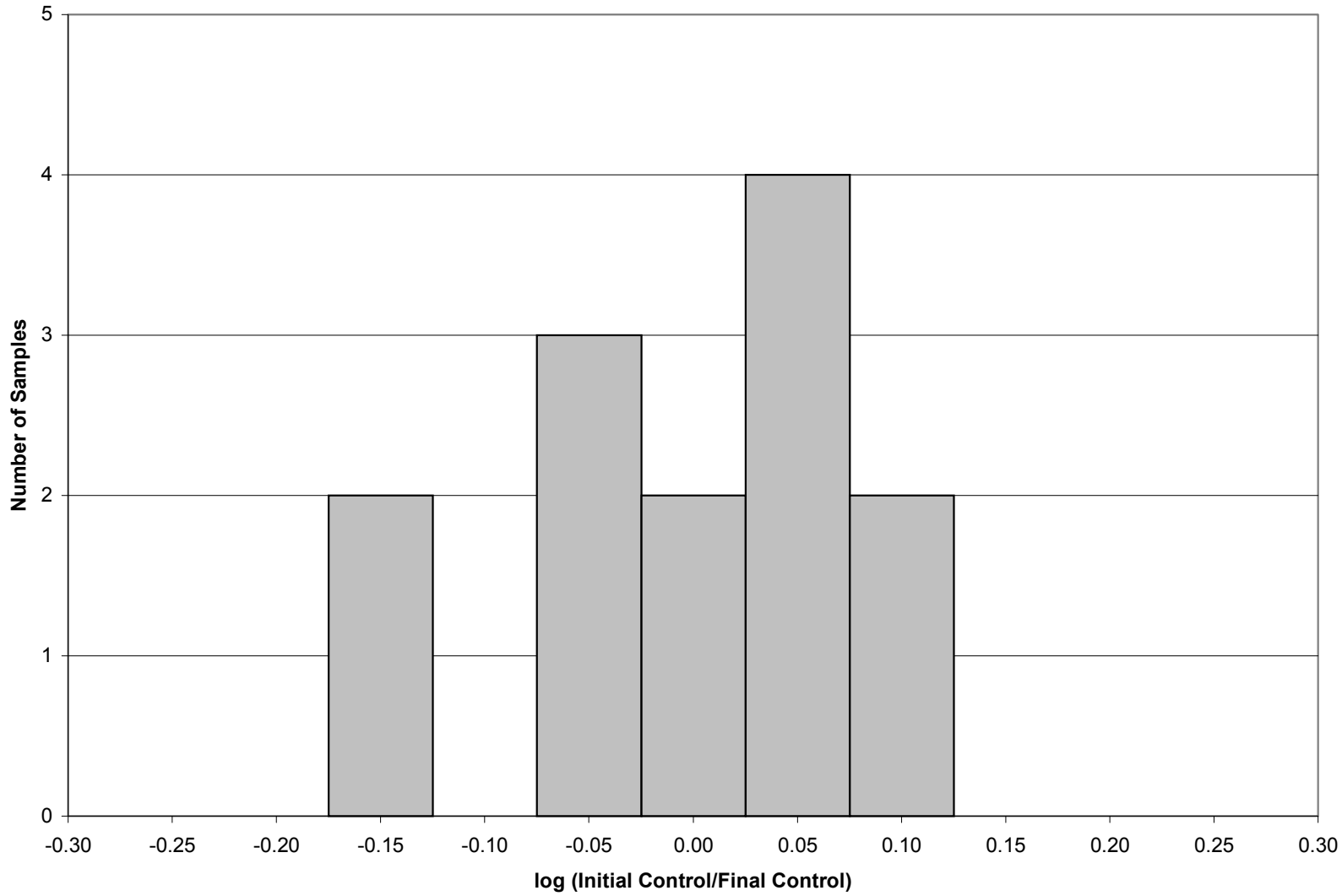

Figure 6-1. Similarity between initial and final dose-response controls.

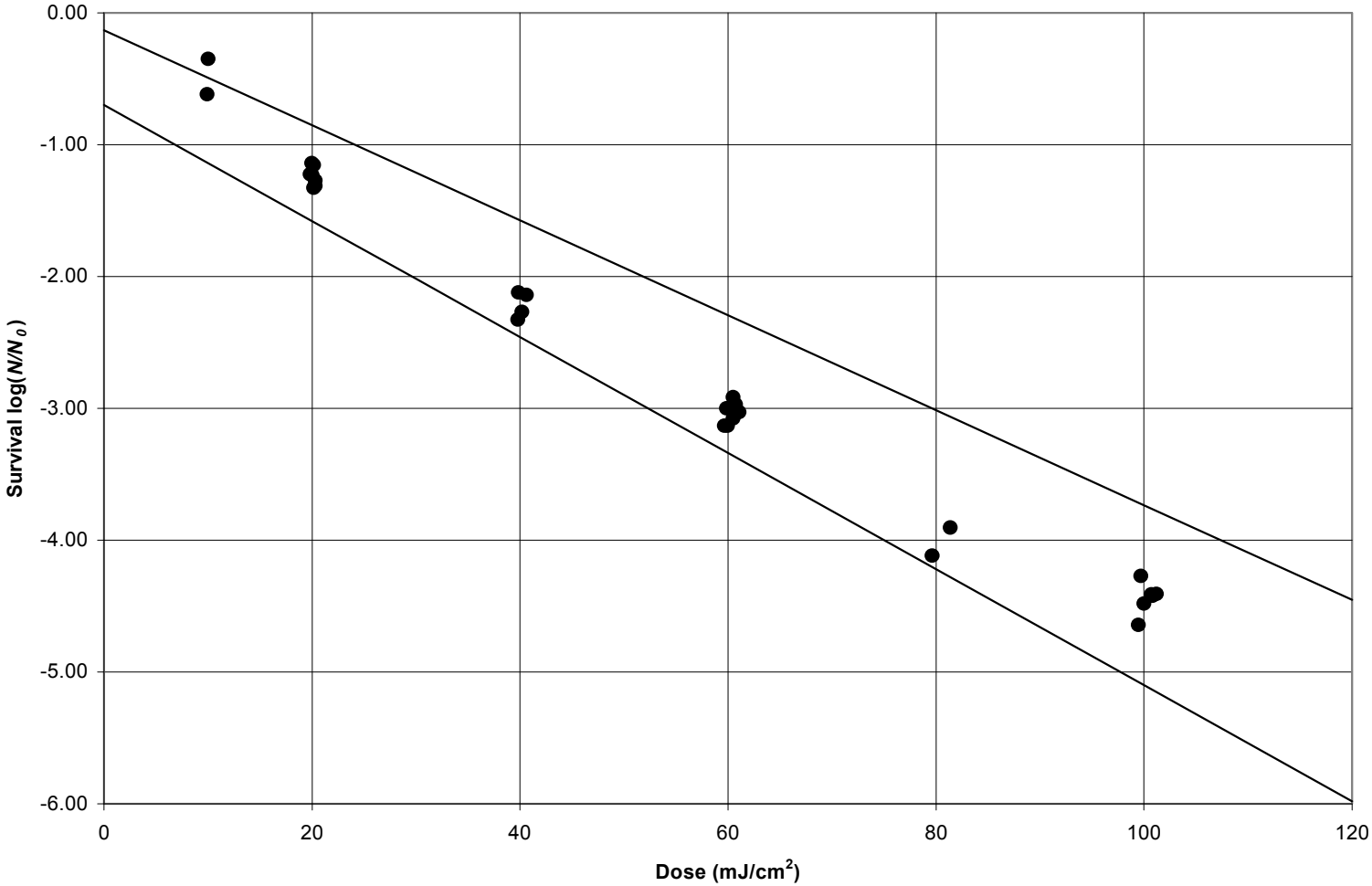

Figure 6-2. Dose-Response data and QA/QC boundary lines.

6.2.4 Collimator Verification and MS2 Sensitivity

Additional dose-response runs were conducted to verify the depth and intensity correction in the sample-dosing dish and to determine the sensitivity of the MS2 bacteriophage to the challenge water and modifiers. Six dose-responses were conducted in solutions prepared in the laboratory: two dose-response series were conducted in 8.5% saline solution and four were conducted in potable water from the test site with modifying agents added. The data for these QA/QC dose-response runs are summarized in Table 6-3.

Table 6-3. Dose-Response Data for QA/QC Runs

	Nominal Dose(1):		**10**	**20**	**40**	**60**	**80**	**100**
	%T (%/cm)	**Matrix**	**Dose, Survival**	**Dose, Survival**	**Dose, Survival**	**Dose, Survival**	**Dose, Survival**	**Dose, Survival**
DR1	99	(2)	--	20.0 / -1.22	40.1 / -2.29	60.1 / -3.17	80.3 / -4.12	100.2 / -4.71
DR2	99	(2)	9.9 / -0.72	--	--	59.7 / -3.19	79. / -4.45	99.6 / -4.88
DRV1	99	(3)	10.1 / -0.76	20.2 / -0.93	40.4 / -2.39	--	--	--
DRV4	99	(3)	9.9 / -0.61	20.0 / -1.18	39.9 / -2.19	--	79.6 / -4.00	--
DRV5	41.4	(3)	10.3 / -0.87	20.4 / -3.11	--	61.3 / -3.11	81.8 / -3.85	102.1 / -5.27
DRV6	53.6	(3)	10.3 / -0.93	20.4 / -1.47	--	61.3 / -3.52	81.7 / -4.40	102.0 / -4.87

(1) Dose in mJ/cm^2; Survival is log (N/N_o)
(2) 8.5% Saline solution; (3)
(3) Potable water + Sodium Thiosulfate + Coffee.

This analysis results in three data sets for comparison: (1) seven valid, seeded challenge water dose-responses; (2) two 8.5% saline solution dose-responses, and (3) four verification dose-responses. The data sets are presented graphically in Figure 6-3, with polynomial fits to allow dose estimates at any survival ratios in the valid range.

Table 6-4 shows the doses from the polynomial fits in Figure 6-3 for a range of survival ratios from -1.0 to -4.5. In addition, the seeded challenge and verification runs are compared to the 8.5% saline solution for percent difference. The VTP requires that each data set should result in a calculated dose within 10% of the unadjusted waters (8.5% saline) for a given survival ratio. With the exception of the results at -4.0 and -4.5, the calculated doses are within 10%. Because the delivered doses measured during the flow test series are at -4 and below, the MS2 calibration curve used for dose delivery estimates is deemed valid.

Table 6-4. Dose-Response Verification Calculations

Survival	Calculated Doses			Comparison to Saline	
	Saline	Seeded Challenge	Verification	Seeded Challenge	Verification
($\log(N/N_0)$)	(mJ/cm^2)	(mJ/cm^2)	(mJ/cm^2)	(% diff)	(% diff)
-1.0	15.5	16.8	15.4	8.7	-0.8
-1.5	24.7	25.7	25.3	4.3	2.5
-2.0	34.3	35.6	35.4	3.9	3.2
-2.5	44.4	46.6	45.7	4.9	2.9
-3.0	55.0	58.5	56.1	6.5	2.2
-3.5	66.0	71.6	66.8	8.5	1.2
-4.0	77.5	85.6	77.6	10.5	0.2
-4.5	89.4	100.7	88.6	12.6	-0.9

6.2.5 Intensity Checks

Intensity checks were performed at the beginning, middle, and end of all dose-response series. The center position was chosen as the reference point for the intensity checks. In all seven valid dose-responses, all three measurements were taken. In all seven of the valid dose-responses, none of the intensity checks exceeded the ± 5% of the average intensity. The intensity checks ranged between -1.302% and 0.754% of the average intensity.

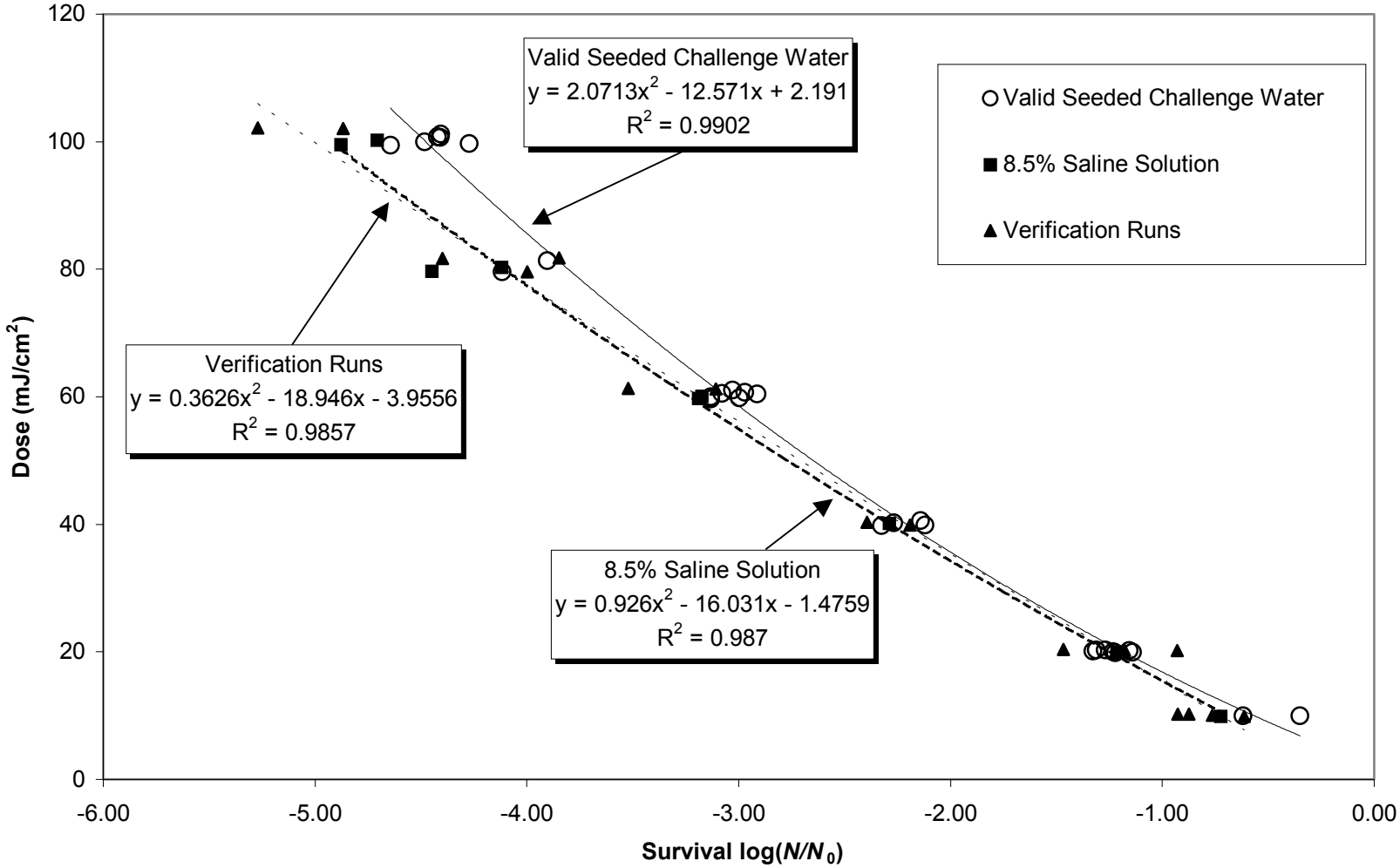

Figure 6-3. Dose-Response validation data.

6.3 Flow Test Data

All raw flow test data are included in Appendix C. Appendix D presents the spreadsheet summaries and the calculations.

6.3.1 Quantitative QC Criteria

6.3.1.1 Flow Test Sample Replicates

The VTP included a schedule of samples that were analyzed for each flow test series, including samples that were plated in replicate for MS2 bacteriophage enumeration. Generally, two samples were plated in replicate each test day for a total of 16 replicate platings. The similarity of these titers allows a quantitative evaluation of the plating procedure.

The titers are compared by calculating the similarity:

$$Similarity = \log\left(\frac{Sample\,Titer\,1\left(pfu/mL\right)}{Sample\,Titer\,2\left(pfu/mL\right)}\right) \tag{6-2}$$

Figure 6-4 shows a distribution of the replicate similarity data. For the 16 samples plated in replicate during this verification test, all were within the acceptable limit of 0.46 log units (a factor of three), with the greatest difference in similarity at 0.31 log units.

6.3.1.2 Duplicate Flows

During each of six flow series, a flow test was duplicated (i.e., a test at the same flow rate) to determine the repeatability of the flow settings during the test. The average survival data and similarity for each of these duplicate flows are shown in Table 6-5.

Table 6-5. Results From Flow Test Duplicates

Day	Flow	Survival Flow A	Survival Flow B	Similarity
Day 3	1,052	-4.06	-3.64	-0.42
Day 3	2,101	-2.57	-2.50	-0.07
Day 3	2,101	2.57	-2.50	-0.07
Day 5	7,355	-1.81	-1.74	-0.07
Day 5	10,508	-1.34	-1.32	-0.02
Day 6	2,101	-0.94	-0.97	-0.03
Day 6	7,355	-0.85	-0.92	-0.08

The maximum similarity is 0.42 log units, which is within the acceptable range of sample replication of 0.5 log units. It demonstrates the repeatability of the flow conditions.

6.3.1.3 Transmittance Replicates

During the verification test, each influent sample was analyzed for %T at 254 nm at the laboratory. In 20 cases, a sample was analyzed in replicate to determine the repeatability of the transmittance measurement. The samples were compared, using the relative percent difference (RPD):

$$RPD = \frac{Analysis\,1 - Analysis\,2}{Average(Analyses)} \times 100\% \tag{6-3}$$

Where:
Average (Analyses) = (Analysis 1 + Analysis 2) /2

All replicate measurements were within the 0.5% allowed by the test plan.

6.3.2 No-Dose Flow

For control purposes, four flow tests were conducted with the lamps turned off at the end of a daily flow series. These no-dose controls were conducted at 1,052 L/min and 10,508 L/min and at both transmittances (see Table 6-6).

These no-dose flows were conducted to determine if there was any "memory" effect from dosed coliphage collecting on the reactor. The survival ratios were in the range of -0.08 to 0.06, resulting in calculated doses as high as 3.2 mJ/cm^2. These results show that the influent and

effluent samples were indistinguishable from no-dose flows, demonstrating that the reactor and flow test methodology introduced no systematic error into the data.

Table 6-6. Results from No-Dose Flows

Series	Flow (L/min)	%T (%T/cm)	Survival log (N/N_0)	Dose (mJ/cm^2)
FLS6	10,508	54	-0.08	3.2
FLS6	1,052	54	0.04	1.7
FLS7	10,508	41	0.04	1.7
FLS7	1,052	41	0.06	1.4

6.3.3 Excluded Data

All flow test data for this verification test was found to be valid.

6.3.4 Power Monitoring

Appendix C contains printouts from the data loggers, which were reviewed after each flow test series. The outputs were examined for consistency of power consumption, detector readings, and flow meter readings. This was an important step of validation to identify any anomalous conditions that may have been present during the flow tests.

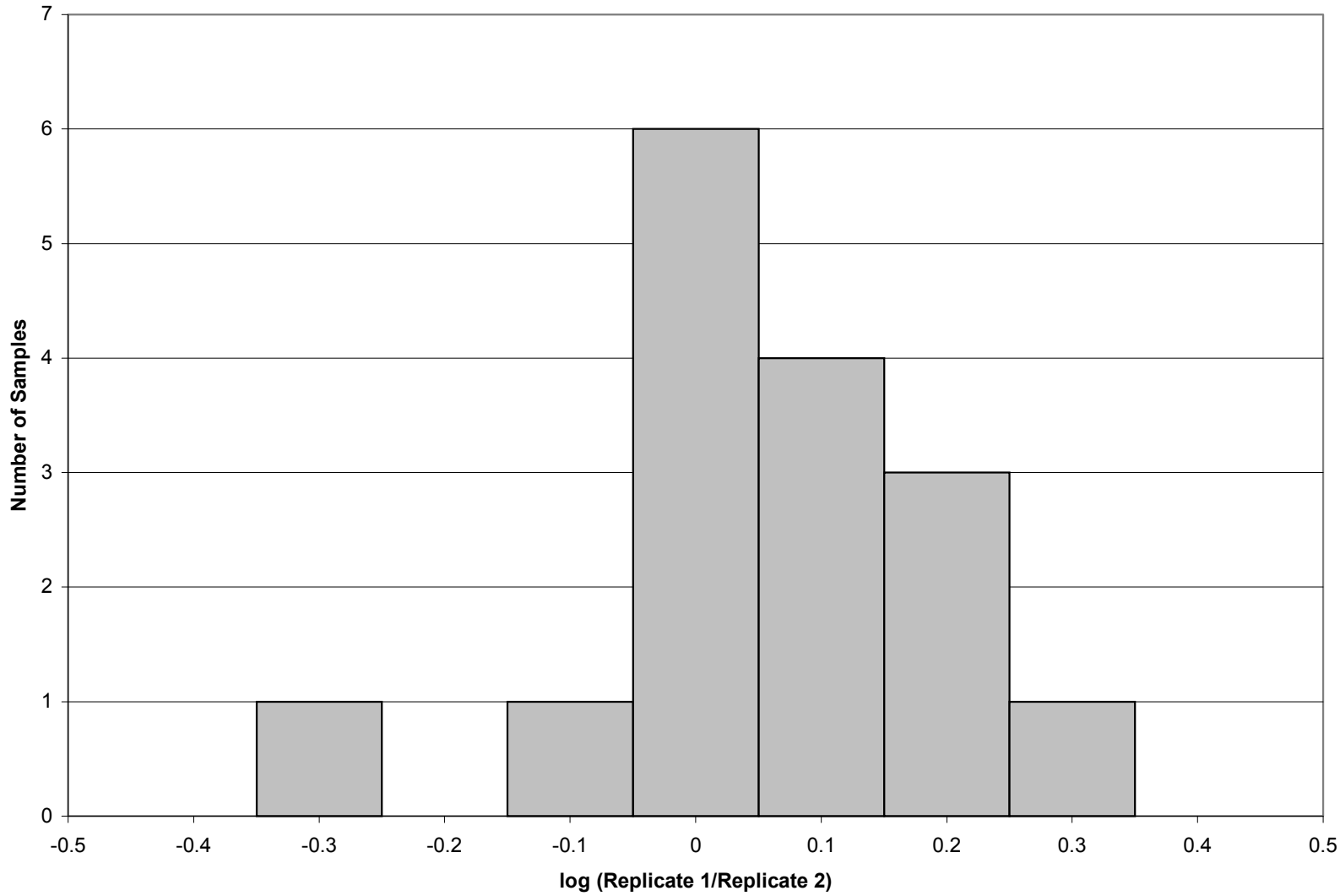

Figure 6-4. Similarity among replicate flow test samples.

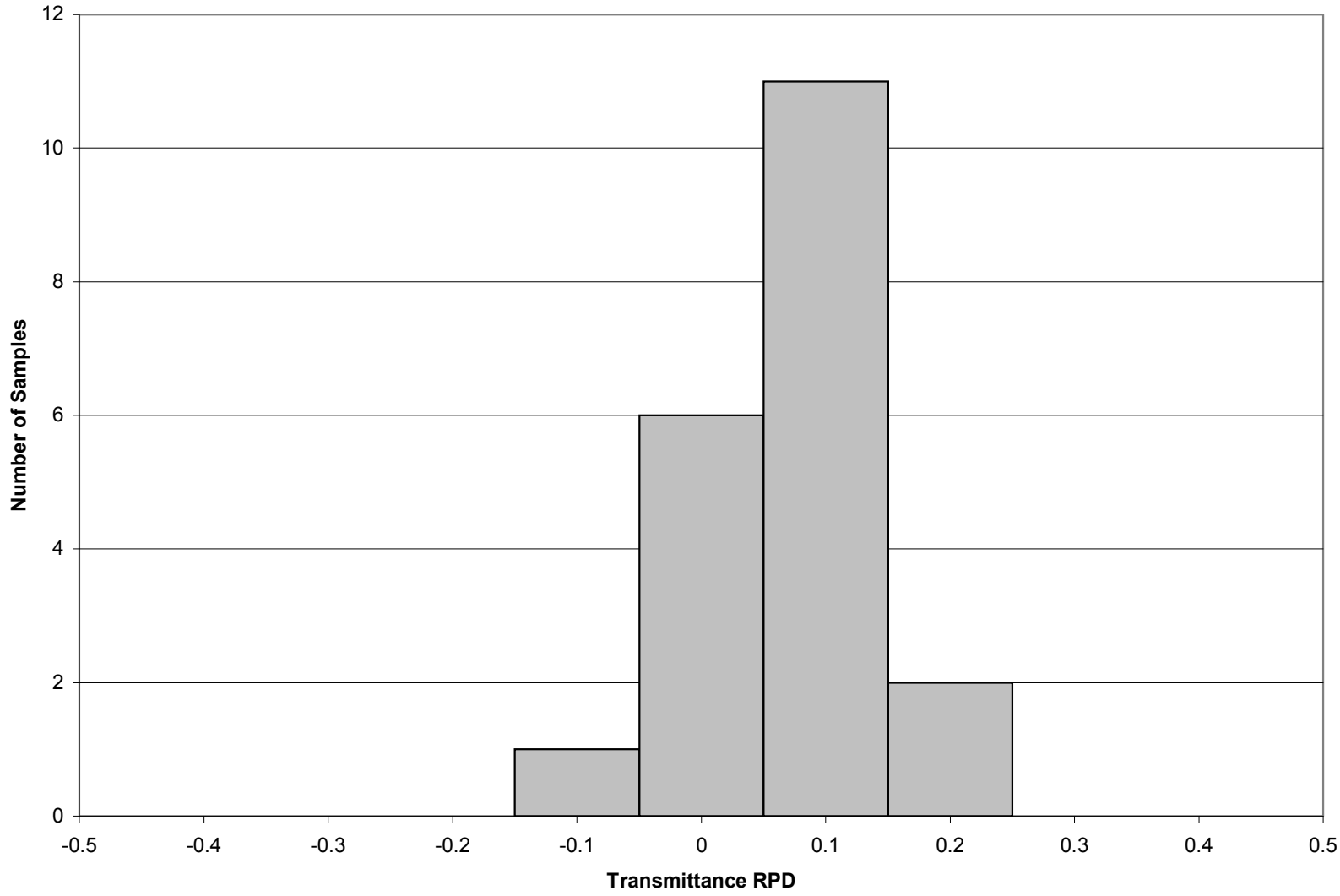

Figure 6-5. Relative percent difference for %T replicates.

Appendices

A Verification Test Plan for the Aquionics, Inc. UV Disinfection System for Reuse Applications, Prepared by HydroQual, Inc. for NSF, December 2002.

B bersonInLine® UV-System User's Manual. February 2002.

C Master Data Volumes 1 and 2: Aquionics bersonInLine® UV System ETV Reuse Testing Program.

D Excel Spreadsheets and Supporting Calculations

NOTE: Appendices are not included in this report. Appendices are available from NSF International upon request.

Glossary

Accuracy - A measure of the closeness of an individual measurement or the average of a number of measurements to the true value. It includes random error and systematic error.

Bacteriophage – A virus that has a bacterium as its host organism.

Dose – Also Fluence. The total amount of germicidal energy imposed on a solution to be disinfected. Units are usually mJ/cm^2 (millijoules per square centimeter).

Effective disinfection zone - The zone in a disinfection lamp assembly where the UV intensity deposits a disinfecting dose into the solution. This zone is exclusive of mounting hardware on the end of the lamp sleeves and the submerged ballasts.

End-of-life (EOL) - This is the UV output condition (i.e., intensity) that is present after the manufacturer's recommended maximum life span for the lamps and the maximum fouling on the quartz sleeves.

Environmental Technology Verification (ETV) - A program initiated by the EPA to use objective, third-party tests to quantitatively verify the function or claims of environmental technology.

Monochromatic – A light output spectrum that consists solely or dominantly of a single, specific wavelength of light.

Plaque forming unit (pfu) - A single unit that is assumed to represent one, viable, MS2 bacteriophage organism.

Polychromatic – A light output spectrum containing many specific wavelengths of light or a continuous spectrum in a range of wavelengths.

Precision - A measure of the agreement between replicate measurements of the same property made under similar conditions.

Representativeness - A measure of the degree to which data accurately and precisely represent a characteristic of a population parameter at a sampling point or for a process condition or environmental condition.

Survival Ratio - The $\log_{10}$ of the ratio of bacteriophage concentration in a UV-dosed solution to a no-dose solution. The values are typically negative numbers because the UV dosing reduces the number of the viable bacteriophage present in the solution.

Test Element – A series of tests designed by the ETV program to validate a group of related operational characteristics for a specific technology.

Testing Organization (TO) - An organization qualified to conduct studies and testing of induction mixers in accordance with the protocol.

Titer – The specific number of viable organisms (e.g., bacteria or bacteriophage) in a given volume of solution.

UV Demand - UV energy that does not contribute to disinfection because of absorption by the chemicals in water.

UV or Ultraviolet Radiation - Light energy with a shorter wavelength than that of visible light in the range of 190 nm to 400 nm.

Vendor - A business that assembles or sells UV disinfection technology.

Verification - Establishing the evidence on the range of performance of equipment and/or devices under specific conditions following an established protocol(s) and test plan(s).

Verification Protocol - A generic, written document that clearly states the objectives, goals, and scope of the testing under the ETV Program. It establishes the minimum requirements for verification testing and for developing a verification test plan. A protocol is used for reference during the manufacturer's participation in the verification testing program.

Verification Statement - A written document that summarizes the final report that has been reviewed and approved by NSF on behalf of the EPA or directly by the EPA.

Verification Test Plan (VTP) - A written document that establishes the detailed test procedures for verifying the performance of a specific technology. It also defines the roles of the specific parties involved in the testing and contains instructions for sample and data collection, sample handling and preservation, and quality assurance and quality control requirements relevant to a given test site.

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National Water Research Institute and American Waste Water Association Research Foundation (2000). "Ultraviolet Disinfection Guidelines for Drinking Water and Water Reuse. Fountain Valley, California.

NSF International (2002). "Verification Protocol for Secondary Effluent and Water Reuse Disinfection Applications." Prepared for NSF International and the U.S. Environmental Protection Agency under the Environmental Technology Verification Program. Ann Arbor, Michigan.

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