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Environmental Technology Verification Report

UV Disinfection for Reuse Applications

Ondeo Degremont, Inc. Aquaray® 40 HO VLS Disinfection System

Prepared by

NSF International

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

ETV ETV ETV

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:	**AQUARAY® 40 HO VLS DISINFECTION 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 Ondeo Degremont, Inc. (ODI) Aquaray® 40 HO VLS Disinfection System for disinfection of granular or fabric filtered secondary wastewater effluent and for membrane filtered secondary wastewater effluent, for water reuse applications. 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 substantially accelerating the acceptance and use of improved and more 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 Aquaray® 40 HO VLS system uses high-output, low-pressure, mercury discharge lamps, oriented vertically and perpendicular to the direction of flow. Each lamp has an ultraviolet (UV) output rating of approximately 52 watts (W) at 254 nm and a total power draw of 165 W. The lamps have an effective arc length of 146.7 cm. Each lamp is housed in a clear, fused quartz sleeve to isolate and protect the lamp from the wastewater. The sleeves have one open end, which is exposed only to the conditions in the sealed stainless steel ballast housing. The quartz sleeves are 170.2 cm long, have an outer diameter of 24.4 mm, and a wall thickness of 1.26 mm, resulting in a UV transmittance (UVT) of approximately 90%.

The test system consisted of three Aquaray® 10 HO VLS modules in series, with 10 lamps per module, mounted inside a baffled, rectangular frame. The lamps were positioned in a staggered rectangular array with centerline spacing of 7.14 x 12.7 cm to duplicate one-fourth of the Aquaray® 40 HO VLS full-size unit, which holds 40 lamps. Each electronic ballast, mounted vertically on top of the modules, powered two lamps in parallel. The ballasts were rated for 165 W of electrical power per lamp so that one lamp failure would not cause the peer lamp to turn off. A separate circuit powered each lamp module so the failure of one lamp module would not deactivate the other modules. The ballast control panel did not allow for lamp power dimming, as it is part of the ballast specification to keep the lamp power steady during fluctuation of supply line voltage. The control cabinet was powered by a 480-volt (V) delta power supply and had separate circuits for each lamp module, a dedicated power supply for the sensor amplifiers, and three digital displays showing the real time voltage output. The UV sensors used in the test system were identical to those supplied in commercial systems.

The test modules were not equipped with a sleeve cleaning system, or the ODI patented air scrub used with commercial systems, because a validation test was not planned for this cleaning system. The wiper drive rod was present on each test module to simulate related headloss and hydraulic behavior.

The reactors were housed in a 7.9 m long, open, stainless steel channel. The untreated water entered the channel through a 30.5 cm wide by 2.13 m high section. A baffle, located 0.46 m from the water inlet pipe, spread the flow over the submerged cross-section of the channel. At 0.92 m from the front of the channel, the width was reduced from 30.5 cm to 17.78 cm, and the height of the channel decreased from 2.13 m to 1.83 m. The first test module was located 1.06 m downstream of the channel narrowing. The space between each test module was 0.60 m, the same space as in full-scale commercial systems. At a distance of 1.06 m from the final lamp unit, the channel width increased to 30.5 cm; the height remained at 1.83 m. The flow in the influent channel had additional flow stabilization from a mixer with a 3-bladed impeller that operated at 350 rpm.

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 a 71 horsepower centrifugal pump to provide challenge water at flow rates up to 7,600 L/min. Challenge water was recirculated at flow rates of 1,100 L/min to mix the tanks. Influent flow was metered with a magnetic flow meter, which was calibrated using 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 Aquaray® 10 HO VLS system was tested under Element 1 of the protocol, Dose Delivery Verification for Reuse Applications, 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 test unit was measured at two positions in the power distribution system. The single-phase 240 V power supply to each lamp module was measured for two hours during the lamp stability test. The total power consumption of the system was measured during the burn-in, shakedowns, and all flow tests.

Headloss measurements for five flow rates were determined by monitoring the channel depth at five locations, spaced before and after the three modules. The hydraulic characterization of the Aquaray® 10 HO VLS module included the measurement of flow-velocity fields at four positions along the channel length. Each flow field consisted of a 2 by 13 matrix of monitoring positions. The flow field was measured in triplicate for the five flow rates, providing 1,560 velocity measurements.

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 modules were placed back in the channel, water was allowed to flow, 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 either potable water (65 percent transmittance (%T) tests) or filtered secondary effluent (55%T tests), 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 (568, 1,325, 1,703, 2,082, and 2,839 L/min) were replicated at least four times for each transmittance. The system was tested using a three-module configuration for the 55%T and 65%T tests. The 55%T test was repeated using a two-module configuration (by turning off the third module).

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, and appropriate equipment/instrumentation calibration procedures. Details on all field procedures, analytical methods, and QA/QC procedures are provided in the verification report.

Verification Performance

Power Consumption and Headloss Results

The power consumption of the Aquaray® 10 HO VLS module was measured at the 480 V, three-phase power supply (total service power) and at the individual module 240 V, single-phase power supplies. Total power consumption for the three-module system, which included power use by the auxiliary circuitry in the control panels and the slight loss of power through the step-down transformer, was 5,260 W. The discrete power measurements taken at the 240 V, lamp-module power supply showed a power consumption of 166 W per lamp, which was very close to the 165 W per lamp specified by ODI.

Headloss through 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 rate (L/min) for the three-module Aquaray® 10 HO VLS module used in this test is approximated by the relation:

$$headloss\ (cm) = 5.69E\text{-}08\ (flow\text{-}L/min)^2 - 3.87E\text{-}04\ (flow\text{-}L/min) + 6.02E\text{-}01$$

The headlosses are measured for the flow rates used in this verification, and are dependent on the channel configuration and the number of reactor modules. The basis and assumptions for direct extrapolation of headloss through the test modules to a full-scale Aquaray® 40 HO VLS system is provided in the verification report.

The protocol required the influent flow velocities to be between 0.8 and 1.2 of the theoretical value. The data show that the influent velocity profile at all flow rates had a significantly non-uniform character, while the three downstream positions had velocity profiles that were quite uniform and well within ±20% of the theoretical flow rates. The average velocity at the influent position was consistently low, due to the inlet geometry of the test system, which introduced a large-scale rolling motion in the influent to the channel. This caused low (or negative) velocities at the bottom and higher velocities at the top. The Aquaray® 10 HO VLS test system design did not attempt to idealize the influent hydraulic characteristics of the system used for this verification. Based on the dose delivery data, the non-uniform influent velocity did not degrade the performance of the Aquaray® 10 HO VLS system.

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:

$$Dose = 1.4822(survival)^2 - 15.063(survival) - 0.1633$$

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

$N_0 =$ MS2 concentration in undosed sample

$N =$ 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 Aquaray® 10 HO VLS, 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 and the three-module test systems 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.

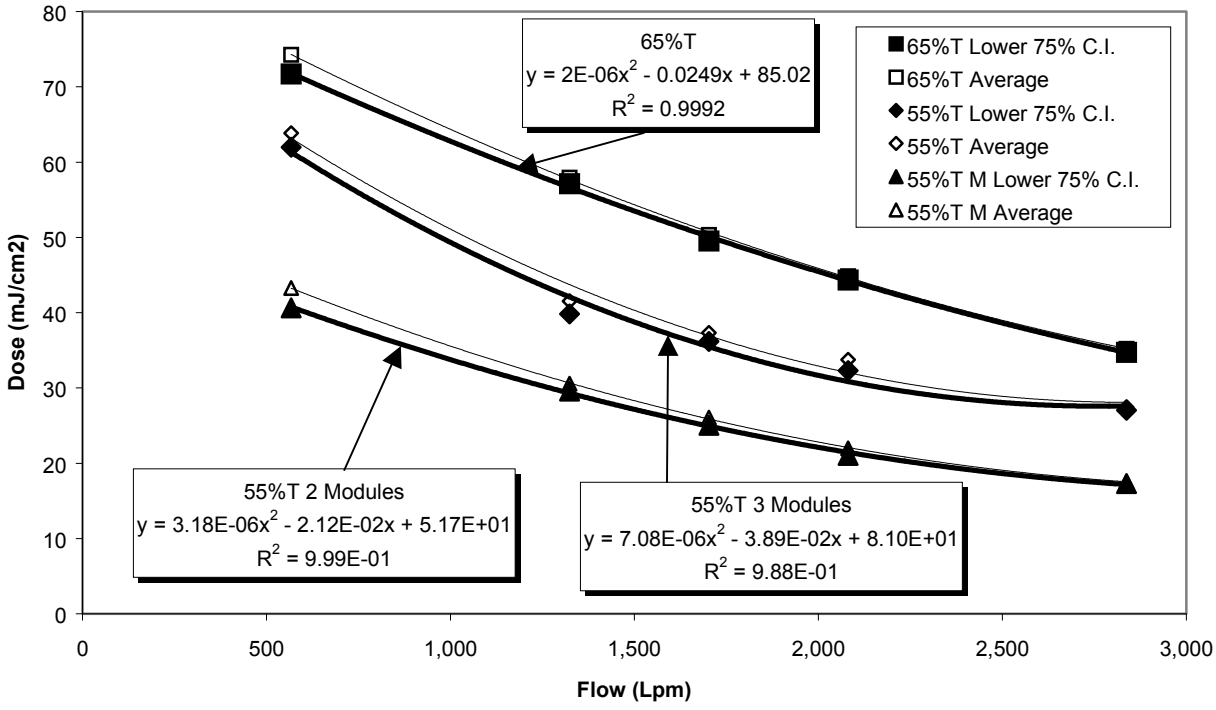

Figure 1. Dose Delivery Curves Based on Lower 75% C.I. For Granular and Fabric Filtered Effluent (55%T) and For Membrane Filtered Effluent (65%T)

Scalability

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

were obtained during the verification testing. The ODI verification test was specifically designed to show that the use of multiple reactor modules produces additive results. The results of the dose-response testing can be used to estimate the dose delivery for different sized systems, using multiple, 40-lamp modules. The verification report provides a detailed discussion on application of the data for larger systems.

Quality Assurance/Quality Control

NSF performed QA/QC audits of the test site at PTRH and HydroQual 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 employed 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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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 Reuse Applications

Ondeo Degremont, Inc. Aquaray® 40 HO VLS Disinfection System

Prepared for

NSF International
Ann Arbor, MI 48105

Prepared by

HydroQual, Inc.

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
ANSI	American National Standards Institute
C	Celsius
CFD	Computational Fluid Dynamics
C.I.	Confidence interval
cm	Centimeter (10^{-2} meters)
DC	Direct current
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.
I	Intensity
in	Inch
ISO	International Standards Organization
kg	Kilogram
kW	Kilowatt
L	Liter
L/min	Liters per minute
log	Base 10 logarithm
m	Meters
mA	Milliamperage
μm	Micron (10^{-6} meters)
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^{-3} meters)
mW/cm^2	Milliwatts 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
ODI	Ondeo Degremont, Inc.
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
PF	Performance Factor
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
rpm	Revolutions per minute
SAG	Stakeholders Advisory Group
Sec	Seconds
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. 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* (NSF, 2000). The Stakeholder Advisory Group (SAG) consists of various academic, commercial, and consulting professionals with experience in disinfection technology. This verification protocol provided the framework for the development, approval, and implementation of the *Verification Test Plan for the Ondeo Degremont, Inc. UV Aquaray® 40 HO VLS Disinfection System for Reuse Applications* (see Appendix A) under which the present ETV was conducted.

1.1.2 The ETV Program for Water Reuse and Secondary Effluent Disinfection

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

Test Element 1: Dose Delivery Verification. This is a series of bioassays with MS2 bacteriophage to test the dose delivery of the disinfection unit 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 is a series of tests to verify the long-term reliability of the unit's configuration.

- Quartz Surface Maintenance test:

  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 test:

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

- Process Control test:

  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 changes in performance as the system ages through regular use.

- Quartz-Fouling Factor Determination test:

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

- Lamp-Age Factor test:

  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 that apply to its technology. Since there is no requirement that the vendor test against all elements of the protocol, the vendor may select from the test elements described above, based on appropriate application to their technology. Further, the verifications in Test Elements 2 and 3, which are oriented to operation and maintenance issues, are not mandatory.

1.1.3 The Ondeo Degremont, Inc. (ODI) Verification Test

This verification test of the ODI Aquaray® 40 HO VLS UV disinfection system focused on the dose delivery, which is the most critical operational behavior and is evaluated within Test Element 1. As such, this verification test primarily consisted of dose delivery verification for the secondary effluent applications at 55% and 65% nominal water transmittances with a lamp-aging factor of 90%. This involved using transmittance-adjusted potable challenge water for bioassay testing with a simulated degraded intensity of 77%, headloss measurements, and flow velocity measurements in the reactor channel.

ODI chose not to completely validate Test Elements 2 and 3 of the protocol, but selected components of Test Element 2 that were appropriate to the operation of this system. Two items were then included in this validation to address the Process Control portion of Test Element 2.

First, the flow pacing approach used with the Aquaray® 40 HO VLS UV system, whereby additional reactor modules in a train are brought online, was validated with the bioassay data collected in this verification test. In addition, the behavior and performance of the intensity monitors were validated during this verification.

1.2 Mechanism of UV Disinfection

UV light radiation is a widely accepted method for disinfecting 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 and 290 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 to 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 one-third 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 watts (W) at 254 nm for a 70-75 W, 1.47-m long lamp. Recent developments have produced low-pressure, high-output (LPHO) lamps (0.01 to 0.001 mm of Hg) by using mercury present in 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.

Medium-pressure lamps operate from 300 to 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 between 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 the 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 transmitted into the water. Such attenuating factors include simple geometric dispersion of the energy as it moves away from the source, absorbance of the energy by the quartz sleeve housing the lamp, and 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 then 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 employed. Such calculations can 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 this verification test, 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. The field tests generate a survival ratio of the organism that can then 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. As such, 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 in the Verification Testing

2.1 NSF's Role

The WQPC's ETV program is administered through a cooperative agreement between the EPA and NSF, its verification partner organization. NSF administers the program, and it selected a qualified Testing Organization (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. In addition to disseminating the Verification Report and Verification Statement, the EPA had review and approval responsibilities for these documents:

- Verification Test Plan
- Verification Report
- Verification Statement

The key USEPA 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 VTP. Mr. 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), Mr. Wilfred Dunne, 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 Verification 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.
One Lethbridge Plaza
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

The UV system that underwent verification was provided by ODI. It consisted of a one-fourth-scale reactor module of their Aquaray® 40 HO VLS UV System. ODI's responsibilities included:

- Providing the test unit for verification and 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 to the requirements of the protocol;
- Providing descriptive details of the system, its operation and maintenance, its technical capabilities, and its intended function for water reuse 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 ODI is:

Mr. Bruno Ferran
Ondeo Degremont, Inc.
2924 Emerywood Parkway

Richmond, Virginia, 23294
Tel: 1-800-446-1150
Fax: 804-756-7643
Email: ferranb@denard.com

2.6 Support Organization's Role

International Light, Inc. was a subcontractor to HydroQual. It provided support for activities that could not be provided by NSF, EPA, HydroQual, or ODI. It also provided calibration services for the UV intensity sensors used for the verification test. Its contact information is:

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

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 ODI UV Disinfection System

3.1.1 Lamps and Sleeves

The Aquaray® 10 HO VLS UV test unit uses high-output, low-pressure, mercury discharge lamps (ODI P/N 61645.GO2) that are oriented vertically and perpendicular to the direction of flow. Each lamp has a UV output rating of approximately 52 watts (W) at 254 nm, a total power draw of up to 165 W, and an effective arc length of 146.7 cm. See Figures 3-1 through 3-4 for the system details.

Each lamp was housed in a sleeve composed of clear, fused quartz (GE214) to isolate and protect the lamp from the wastewater. The sleeves had only one open end, which remained exposed only to the conditions in the sealed, stainless steel ballast housing (see Figure 3-2). These quartz sleeves were 170.2 cm long, had an outer diameter of 24.4 mm, and had a wall thickness of 1.26 mm that resulted in a UVT of approximately 90%.

The lamps and sleeves were identical to those used in the full-scale Aquaray® 40 HO VLS UV system.

3.1.2 Lamp Aging

Lamp aging tests were conducted following the National Water Research Institute (NWRI) and American Waste Water Association Research Foundation (AWWARF) (NWRI and AWWARF, 2000) protocol under the direction of HydroQual. The details of the aging test protocol and results are included in the report *UV Lamp Age-Factor Testing for ODI High-Output, Low Pressure Lamps* (HydroQual, 2002). In brief, seven lamps, each from two different lots (14 lamps total), were operated under controlled conditions to determine the change in lamp intensity as the lamps aged through 12,083 hours of operation and 2,072 on/off cycles. After allowing each of the 14 lamps to warm up for one hour, their intensity output was measured. This was done approximately every two months. The last measurement was performed at 10,369 hours.

The data for the lamp intensity measurements are shown in Figure 3-5, along with the average trend of the 14 lamps. The data are presented normalized to the intensities measured after a 100-hour burn-in. The lamp intensity values at 5,326 hours are suspect because the subsequent cleaning of the chamber and the optics returned the intensities to higher values. In general, the natural variability of the lamp intensity measurement is greater than the trend of lamp aging. As a result, the lamp intensity did not significantly change over the 10,369-hour period. However, the variability of the valid lamp intensity measurements encompasses values down to 90% of the original, 100-hour intensities. On this basis, the chosen end-of-life (EOL) lamp factor for this verification test was 0.9.

3.1.3 Lamp Intensity vs. Temperature

The UV output of low-pressure lamps varies somewhat, depending on the temperature of operation. The UV output is directly related to the temperature of the water in which the lamps are submerged. Thus, the temperature effect on the verification testing was addressed. Full-scale applications will also need to address the effect of wastewater temperature on lamp intensity.

ODI has conducted experiments to determine the variability of lamp intensity as a function of water temperature. The test apparatus consisted of a chamber that housed a standard lamp in a standard quartz sleeve that was immersed vertically in water. A chiller unit controlled the temperature of the water, and lamps were allowed to heat up for one hour before intensity measurements were taken. The intensities of three lamps were monitored at four different water temperatures and at four different distances from the end. The same ballast was used for all tests.

The average lamp intensity data are shown in Figure 3-6. The intensity varies as a function of the water temperature. Applications of this disinfection technology are typically used with water temperatures in the range of 15-30 ºC. Under these conditions, the intensity output of the lamps should not decrease by more than 7% from their maximum output at 22.8 °C.

The lamp intensity as a function of temperature can be calculated for temperatures in the range of 15-30 ºC with the following empirical relation:

$$
\begin{aligned}
&I_{lamp} = -1.63 \times 10^{-3} T^2 + 0.0742T + 0.591 \\
&Where: \\
&T = \text{Temperature of Water in C} \\
&I_{lamp} = \text{Lamp Intensity in mW/cm}^2
\end{aligned}
\qquad (3\text{-}1)
$$

3.1.4 Reactor Modules

The test system consisted of three modules with ten lamps, each mounted inside a rectangular frame with baffles. The lamps were positioned in a staggered, rectangular array with centerline spacing of 7.14 x 12.7 cm to duplicate one-fourth of the Aquaray 40 HO VLS System (see Figures 3-1 and 3-2). The reactor modules were completely surrounded by a rectangular frame that supported the lamp sleeves at the top and bottom ends. A small baffle was present with each row of lamps.

3.1.5 Sleeve Cleaning System

The test modules were not equipped with the sleeve cleaning system or the ODI-patented air scrub found with the full-scale modules because there was no validation test planned for this equipment. Nevertheless, the wiper drive rod was present on each test module to simulate related headloss and hydraulic behavior.

3.1.6 Electrical Controls

The lamps were powered by electronic ballasts (ODI P/N 61862.GO1) that were mounted vertically in a NEMA 4X enclosure that was located on top of each module. Each ballast was rated for 165 W of electrical power per lamp; each ballast powered two lamps in parallel so that the failure of one lamp would not cause the peer lamp to turn off.

The ballast controls were located in the control cabinet. A separate circuit powered each reactor module so the failure of one reactor module would not deactivate the other two. The ballasts' control panel did not allow for dimming the lamp power. In fact, it is part of the ballast specification to keep the lamp power steady during fluctuation of the line voltage.

The control cabinet supplied for the test unit was simpler than that offered commercially. However, for the purpose of this verification test, critical operational variables, such as lamp output, did not differ from the commercial unit. The main enhancement of the commercial control panel is one of operator convenience, where parameters such as lamp-hours, on/off cycles, lamp failure, flow rates, and UV intensity are monitored and recorded with a computerized user interface. The control cabinet supplied for this test was powered by a 480 Volts (V) delta power supply and had separate circuits for each reactor module.

3.1.7 UV Detectors

SWW1 (ODI P/N 61848.GO1) UV sensors were included in the test system and were identical to those supplied in full-scale systems. Each reactor module had a sensor located approximately 30 cm (12 in) below the water surface and 1.55 cm (0.61 in) from a lamp sleeve (see Figure 3-2).

Each sensor included a remote, dedicated amplifier that operated on 12 V DC. The intensity measurement was reported via an analog signal between 0 and 5 V DC. With a UVT below 75%, the SWW1 sensor output should not exceed 3.5 V DC with clean sleeves and new lamps. The sensors had a wavelength selectivity of 96% between 200 nm and 300 nm and a linear (1%) working range of 0.01-20 mW/cm^2. The measurement uncertainty of the sensor was rated at less than 5% of the working range ($\pm$ 1 mW/cm^2). The stability of the sensor was rated at 5% over 10,000 hours and a range of temperatures from 2-30 °C.

The control cabinet for the test unit had three digital displays that showed the voltage output in real time. The control cabinet also contained a dedicated power supply for the sensor amplifiers.

Although the verification of the detectors was not an element of this test plan, the intensity measured by these detectors was monitored during the tests.

3.1.8 Design Operational Envelope

The Aquaray® 40 HO VLS system is used for disinfection of primary, secondary, tertiary, and reused wastewaters. Upon set-up of a full-scale reactor, two intensity alarms are set: a low-intensity warning alarm and a low-intensity failure alarm. The low-intensity failure alarm is set to activate when a low-dose condition exists. Three common factors can contribute to a low-

dose condition: (1) the end of the lamp life (10,000 hours is recommended for wastewater reuse); (2) quartz sleeve fouling; or (3) low transmittance conditions.

For future Aquaray® 40 HO VLS systems that are treating media filtered wastewater for water reuse, the low-intensity failure alarm should be set equal to the high 75% confidence interval (C.I.) reading that is obtained with 46% UVT. For membrane filtered water, the low-intensity failure alarm should be set equal to the high 75% C.I. reading obtained with 56% UVT. The low intensity warning alarm should be set at the median between the sensor readings at 46% and 55% UVT for the media filtered water and between the sensor readings at 56% and 65% UVT for the membrane filtered water.

In terms of intensity reduction due to lamp aging and quartz fouling, the suggested operational protocols comply with the conditions in this verification test. Quartz fouling of 80% and lamp age intensity reduction of 90% (at 10,000 hours for wastewater reuse) were simulated during this test and are the conditions under which the typical full-scale setup would generate a low-intensity alarm.

A typical, full-scale, reactor train would consist of two or more Aquaray® 40 HO VLS modules. As the dose delivery conditions deteriorate (due to high flows or intensity reduction), additional, upstream rows of lamps (5 rows of 8 lamps per Aquaray® 40 HO VLS module) would be progressively brought online. (Note that the farthest-downstream module always stays lit for safety purposes.)

Refer to Appendix B for additional information on the operation and maintenance of the Aquaray® 40 HO VLS system or contact ODI.

3.2 UV Test Unit Specifications

3.2.1 Test Channel

The reactors were housed in an open, stainless steel channel that was 7.9 m (26 ft) long (see Figure 3-3). The untreated water entered the channel via a 30.5 cm (12 in) wide by 2.13 m (7 ft) high section of the pipe. A baffle located 0.46 m (1.5 ft) from the water inlet pipe smoothes the flow and spreads it over the submerged cross-section of the channel. Approximately 0.92 m (3 ft) from the front of the channel, the dimensions of the channel were reduced to 17.78 cm (7 in) width and 1.83 m (6 ft) height. The first test module (test module #3) was located 1.06 m (3.5 ft) downstream of the channel narrowing. The space between each test module was 0.60 m (2 ft) as in full-scale systems. The channel width increased back to 30.5 cm (12 in) approximately 1.06 m (3.5 ft) after the final lamp unit. It should be noted that the width of the full-scale channels does not change in the direction of the flow.

Although the test channel allowed orifice plates to be used in the influent and effluent end, orifice plates were not used during the verification test. Simulation of worst-case influent hydraulics was an important part of this verification. The influent flow in the channel was somewhat stabilized by the addition of a mixer, as shown in Figure 3-4 and discussed in Section 7. The mixer was sized by ODI, based on an existing water reuse system located in Windsor, CA, which dissipates an electrical mixing power of 0.10 W per gallon through a single-module-

wide channel with seven, low-output Aquaray® 40 HO VLS modules arranged in series. Assuming that 100% of the mixer's electrical power converts to mixing energy, the resulting maximum velocity gradient (G) was 150/sec for a water temperature of 15 ºC. Velocity gradients for typical rapid mixing operations in wastewater range from 250/sec to 1,500/sec. The influent control box of the Aquaray® 10 HO VLS system channel used in this verification test contained approximately 130 gallons of water for a liquid level of 60 in. The mixer used was an XJ43 LIGHTNIN, which rotated at 350 rpm and was equipped with a 5.9 in. diameter, 45° pitched, 3-blade impeller.

3.2.2 Scaling Considerations

The Aquaray® 10 HO VLS system that was tested was a one-fourth-scale unit, used for validating the dose delivery of the full-scale Aquaray® 40 HO VLS system. The lamps, ballasts, and sleeves were identical to those used in the full-scale system. The lamp assemblies were installed in a channel under conditions identical to commercial applications with respect to lamp array geometry and lamp submergence (see Figure 3-4).

The only geometric differences between the test- and full-scale modules were the width of the channel and the width of the baffles. The width of the full-scale Aquaray® 40 HO VLS module is 60.96 cm (24 in); the width of the Aquaray® 10 HO VLS test unit was 17.78 cm (7 in), giving a width ratio of 3.43. This ratio should be approximately 4. As a result, there is a lower radiation density in the test unit, which makes this validation inherently conservative (see Section 4.4.5.1). Both the Aquaray® 10 HO VLS and the Aquaray® 40 HO VLS reactor modules have one baffle for each row of lamps on the channel side where the lamp-wall spacing is largest.

The most critical dose delivery occurs in the system when the water is passing between the lamps' axes (hence the baffles). The cross-sectional area is the narrowest and, therefore, at that point the velocity is the highest. Because the Aquaray® 10 HO VLS module is slightly wider than one-fourth of the Aquaray® 40 HO VLS module, the baffles are also slightly wider to balance the velocity as well as headloss between the two different scales.

The theoretical cross-sectional velocity passing through this critical zone is:

$$V_{CS} = \frac{Q}{(W_{CH} - W_B - nd)H}$$

$$\begin{aligned} &Where: \\ &Q = \text{Flow} \\ &W_{CH} = \text{Width of Channel (or Module)} \\ &W_B = \text{Width of Baffle} \\ &n = \text{Number of Lamps per Row} \\ &d = \text{Diameter of Lamp Sleeves} \\ &H = \text{Height of Water Column} \end{aligned} \qquad (3\text{-}2)$$

Essentially, the Aquaray® 10 HO VLS test unit was designed to accommodate one-fourth of the flow of the Aquaray® 40 HO VLS unit with an identical, critical, cross-sectional velocity. Thus, with the subscript "40" representing a train of Aquaray® 40 HO VLS modules and the subscript "10" representing the Aquaray® 10 HO VLS test system:

$$V_{CS40} = V_{CS10}$$
$$and$$
$$Q_{40} = 4Q_{10}$$

So:

$$\frac{4Q_{10}}{(W_{CH40} - W_{B40} - 8d)H} = \frac{Q_{10}}{(W_{CH10} - W_{B10} - 2d)H} \quad (3\text{-}3)$$

Knowing that the baffle width in the Aquaray® 40 HO VLS module (W_{B40}) is 4.06 cm (1.60 in), the lamp sleeve diameter (d) is 2.438 cm, and the widths discussed above, the necessary width of the Aquaray® 10 HO VLS module (W_{B10}) can be determined:

$$W_{B10} = W_{CH10} - 2d - \frac{W_{CH40} - W_{B40} - 8d}{4} \quad (3\text{-}4)$$

Solving numerically with all units in cm:

$$W_{B10} = 17.78 - 2 \times 2.438 - \frac{60.96 - 4.06 - 8 \times 2.438}{4} = 3.56\text{cm} \quad (3\text{-}5)$$

Based on this solution, the Aquaray® 10 HO VLS reactor modules had baffles that were 3.56 cm (1.40 in) to better simulate the Aquaray® 40 HO VLS reactor module hydraulics, which has 4.06 cm (1.60 in) baffles.

3.2.3 Flow Rates

The flow rates in this verification test are compared with those in a full-scale reactor train in Table 3-1. A reactor train is defined as a channel that contains two or more Aquaray® 40 HO VLS modules in series and has a width of one Aquaray® 40 HO VLS module.

The Aquaray® 40 HO VLS system is intended to operate in conditions up to 4.3 million gallons per day (MGD) per train if dose delivery considerations allow. The high flow rate (11,356 L/min) is just over the typical maximum operation range of such full-scale units. However, in most cases, the flow rate would be lower. As such, this test was a simulation of dose delivery in a full-scale train with flow rates between 2,271 L/min and 11,356 L/min (0.86 and 4.32 MGD). Under the same conditions, a channel that is x Aquaray® 40 HO VLS modules wide (or x trains) is intended to operate with flows of up to x times 4.3 MGD.

Table 3-1. Verification Test and Scaled Flow Conditions

One-Fourth Scale Aquaray® 10 HO VLS Test Unit			Train of Full-Scale Aquaray® 40 HO VLS System		
(MGD)	(L/min)	(gpm)	(MGD)	(L/min)	(gpm)
0.22	568	150	0.86	2,271	600
0.50	1,325	350	2.02	5,299	1,400
0.65	1,703	450	2.59	6, 814	1,800
0.79	2,082	550	3.17	8,328	2,200
1.08	2,839	750	4.32	11,356	3,000

3.3 Verification Test Claims

The overall objective of this verification test was to validate disinfection performance of the ODI Aquaray® 40 HO VLS UV System for water reuse applications. The nominal transmittances of the specific application waters were adjusted to simulate sleeves fouled to 80%T, lamp intensities reduced to 90%T, and lamp intensity adjusted for optimum temperature conditions. Within this goal, four specific objectives were identified:

1) Verify the flow-dose relationship for the system at a nominal UVT of 65% to simulate membrane filtered effluent. (Note: The actual UVT was 56%.)

2) Verify the flow-dose relationship for the system at a nominal UVT of 55% to simulate granular filtered effluent. (Note: The actual UVT was 46%.)

3) Verify the dose delivered by the farthest downstream reactor module (#1) by collecting samples disinfected only by reactor modules #2 and #3. These tests were conducted at a nominal transmittance of 55% (actual 46%) for a granular filtered effluent simulation.

4) Verify the velocity profiles on the influent end, between lamp units #3 and #2, between lamp units #2 and #1, and on the effluent end of the reactor train.

Note: The application of this disinfection system to reverse osmosis filtered effluent was not validated.

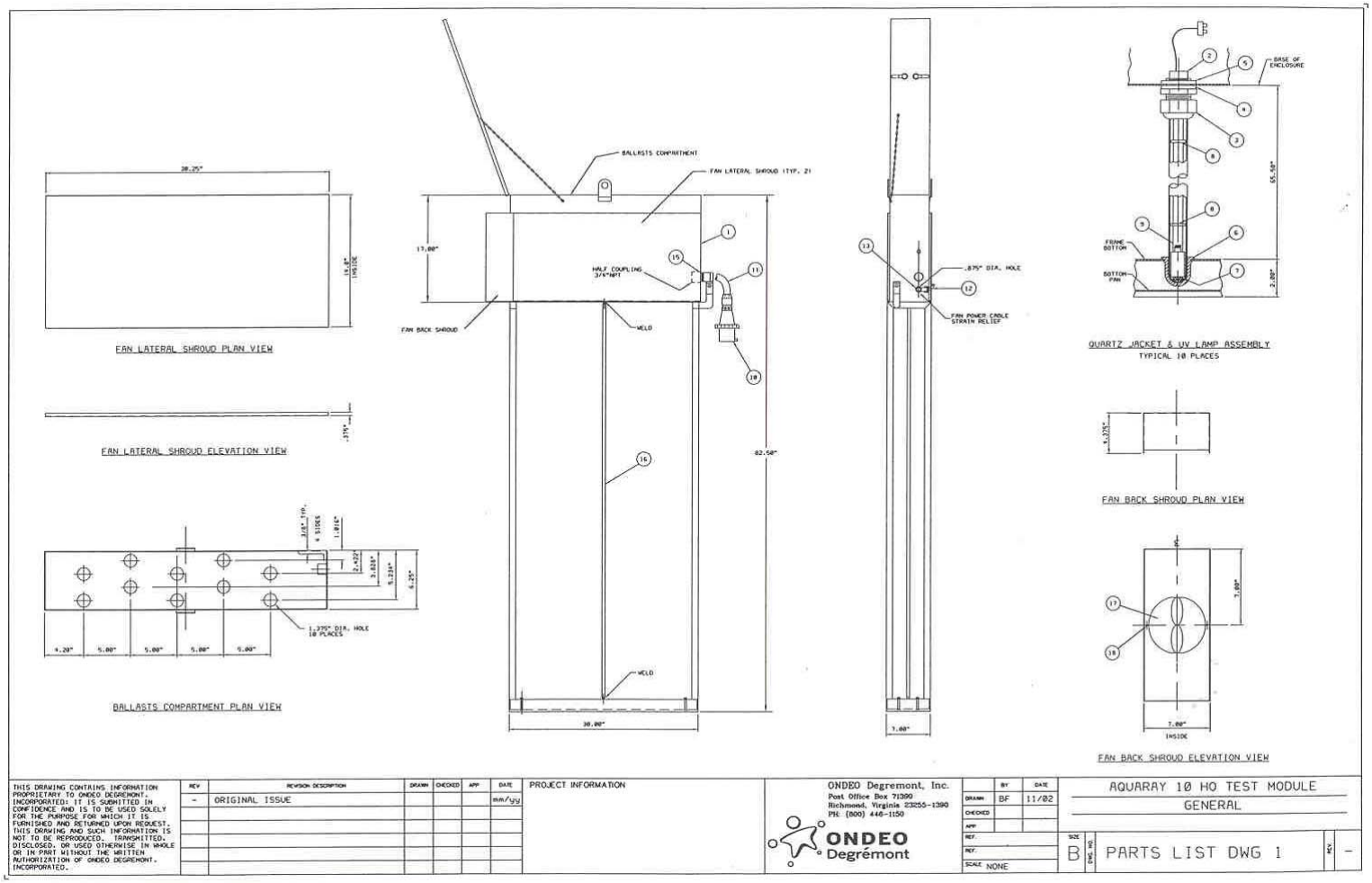

Figure 3-1. Reactor module and sleeve assembly detail.

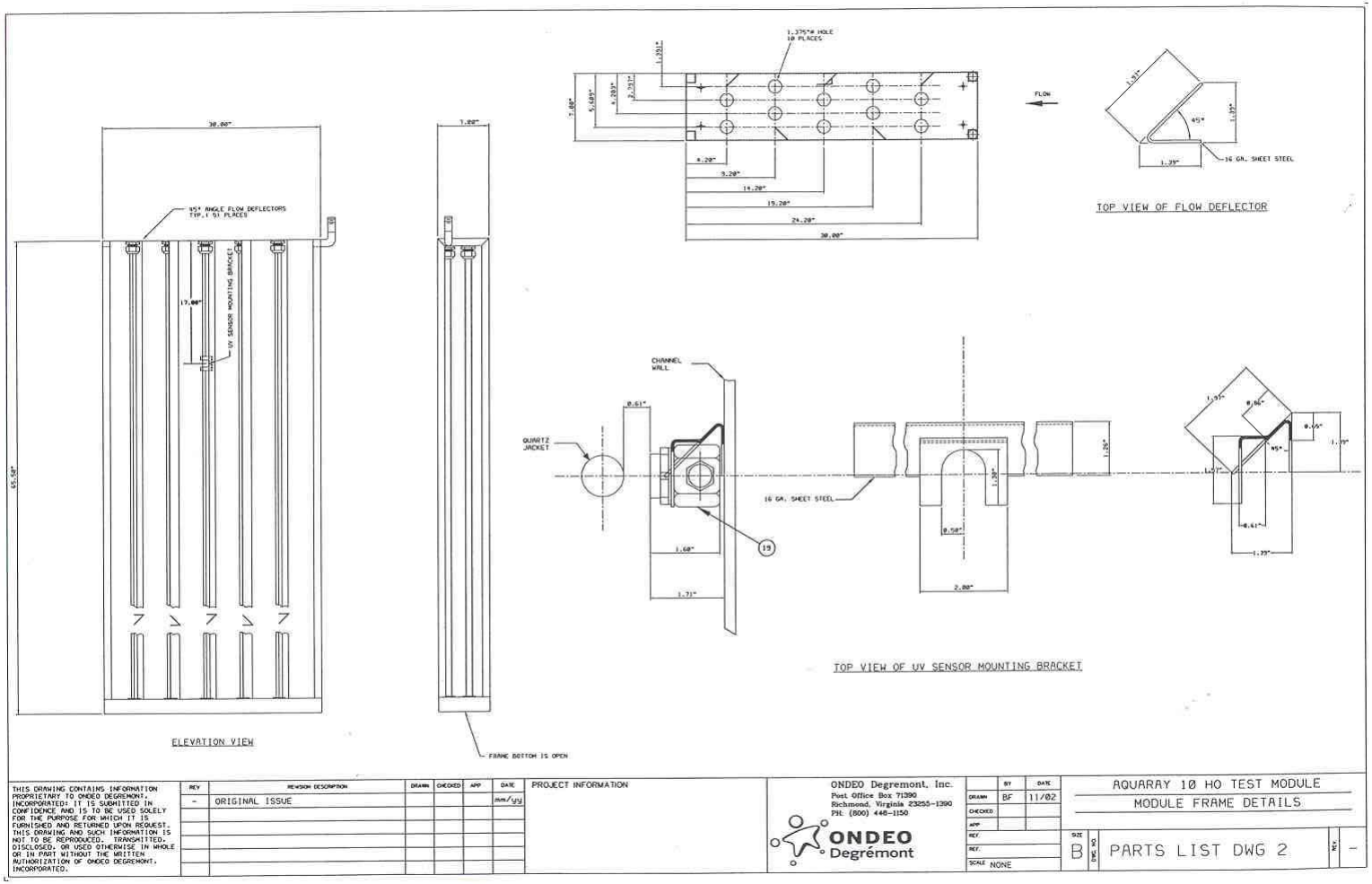

Figure 3-2. Reactor module and detector detail.

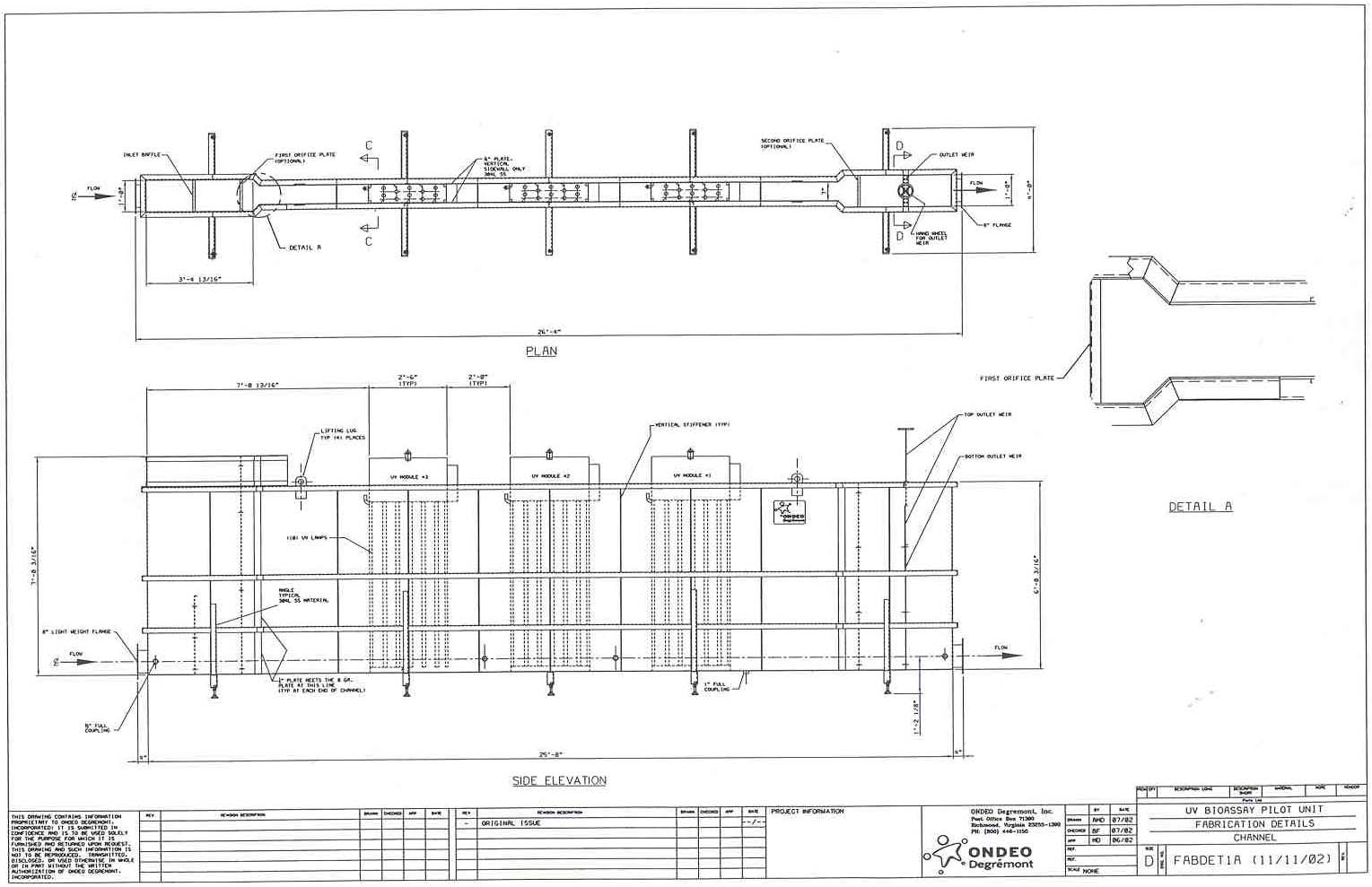

Figure 3-3. Schematic of test unit.

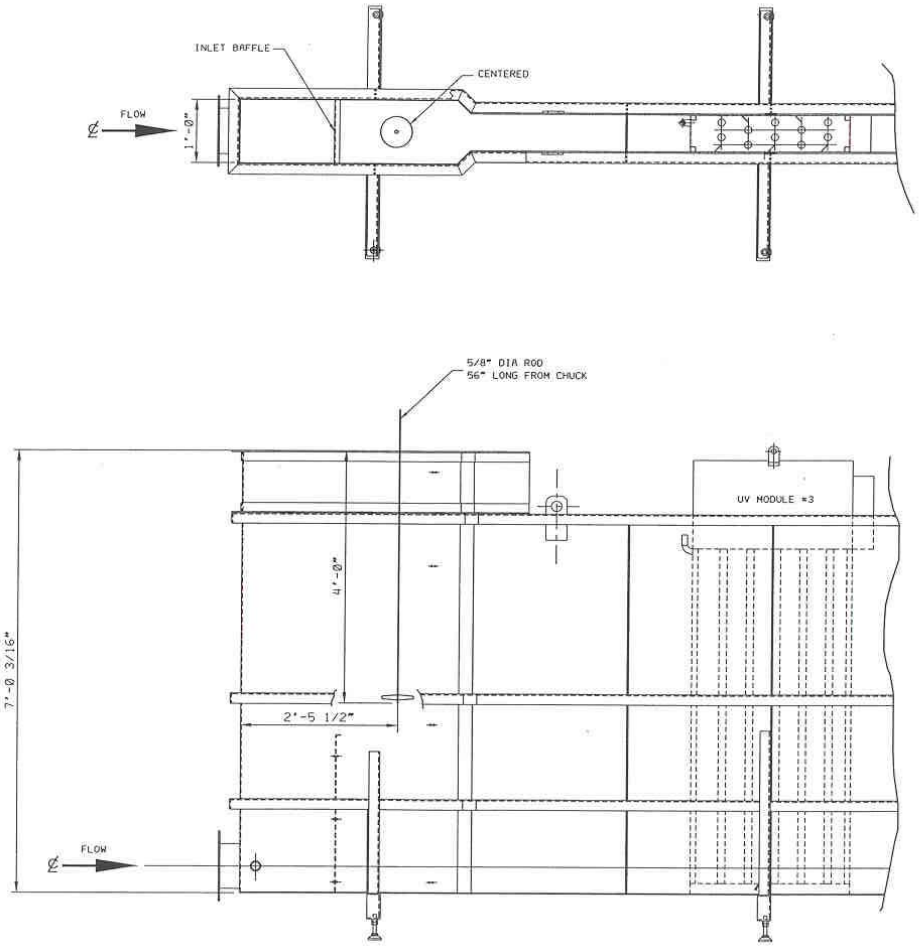

Figure 3-4. Influent mixer.

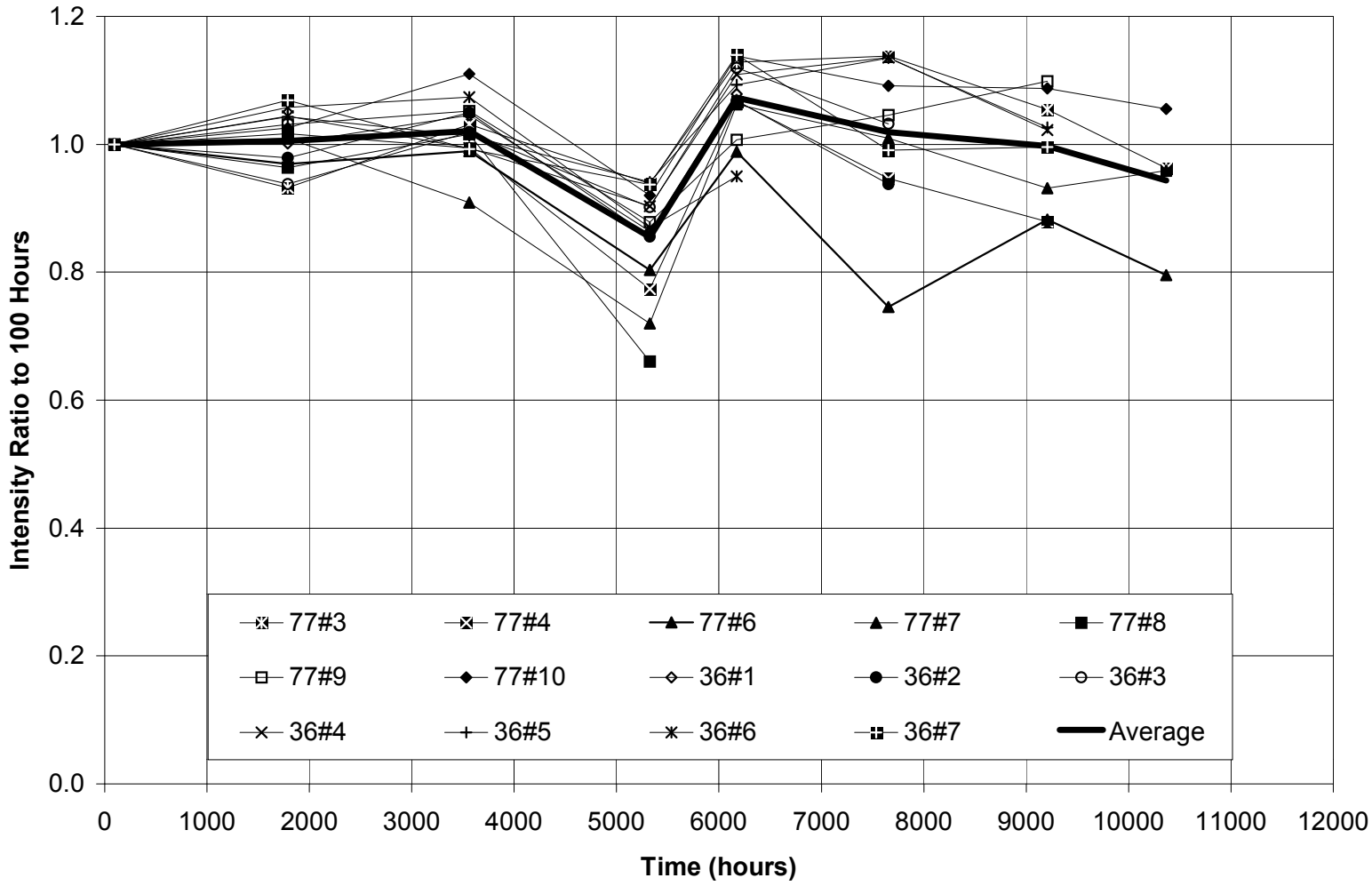

Figure 3-5. Lamp intensity as a function of age.

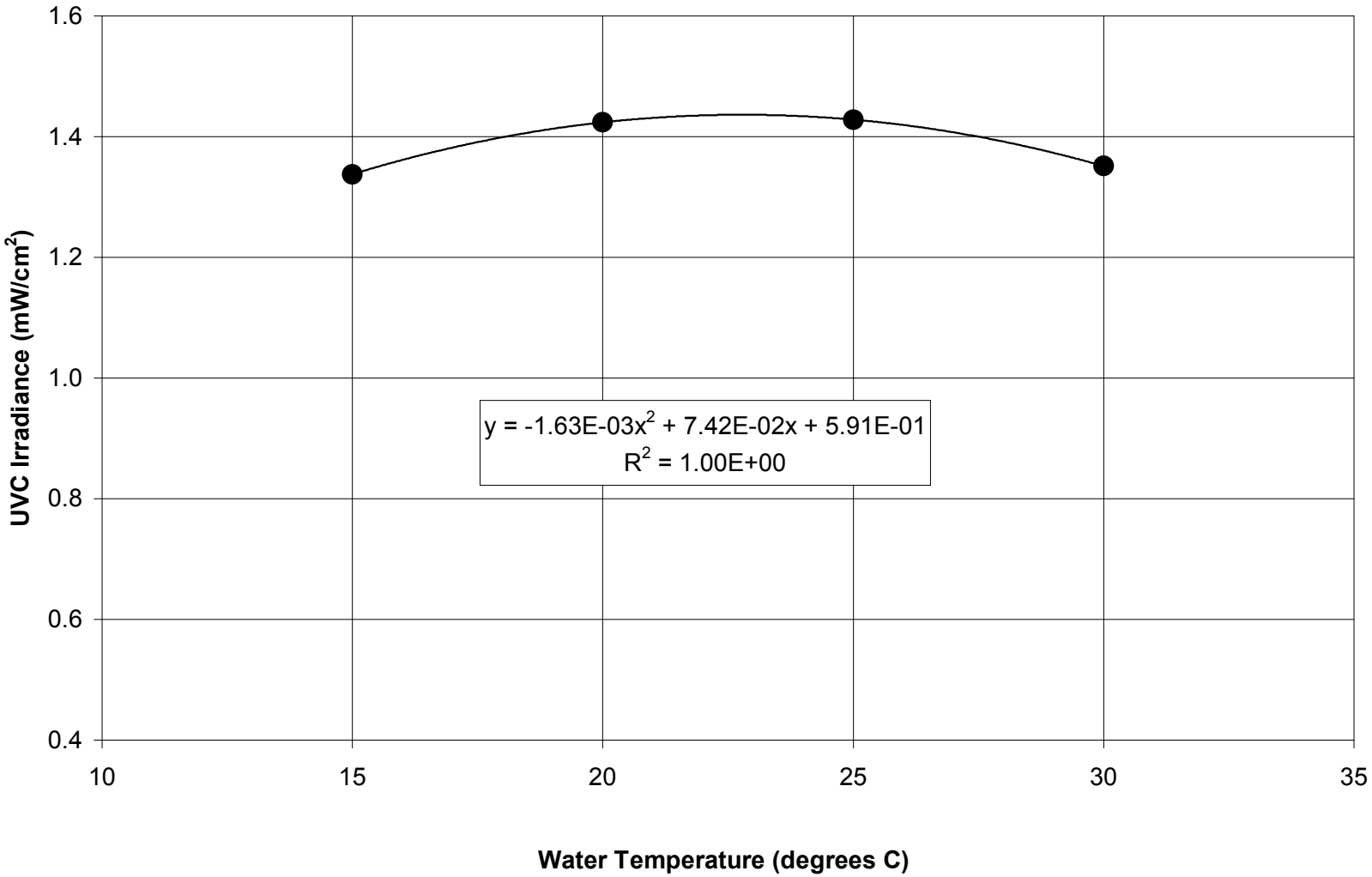

Figure 3-6. Lamp intensity as a function of water temperature.

Chapter 4
Procedures and Methods Used during Verification Testing

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 media filtration. Sources of primary effluent, secondary effluent, granular media filtered secondary effluent, and potable water were available at the test site.

The test site 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 where the challenge waters were discharged. The test site included a semi-permanent structure for housing the test unit 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 Aquaray® 10 HO VLS disinfection unit. The test unit was fed with challenge water prepared in a batch tank that was pumped to the influent side of the test channel. The effluent was discharged to the adjacent aeration tank. Power from the PTRH plant's electrical supply was used for the test unit.

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 2000 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 10.6-16.6 ºC, the transmittance was in the range of 98.2-98.9%T at 254 nm, and the turbidity was in the range of 0.12-0.92 Nephelometric Turbidity Units (NTU).

The second water source used for these bioassay tests was taken from the effluent side of the granular media 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 15.0-17.2 ºC, the transmittance was in the range of 71.1-86.0% at 254 nm, and the turbidity was in the range of 0.82-2.0 NTU.

4.1.3 Challenge Water Tanks

The test site contained two 80,000-liter tanks supplied by Adler Tank Rental, Newark, NJ. 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 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.

The tanks were supplied with a fresh coating of epoxy paint on the interior to prevent corrosion and any chemical reaction with the water. A float-type level indicator was present on both tanks. A 30 kW electrical submersion heater was installed in one tank to warm the relatively cool potable water to the appropriate challenge test temperature in the range of 15.0 ºC. This was achieved by filling the tank the day before the test and allowing it to heat overnight.

4.1.4 Pump

The test challenge waters were pumped to the test unit or recirculated to the challenge water tanks with a Godwin CD150M Dri-Prime Centrifugal Pump from Bridgeport, NJ. The pump was trailer mounted with jack stands for semi-permanent installation. It was equipped with a diesel-powered 53 kW (71 hp) motor to provide flow rates up to 7,600 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, turbidity, and transmittance measurements (see Figure 4-2).

4.1.5 Flow Meter

A Fisher-Porter 10D1462 150 mm magnetic flow meter measured flow to the test system. The flow meter was installed with a straight run of six-inch pipe 152 cm before and 91 cm after the flow meter to reduce turbulence that could impact meter performance. The calibration was verified before testing using the tank drawdown method (see further description of the flow meter calibration in Section 6.1.1).

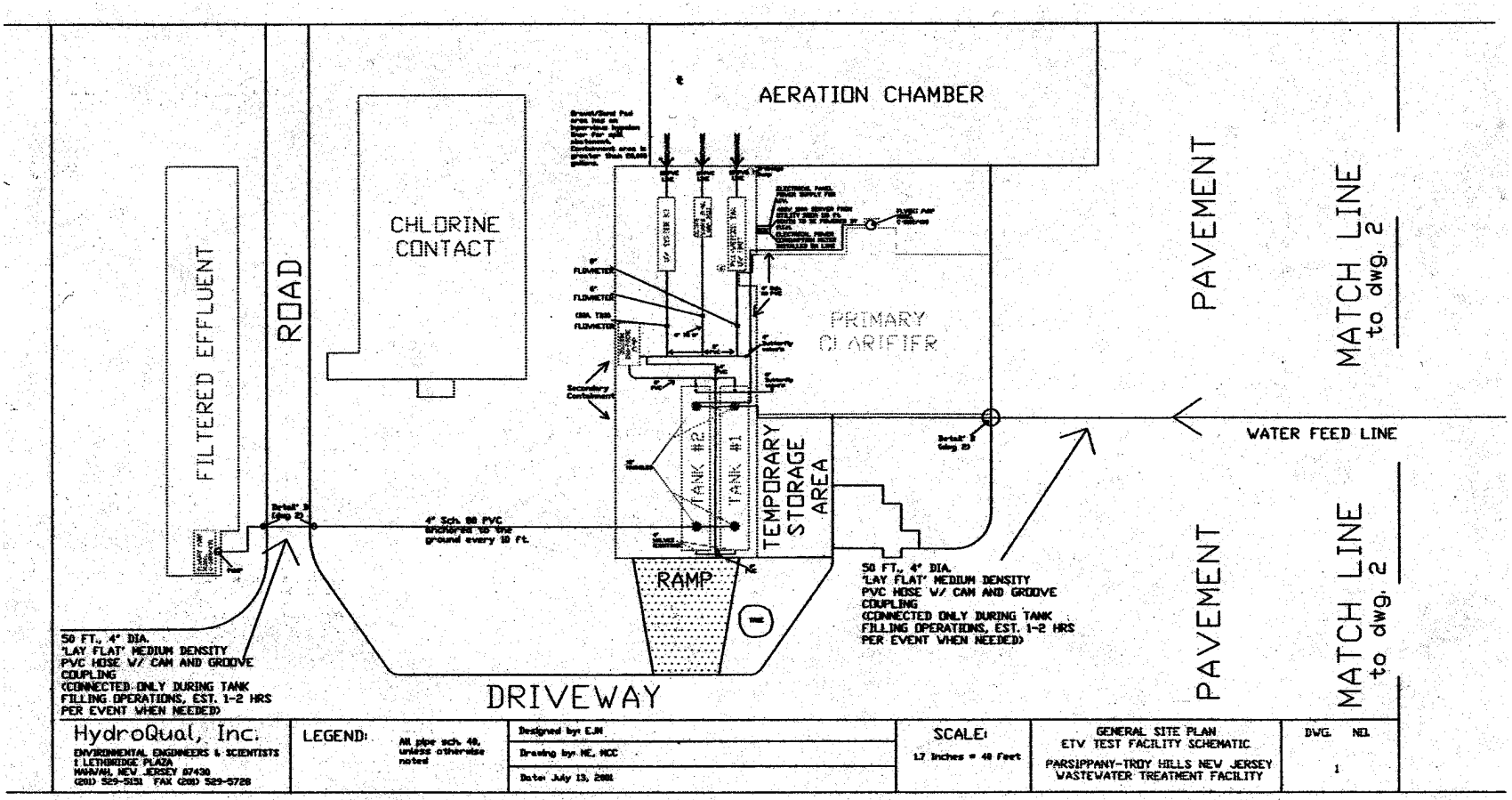

Figure 4-1. General site plan of the ETV test facility at the PTRH WWTP.

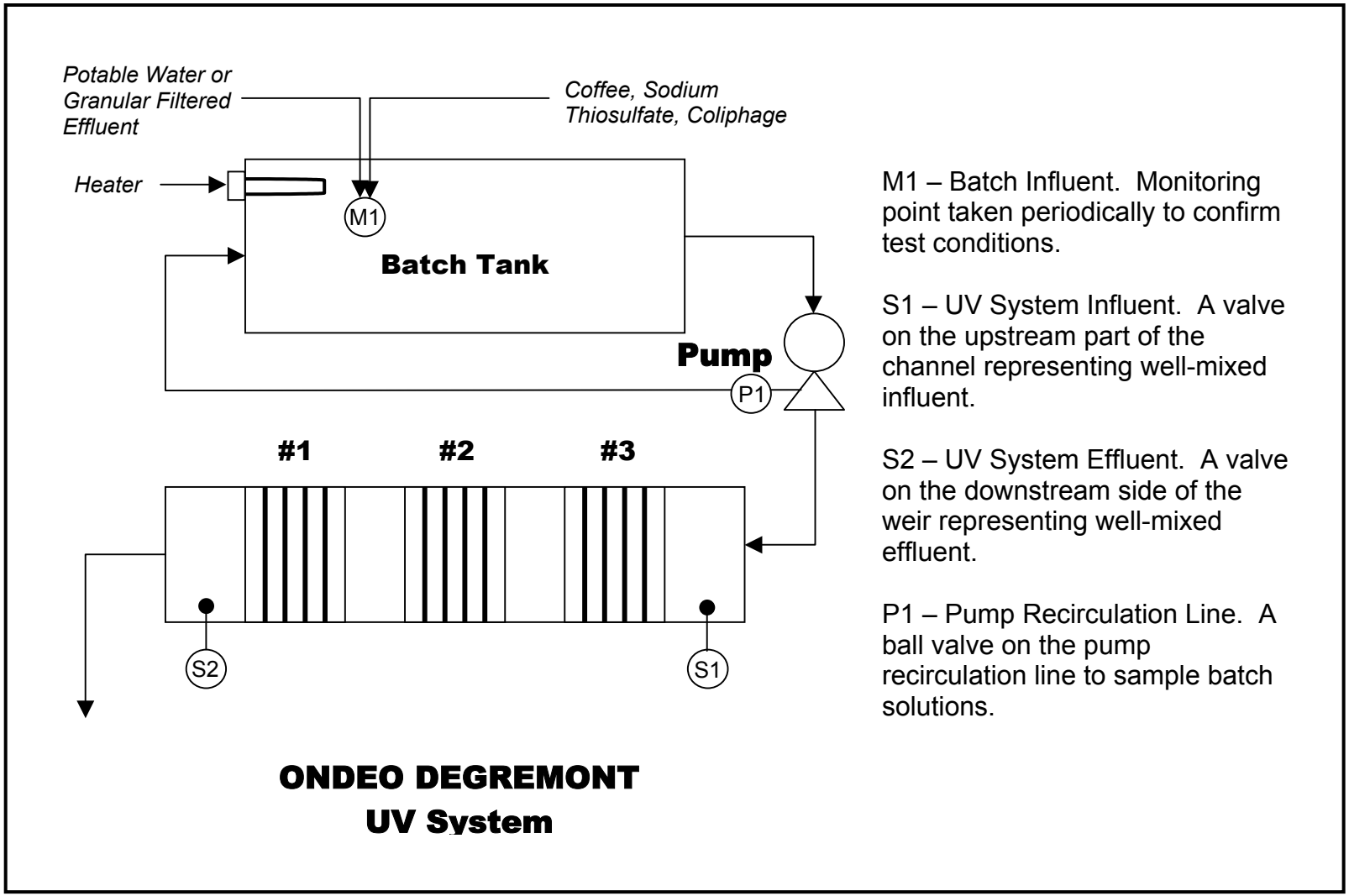

Figure 4-2. Flow schematic and sampling points.

4.2 Disinfection Unit 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. The lamps were turned on to 100% power with filtered secondary effluent flowing through the channel at a rate of approximately 1,400 L/min to prevent the lamps from overheating. HydroQual personnel monitored this process by checking the system status one to two times a day. The system was checked to verify that all lamps were operating, the water temperature was checked, and the built-in detector readings were recorded. The power data logger was set up to record power consumption throughout the period. Notes about the lamp burn-in are in Appendix C.

The lamps were operated continuously at full power throughout the burn-in period, which spanned 5 days. No lamps failed during this period.

4.2.2 Power Consumption and Intensity Stability Characterization

4.2.2.1 Power Consumption Measurement

Power consumption for the test unit was measured at two positions of the power distribution system. First, the single-phase 240V power supply to each reactor module was measured for two hours during the lamp stability test. Second, the total power consumption of the system was measured during the burn-in, shakedowns, and all flow tests (with two or three modules activated).

4.2.2.2 Intensity Stability Determination

The intensity stability of the test unit reactor modules was monitored with the built-in detectors and with the IL-1700 radiometer with the SUD240 detector mounted on a rack in the water column to monitor one lamp in the downstream position (Reactor module #1). Both detector systems gave only relative intensity readings that were a function of the lamp emission geometry, distance, water transmittance, and input optic geometry. The output from the IL-1700 radiometer was recorded in mJ/cm^2; the outputs from the built-in detectors were recorded in volts.

The test unit was started with a flow of 568 L/min and 98.4%T potable water at approximately 15 ºC. The lamps were turned on. After 10 minutes, output from the built-in detectors and the IL-1700 radiometer as well as the power consumption of the reactor modules were recorded. Measurements were recorded every 15 minutes thereafter for a period of two hours.

4.2.3 Headloss Measurements

Measurements of headloss through the channel were made with reference to graduations that were marked on the inside of the channel. The channel was leveled within 0.5 cm before the start of the testing.

First, the channel was flooded with water to establish a horizontal reference. Then, using an indelible marker, each measuring position was marked with a scale. The vertical datum was the bottom of the channel-run; thus, measurements represented the depth of water in the channel.

For this verification, the water level was measured at five positions. The first three positions were located 30.5 cm in front of each of the three reactor modules. The next position was 30.5 cm after the downstream module, and the final position was 30.5 cm upstream of the effluent weir. The measurement positions, located with respect to the front of the influent box, were 2.46 m, 3.83 m, 5.20m, 6.57 m, and 7.64 m.

The water level was measured at each position after the flow had stabilized, and the weir was adjusted to maintain the influent water level at the first position at a depth of 157.5 cm.

4.2.4 Velocity Profile Measurements

The primary hydraulic characterization of the ODI Aquaray® 10 HO VLS test unit involved the measurement of detailed flow-velocity fields in the channel. The flow fields were measured in four positions along the channel length and are listed here from the upstream to downstream position.

(1) 30.5 cm (12 in) upstream of the first reactor module (module #3)

(2) Midway between reactor modules #3 and #2

(3) Midway between reactor modules #2 and #1

(4) 30.6 cm (12 in) downstream of the last reactor module (module #1)

Each flow field consisted of a 2 by 13 matrix of monitoring positions. The two horizontal positions were selected to divide the 17.8 cm (7 in) channel width into thirds; they were located 5.9 cm (2.3 in) from each wall. The thirteen vertical positions were evenly spaced at 11.7 cm (4.6 in) and were measured from the bottom of the channel in the positions listed in Table 4-1. The influent velocity profiles were also measured with and without the mixer (see Section 7).

Table 4-1. Vertical Flow Field Positions

Position	Height (cm)	Height (in.)
13	152.4	60.0
12	140.7	55.4
11	129.0	50.8
10	117.2	46.2
9	105.5	41.5
8	93.8	36.9
7	82.1	32.3
6	70.3	27.7
5	58.6	23.1
4	46.9	18.5
3	35.2	13.8
2	23.4	9.2
1	11.7	4.6

Flow velocity measurements were made with a Marsh-McBirney 201D electromagnetic flowmeter detector. In order to accurately locate the flowmeter detector both horizontally and vertically, it was mounted on a frame constructed of aluminum rods. The frame was located downstream of the flowmeter detector to minimize the disturbance to the water column. The flow field was measured, in triplicate, for all five flow rates addressed in this verification test. A total of 1,560 velocity measurements were made.

4.2.5 Shakedown Flows

During the start of the verification test bioassays, some shakedown flows were conducted to evaluate dose delivery at different transmittances and to evaluate different sampling schemes to quantify the dose delivery of one module. These flows also allowed an initial calibration run of the test unit and allowed the dilutions for the microbiological enumeration to be determined. During this period, the technicians became familiar with the equipment operation and sampling scheme. These flows were conducted using the methodology described in Section 4.4. The results are in Appendix C.

4.3 MS2 Propagation 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.

Briefly, the host strain (*E. coli*) was grown at 37 °C in Trypticase yeast-extract glucose broth until the log-growth phase was reached. The required 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 and 0.22 μm filters to remove cell lysate and to remove any other bacteria that may be present. 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 8.5% saline water, (b) field influent samples collected from the field-challenge batch solutions for flow tests, and (c) verification runs that were conducted with 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:

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

Necessary exposure time:

$$Time = Dose \times I$$

Where:

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 (mWs/cm^2).

(4-1)

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 4.4.6.

For this verification test, 23 dose-response runs were conducted. Two were in 0.85% saline solution, 18 were conducted with seeded challenge waters, and three were conducted with simulated challenge waters.

4.4 Dose Flow Assays

4.4.1 Lamp Sleeve Preparation

Before each flow test series, the lamp racks were lifted from the channel for manual cleaning and inspection. Then the lamp sleeves were scrubbed with glass, non-abrasive sponges and an acidic cleaning solution (e.g., 1 M Citric Acid). The lamp racks were replaced in the channel, water was allowed to flow, and the lamps were turned on to verify that all were operating properly.

4.4.2 Challenge Water Batch Preparation

The bioassay flow tests were conducted on a mixture of potable water with instant spray-dried coffee and sodium thiosulfate or granular filtered effluent. Both batches of water were mixed with MS2 bacteriophage. An 80,000-Liter batch of challenge water was prepared immediately before each flow test series.

First, the tank was filled approximately three-fourths full with potable water or filtered effluent, the total chlorine was checked, and 1.5 kg of sodium thiosulfate was added for potable water (approximately six times the amount required for neutralization of the chlorine). An internal recirculation pump with a flow rate of approximately 2,000 L/min was run during batch preparation. After filling, the total chlorine was measured to verify total neutralization. The instant coffee was progressively added to reduce the transmittance to the target level (46%T or 56%T), with frequent transmittance checks made. Finally, one Liter of MS2 bacteriophage was added and allowed to circulate for at least 30 minutes to mix fully.

A 30 kW heater was installed in the tank to warm up the potable water to 15 ± 1 ºC. The tank was filled with potable water the day before and allowed to warm overnight.

4.4.3 Lamp Warm Up

While the challenge water was being prepared, potable water was allowed to flow through the channel at a rate of approximately 568 L/min and the lamps were turned on. The lamps were allowed to warm up for at least two hours before the challenge waters were introduced.

4.4.4 Flow Testing

Flow testing was conducted by pumping the water through the channel at the various specified flow rates. Enough time was allowed for at least five volume changeovers in the lamp assemblies, the flow rate was checked again, and sampling commenced. Water that had passed through the test unit was discharged to the wastewater treatment plant.

Grab samples were collected in sterile, 120 mL single-use specimen cups. Influent samples were collected at a valve at the influent box. Effluent samples were collected at a valve on the effluent side of the weir. Each sampling valve protruded two inches into the channel approximately five inches above the floor. The influent sampling valve was located upstream of the flow spreader baffle where there was a strong mixing. The effluent sampling valve was located downstream of the channel outlet weir where, again, turbulence was paramount. The valves were allowed to flush freely for several seconds before samples were collected. Both 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 for a total of 71 valid flow tests.

4.4.5 Challenge Water Transmittance

4.4.5.1 Intensity vs. Transmittance in Reactor modules

In order to establish the reduced challenge-water transmittances used in these bioassay experiments, it is first necessary to quantify the effect that UVT has on the average intensity (I_{AVE}) in the reactor modules.

The I_{AVE} versus transmittance relationships were developed for the Aquaray® 10 HO VLS test unit and the full-scale Aquaray® 40 HO VLS reactor modules. These calculations were performed using a line source integration model by Janex[6], and the UVDIS point-source integration model. Both approaches give similar results, but the former is presented here in detail.

The calculations involved determining the intensity at each point in a cross-sectional plane of the reactor module (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 moved through the UV absorbing water. The impact of light reflection and refraction at the air and quartz as well as the quartz and water interfaces was not included in the equations. The average intensity of the radiation field was then calculated for a range of transmittances.

Specifically, these calculations employed numerical models using low-pressure lamps with an arc length of 146.7 cm, a lamp power at 254 nm of 46.8 W, and a transmittance range of 20-70% at 254 nm. The quartz sleeves had a wall thickness of 0.125, a radius of 1.219 cm, and a 90%T at 254 nm.

Geometrically, two models were computed: one with the one-fourth-scale 10-lamp unit and one with the full-scale 40-lamp unit. For both models, the small volumes displaced by the baffles were removed from the irradiated area. UVDIS modeling with the one-fourth-scale reactor gave I_{AVE} versus %T results within 1% of the above model.

The results for both models are shown in Table 4-2 and in Figure 4-3. It is clear from Figure 4-3 that the I_{AVE} for the full-scale Aquaray® 40 HO VLS system is higher than for the Aquaray® 10 HO VLS system used in these validation tests. The difference is 16-20%, as quantified by the ratios shown in Table 4-2. Based on these results, using the Aquaray® 10 HO VLS system for the bioassay validation is an inherently conservative approach. The higher I_{AVE} present in the Aquaray® 40 HO VLS system would likely have resulted in higher dose delivery efficiency, if the verification test bioassays had been conducted on a full-scale unit.

Table 4-2. Average Intensity (IAVE) versus Transmittance Results

UVT (%T/cm)	Modeled I_{AVE} Aquaray® 10 (mW/cm^2)	Modeled I_{AVE} Aquaray® 40 (mW/cm^2)	Ratio ($I_{AVE}40/I_{AVE}10$)
70	7.815	9.404	1.20
65	6.588	7.839	1.19
60	5.621	6.636	1.18
55	4.839	5.679	1.17
50	4.192	4.898	1.17
45	3.646	4.245	1.16
40	3.177	3.691	1.16
35	2.768	3.209	1.16
30	2.406	2.786	1.16
25	2.079	2.406	1.16
20	1.778	2.057	1.16

The above results from the line source integration model were fitted with third-order polynomials that empirically quantify the relationships. For subsequent calculations, the relationship for the Aquaray® 10 HO VLS system is:

$$I_{AVE} = 3.338 \times 10^{-5}(\%T)^3 - 2.668 \times 10^{-3}(\%T)^2 + 0.1370(\%T) + 0.1832 \quad (4\text{-}2)$$

4.4.5.2 Bioassay Transmittances

The dose flow assays for this reuse verification test used simulated wastewaters with two different UVTs at 254 nm. The nominal target transmittances were 55% for the granular filtered water and 65% for the membrane filtered water (simulated by dechlorinated, potable water).

The ODI Aquaray® 40 HO VLS disinfection system was designed with a fixed output lamp and power supply system. As such, the lamps could not be turned down to simulate the specific test conditions. As an alternative, further lowering of the transmittance to reduce the average intensity field in the reactor was used to simulate the specific test conditions. Three conditions were considered in this calculation:

(1) The EOL lamp intensity condition that was simulated was 90% of the intensity after the 100-hour burn-in. See Section 3.1.2.

(2) The quartz-sleeve fouling factor was the default value of 80%T specified in the Verification Protocol (NSF, 2002).

(3) The relative intensity was increased 7% to simulate the lamp output present at optimum temperature conditions; the tests were conducted with 15 °C water. See Section 3.1.3.

The reduced target intensity was the product of all three corrections:

$$I_{reduced} = 0.90 \times 0.80 \times 1.07 \times I_{average} = 0.77 \times I_{average} \quad (4\text{-}3)$$

Thus, based on these three conditions, the transmittance was reduced from the nominal value to reduce the average intensity to 77% using the relationship developed in Section 4.4.5.1.

The average intensity was calculated for the nominal %T (e.g., 65%) and then multiplied by the 0.77 intensity-reduction factor. Then a reduced %T was determined, which achieved this reduced average intensity. The results are shown in Table 4-3.

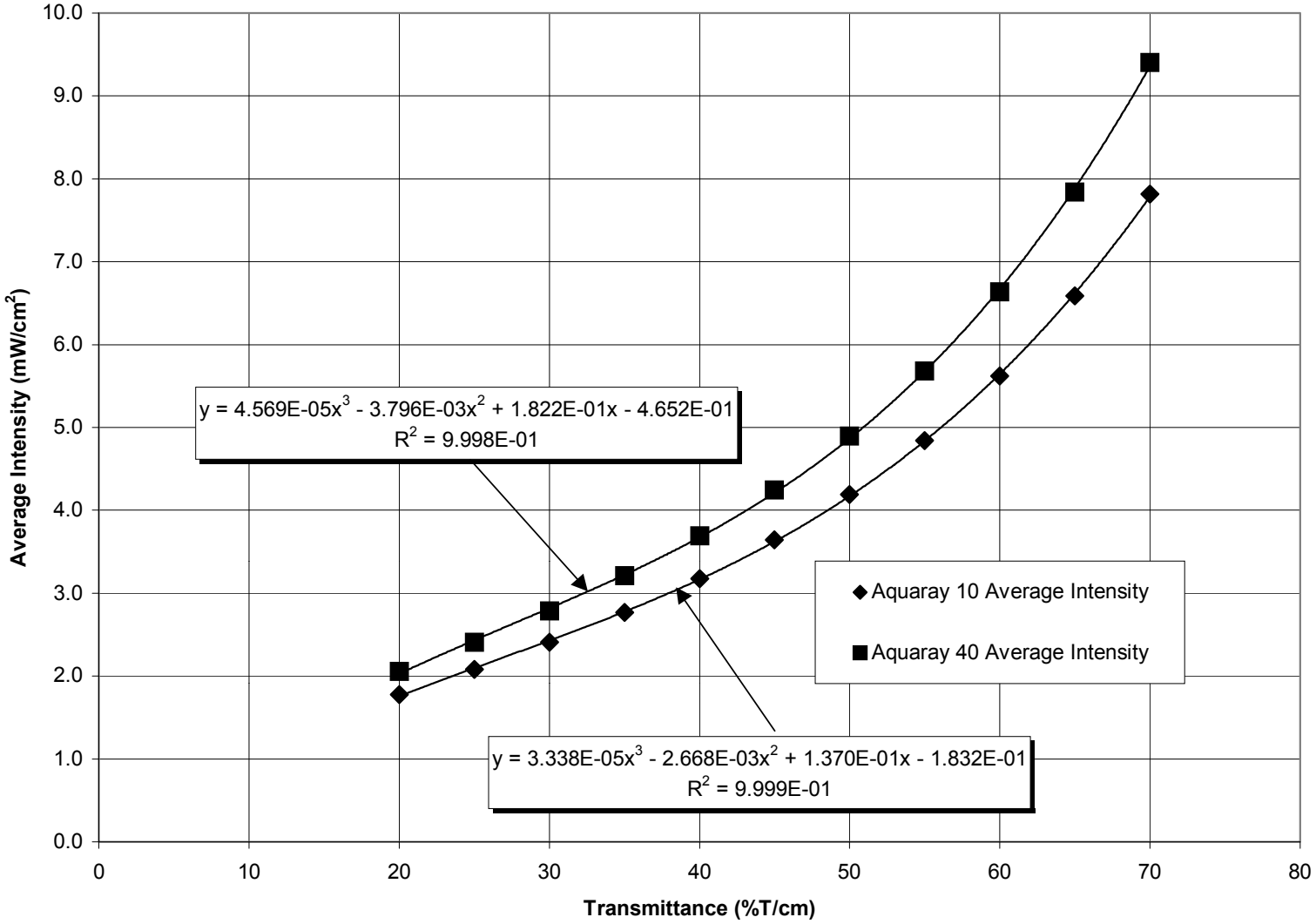

Figure 4-3. Average intensity in the Aquaray® 10 and 40 HO VLS modules as a function of transmittance.

Table 4-3. Transmittance Reduction Calculation Results

Transmittance (%T/cm)	I_{AVE} (mW/cm^2)	x 0.77
55.0	4.835	3.723
46.0	3.723	
65.0	6.616	5.095
56.7	5.095	

As a result of these calculations, the testing was performed at adjusted transmittances. For the 65%T nominal conditions, the actual transmittance was 56%; for the 55%T nominal conditions, the actual transmittance was 46%.

4.4.5.3 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 a quartz, 1 cm, path-length cell. The zero reference standard was Grade 2 laboratory deionized water (ISO, 1987).

4.4.6 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:

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

N_0 = MS2 Concentration in Undosed Sample (4-4)

N = MS2 Concentration in Dosed Sample

4.4.7 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 Unit Startup and Characterization

5.1.1 Power Consumption and Stability Measurement

5.1.1.1 Power Consumption

The power consumption of the ODI Aquaray® 10 HO VLS test system was measured at the power supply points described in Section 4.2.2.1. As the output of the system was not adjustable, these measurements represented the full-power operating conditions of the Aquaray® system.

Average power consumption measurements at the different positions of the supply are presented in Table 5-1. The measurements of the 480 V 3-phase supply (total service power) with two or three reactor modules activated resulted in the highest values for power consumption per lamp. These measurements include the auxiliary circuitry in the control panels and the slight loss of power through the step-down transformer. However, subtracting these two values results in power consumption of 163 W per lamp for one module (10 lamps). This compares favorably with the discrete power measurements taken at the 240 V lamp-module power supply with a power consumption of 166 W per lamp. Overall, the measured power consumption came very close to the 165 W specified by ODI in section 3.1.6. Subsequent discussion and power and dose normalizations will use the 166 W per lamp value.

Table 5-1. Power Consumption Measurements

Method	Lamps	Power (W)	Power per Lamp (W)
480V 3-phase supply 3 modules	30	5,260	175
480V 3-phase supply 2 modules	20	3,630	182
Difference between 3 and 2	10	1,630	163
240V 1-phase supply one module	10	1,660	166

5.1.1.2 Lamp Output Stability

The outputs of the lamps were monitored with the three built-in detectors and with the IL-1700 radiometer with the SUD240 detector, as described in Section 4.2.2.2. The power consumption of each module was also measured for each flow test. Measurements were recorded 10 min after lamp startup and at 15 minute intervals for two hours thereafter. Raw data is in Appendix C; a summary of the data is shown in Table 5-2. Summary data and calculations are presented in Appendix D.

Figure 5-1 shows that the lamp intensity measurements from the IL-1700 radiometer with the SUD240 detector were slightly different than the built-in detectors. Two of the built-in detectors show 100% intensity at the beginning (10 min), while the IL-1700 radiometer shows 88%. By either measure, lamp output is greater than 95% after 25 minutes. The lamp intensity evolution during the first 10 minutes is simplified in Figure 5-1 because the first data were acquired at 10 minutes. Separate data from ODI shows that the lamp intensity reaches 90% within the first three minutes.

Based on these lamp output measurements, the lamps were allowed two hours to warm up before the daily bioassay testing was conducted.

Table 5-2. Power Consumption and Intensity Stability Measurements

	Module Power Consumption			Intensities				Relative Intensities			
Time	P1	P2	P3	I_{SUD}	I Mod 1	I Mod 2	I Mod 3	I_{SUD}	I Mod 1	I Mod 2	I Mod 3
(min)	(kW)	(kW)	(kW)	(mW/cm^2)	(V)	(V)	(V)	(%)	(%)	(%)	(%)
0	0.00	0.00	0.00	0.00E+00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
10	1.66	1.66	1.66	3.78E-04	5.26	6.33	6.65	87.9	100.0	96.5	100.0
25	1.67	1.66	1.65	4.10E-04	5.06	6.48	6.63	95.3	96.2	98.8	99.7
40	1.67	1.66	1.65	4.16E-04	5.02	6.50	6.59	96.7	95.4	99.1	99.1
55	1.66	1.65	1.64	4.21E-04	5.11	6.38	6.29	97.9	97.1	97.3	94.6
70	1.66	1.66	1.64	4.24E-04	4.99	6.48	6.28	98.6	94.9	98.8	94.4
85	1.67	1.66	1.64	4.27E-04	5.06	6.49	6.42	99.3	96.2	98.9	96.5
100	1.67	1.67	1.67	4.29E-04	5.10	6.55	6.64	99.8	97.0	99.8	99.8
115	1.67	1.66	1.66	4.30E-04	5.02	6.56	6.52	100.0	95.4	100.0	98.0
130	1.67	1.66	1.66	4.30E-04	4.97	6.56	6.44	100.0	94.5	100.0	96.8

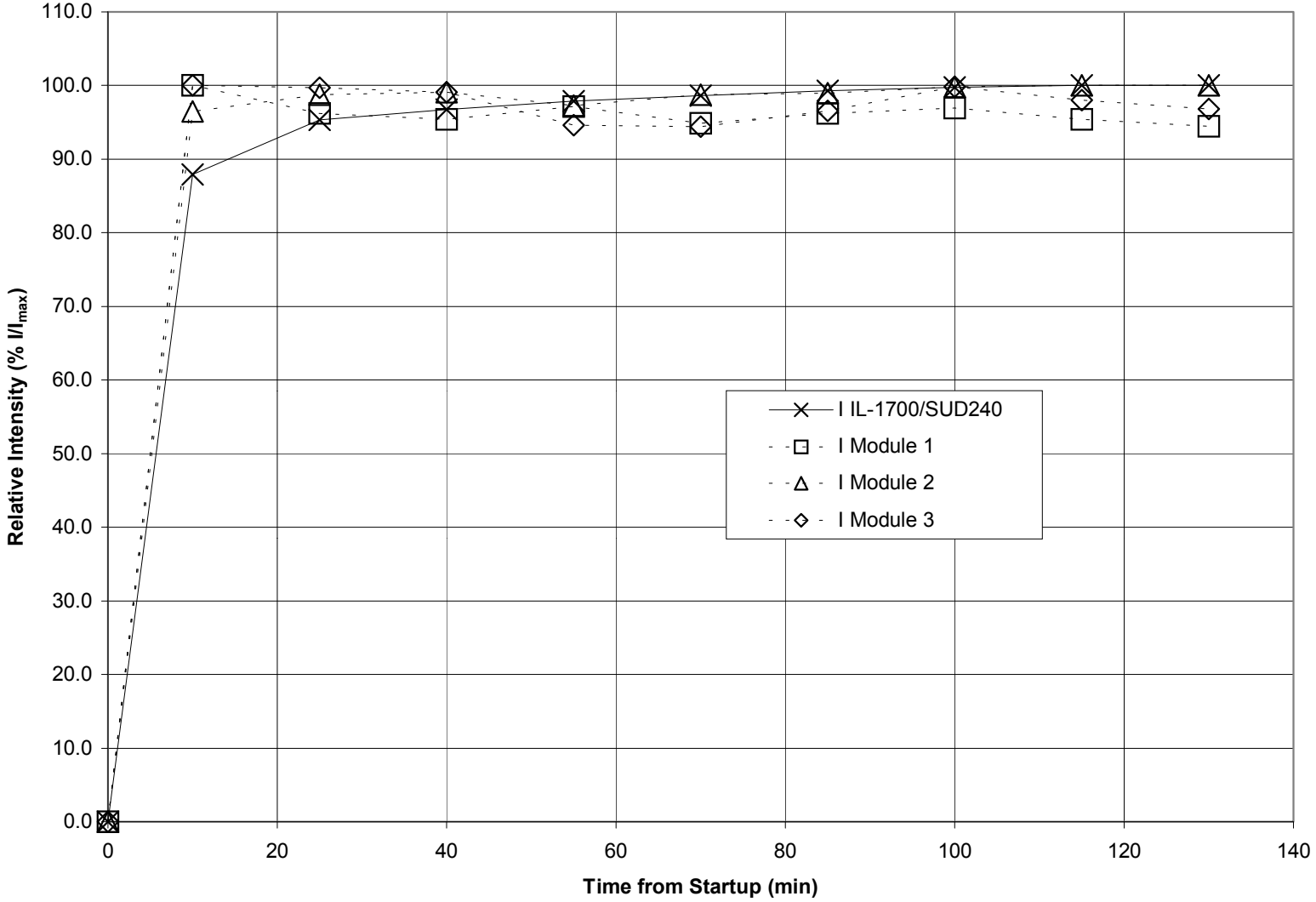

Figure 5-1. Lamp output intensity stability measurements.

5.1.2 Headloss Measurements

Headloss measurements were acquired with the method described in Section 4.2.3. Raw data and notes are in Appendix C. Summary data and calculations are presented in Appendix D. Headloss measurements were derived from the hydraulic profile data shown in Table 5-3; the data are presented graphically in Figure 5-2.

Table 5-3. Hydraulic Profile Data

Flow (L/min)	Height at 2.46 m (cm)	Height at 3.83 m (cm)	Height at 5.20 m (cm)	Height at 6.57 m (cm)	Height at 7.64 m (cm)
568	157.5	157.5	157.5	157.5	157.4
1,325	157.5	157.5	157.5	157.4	157.2
1,703	157.5	157.5	157.2	156.7	156.2
2,082	157.5	157.2	157.1	156.3	155.6
2,839	157.5	156.7	155.1	153.9	153.0

The headlosses through the system were evaluated in two ways. First, the overall headloss was calculated for the Aquaray® 10 HO VLS train (three reactor modules in series) by subtracting the water level at the 6.57 m position from the 2.46 m position for each flow rate. Then the headloss per module was determined by dividing this value by three.

The measured headlosses are presented in Table 5-4 for the Aquaray® 10 HO VLS test unit and full-scale systems. These headlosses are determined for the scaled-up flow rates applied to a train of Aquaray® 40 HO VLS modules, since test and full-scale water velocities are identical between the lamps (see Section 3.2.2).

Figure 5-3 shows that, for the Aquaray® 40 HO VLS system, the headloss was minimal until scaled-up flow rates exceeded 1.5 MGD. Figure 5-3 also shows second-order polynomial fits for the data to allow calculation of headloss (in) at any arbitrary flow (MGD). The resulting relations are:

$$3\,Module\,Headloss\,(in) = 0.154(Flow\,MGD)^2 - 0.400(Flow\,MGD) + 0.236$$

and

$$Headloss\,per\,Module\,(in) = 0.0514(Flow\,MGD)^2 - 0.133(Flow\,MGD) + 0.0787 \quad (5\text{-}1)$$

Headloss though 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:

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

Where

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

Where :

V = Velocity

ρ = Fluid Density

a = Constant for Viscous Flow Term

b = Constant for Inertial (Turbulent) Flow Term

(5-2)

Under ideal conditions, both the constants *a* and *b* should be positive. The above equations derived from Figure 5-3 have non-zero intercepts and the constant *a* is negative. This apparent non-ideality likely results from the fact that viscous losses are minimal (i.e., not measurable with the employed technique), so the negative value of *a* is compensated by the non-zero intercept. However, turbulent headlosses quickly dominate the behavior at higher flow rates. It is important to note that the headloss measured outside the lamp units provides little information about the hydraulic behavior within the lamp units.

The preceding relationships are only applicable up to the maximum flow rates validated in this verification test. For the Aquaray® 40 HO VLS system, this corresponds to a maximum flow of 11,356 L/min (4.32 MGD).

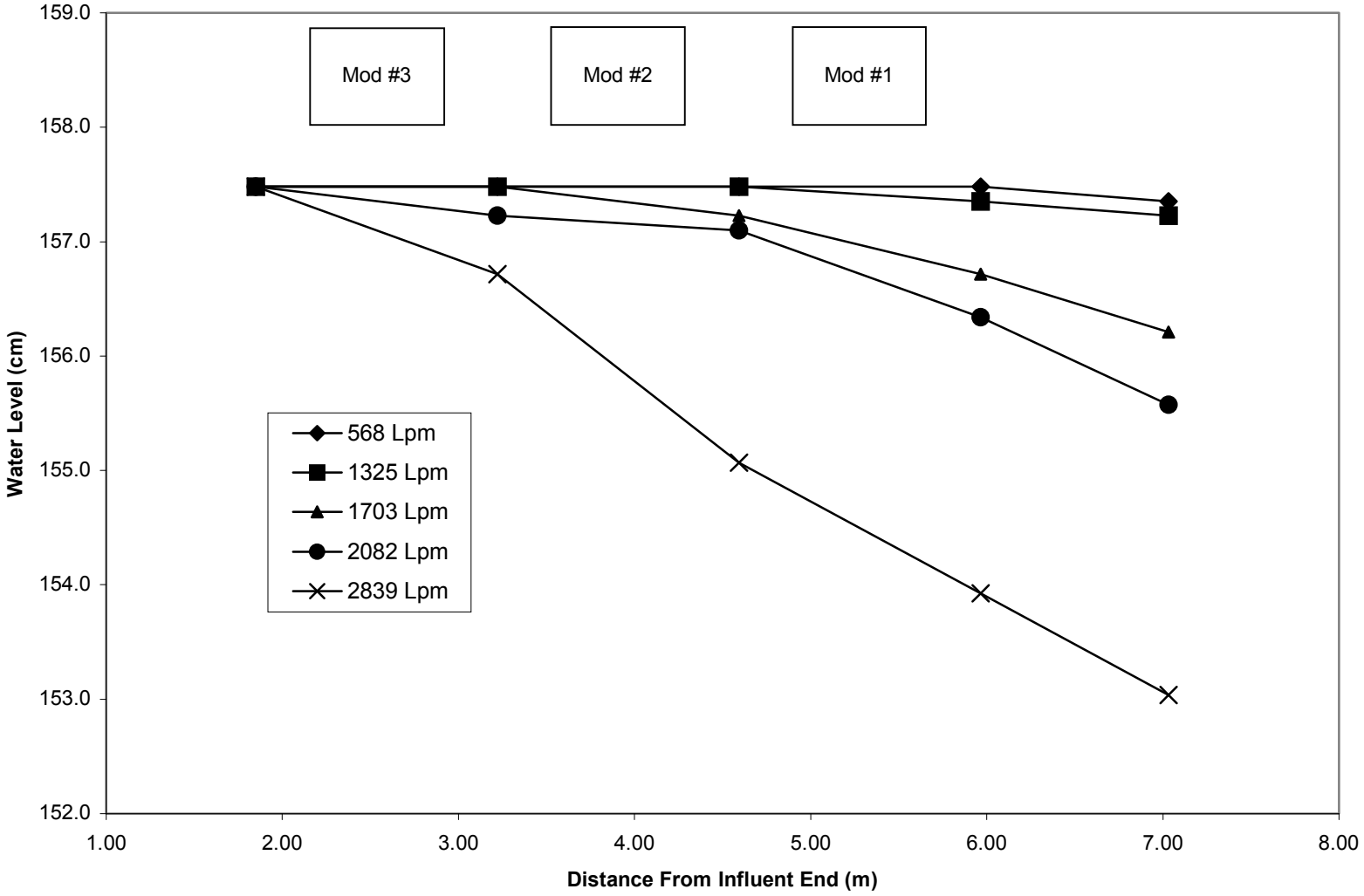

Figure 5-2. Hydraulic profile data.

Table 5-4. Headlosses for Aquaray® 10 HO VLS and Aquaray® 40 HO VLS Systems

Test System (Aquaray® 10 HO)				Train of Full-Scale Aquaray® 40 HO					
Velocity	**Flow**	**Flow**	**Flow**	**Flow**	**Flow**	**Flow**	**Headloss/ 3 Modules**	**Headloss/ Module**	**Headloss/ Module**
(cm/s)	(L/min)	(gpm)	(MGD)	(L/min)	(gpm)	(MGD)	(cm)	(cm)	(in)
3.44	568	150	0.22	2,271	600	0.86	0.00	0.00	0.000
8.02	1,325	350	0.50	5,299	1,400	2.02	0.13	0.04	0.017
10.31	1,703	450	0.65	6,814	1,800	2.59	0.76	0.25	0.100
12.60	2,082	550	0.79	8,328	2,200	3.17	1.14	0.38	0.150
17.18	2,839	750	1.08	11,356	3,000	4.32	3.56	1.19	0.467

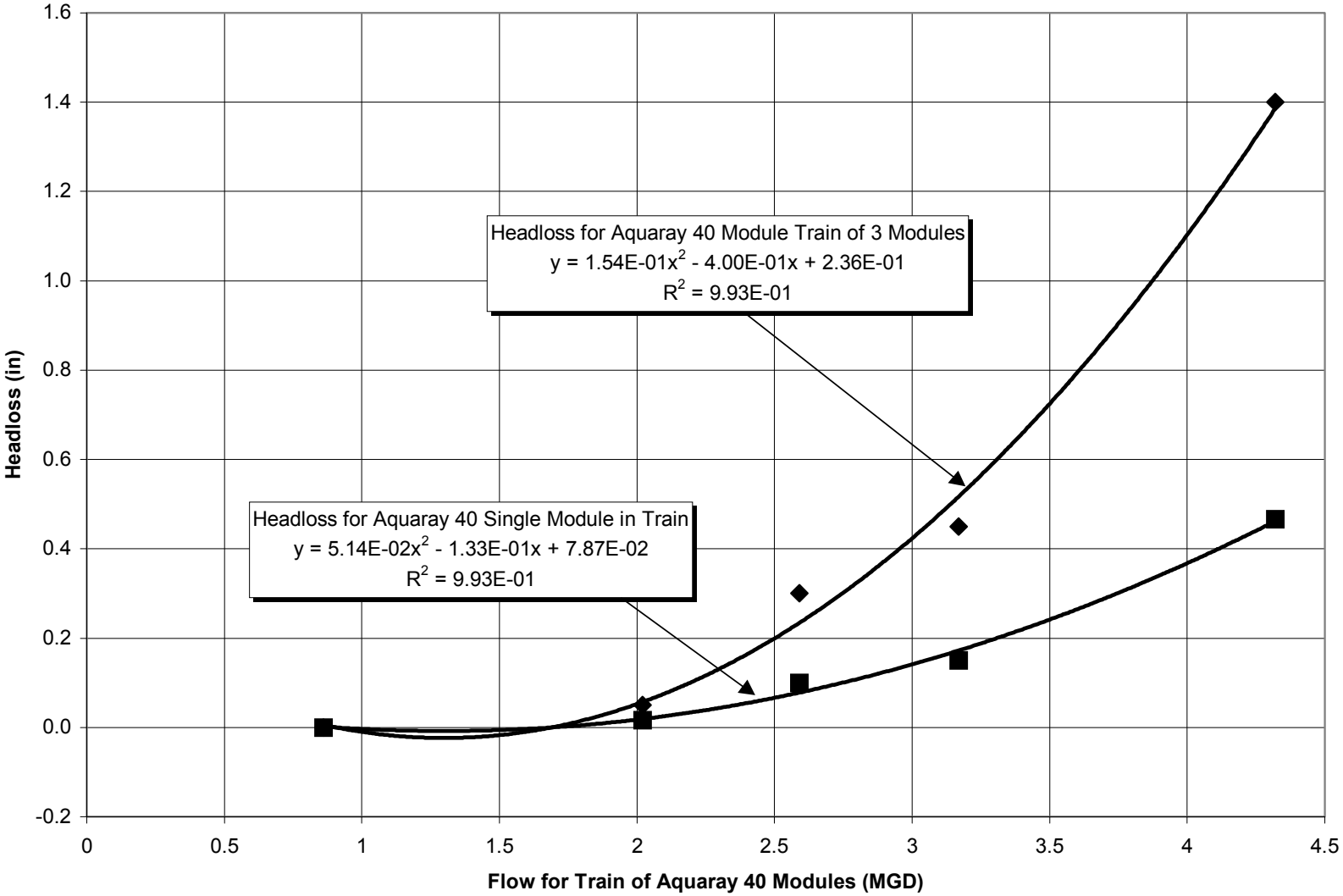

Figure 5-3. Headloss as a function of flow for train of Aquaray® 40 HO VLS modules.

5.1.3 Velocity Profile Measurements

The raw data for the 1,560 velocity profile measurements are presented in Appendix C and are summarized here. The velocity fields were measured at four locations along the channel length, at two positions across the channel width, and at 13 vertical positions (see Section 4.2.4). For each flow velocity and position, the two vertical columns of velocity measurements (13 each) were generally indistinguishable. As such, the data presented in Table 5-5 shows the average measurement at each vertical position for the triplicate flows. Thus, each velocity in Table 5-5 represents the average of six individual measurements.

Table 5-5 also includes the theoretical velocities based upon the nominal flow rate, a 17.8 cm (7 in) wide channel, and a 155 cm (61 in) water depth. The Verification Protocol (NSF, 2002) and the NWRI Reuse Protocol (NWRI and AWWARF, 2000) require all influent flow velocities to be between 0.8 and 1.2 of the theoretical value, unless an alternative velocity field can be measured and demonstrated to provide satisfactory performance. These reference values also are included in Table 5-5.

Figure 5-4 shows the velocity profiles at each location in the channel for each flow rate. In addition, the bold, vertical, dashed lines show the ± 20% range of the theoretical velocities.

Figure 5-5 shows the average flow velocity at each position and at each flow rate. Again, the theoretical velocity and the ± 20% lines are shown. See Section 7 for comparisons of influent velocity profiles with and without the mixer.

Table 5-5. Flow Velocity Profiles

Conditions		Velocities				Theoretical Velocities	
	Height	**Influent**	**#3 - #2**	**#2 - #1**	**Effluent**		
	(cm)	(cm/s)	(cm/s)	(cm/s)	(cm/s)		(cm/s)
568 L/min							
(150 gpm)	152.4	4.37	3.56	3.61	3.51		
	140.7	4.98	3.76	3.51	3.35		
	129.0	4.78	3.61	3.45	3.40		
	117.2	4.78	3.51	3.51	3.56		
	105.5	4.06	3.51	3.51	3.40		
	93.8	3.81	3.45	3.45	3.25		
	82.1	3.45	3.45	3.51	3.45		
	70.3	3.15	3.46	3.25	3.56		
	58.6	2.39	3.40	3.45	3.45		
	46.9	1.07	3.66	3.61	3.56		
	35.2	1.98	3.71	3.56	3.51	1.2*V	4.12
	23.4	1.63	3.61	3.56	3.45	V	3.44
	11.7	1.32	3.66	3.61	3.71	0.8*V	2.75
	Average:	3.21	3.56	3.51	3.47		
1,325 L/min							
(350 gpm)	152.4	11.1	8.79	8.43	8.48		
	140.7	11.1	8.69	8.33	8.33		
	129.0	11.4	8.43	8.23	8.28		
	117.2	8.28	8.33	8.23	8.33		
	105.5	8.08	8.33	8.33	8.23		
	93.8	8.84	8.28	8.13	8.28		
	82.1	8.03	8.48	8.69	8.23		
	70.3	7.77	8.38	8.28	8.08		
	58.6	6.60	8.18	8.03	8.13		
	46.9	3.30	7.87	7.87	7.42		
	35.2	4.32	7.82	8.18	7.92	1.2*V	9.62
	23.4	0.10	7.98	7.82	7.62	V	8.02
	11.7	-0.71	7.82	7.82	7.42	0.8*V	6.41
	Average:	6.78	8.26	8.18	8.06		

1,703 L/min							
(450 gpm)	152.4	18.7	10.7	10.6	10.7		
	140.7	20.4	10.6	10.4	10.6		
	129.0	20.9	10.7	10.5	10.3		
	117.2	18.1	11.3	10.8	10.6		
	105.5	16.4	10.8	10.6	10.5		
	93.8	13.2	10.7	10.7	10.5		
	82.1	10.6	11.0	10.9	11.1		
	70.3	5.23	11.0	10.8	10.5		
	58.6	2.84	11.1	10.8	10.8		
	46.9	0.46	9.50	10.5	10.4		
	35.2	0.30	10.8	10.6	10.5	1.2*V	12.3
	23.4	-1.02	10.5	10.6	10.6	V	10.3
	11.7	-1.47	10.6	10.5	10.6	0.8*V	8.24
	Average:	9.58	10.7	10.6	10.6		
2,082 L/min							
(550 gpm)	152.4	15.3	12.9	12.7	13.4		
	140.7	13.3	12.7	12.8	13.3		
	129.0	13.3	12.6	12.6	13.1		
	117.2	12.7	12.8	12.7	13.3		
	105.5	13.3	12.7	12.4	13.2		
	93.8	13.2	12.6	12.7	13.1		
	82.1	13.2	13.2	12.8	13.1		
	70.3	11.8	13.0	12.8	13.2		
	58.6	10.2	12.6	12.7	12.9		
	46.9	9.35	12.4	13.0	12.9		
	35.2	7.06	12.3	11.6	13.0	1.2*V	15.1
	23.4	3.56	12.0	12.6	12.7	V	12.6
	11.7	-2.44	11.5	12.6	12.7	0.8*V	10.1
	Average:	10.3	12.6	12.6	13.1		

2,839 L/min							
(750 gpm)	152.4	19.1	17.4	17.6	17.3		
	140.7	17.4	17.5	17.4	17.2		
	129.0	18.0	17.5	17.3	17.2		
	117.2	17.9	17.7	17.4	17.3		
	105.5	17.5	17.9	17.6	17.0		
	93.8	18.2	17.6	17.7	17.2		
	82.1	17.9	17.5	17.5	17.2		
	70.3	17.4	18.0	17.5	17.2		
	58.6	19.3	17.6	17.6	17.0		
	46.9	17.2	17.2	17.3	17.3		
	35.2	13.9	16.1	16.8	17.5	1.2*V	20.6
	23.4	2.13	14.6	16.9	17.2	V	17.2
	11.7	-3.56	14.3	16.7	17.2	0.8*V	13.7
	Average:	14.8	17.0	17.3	17.2		

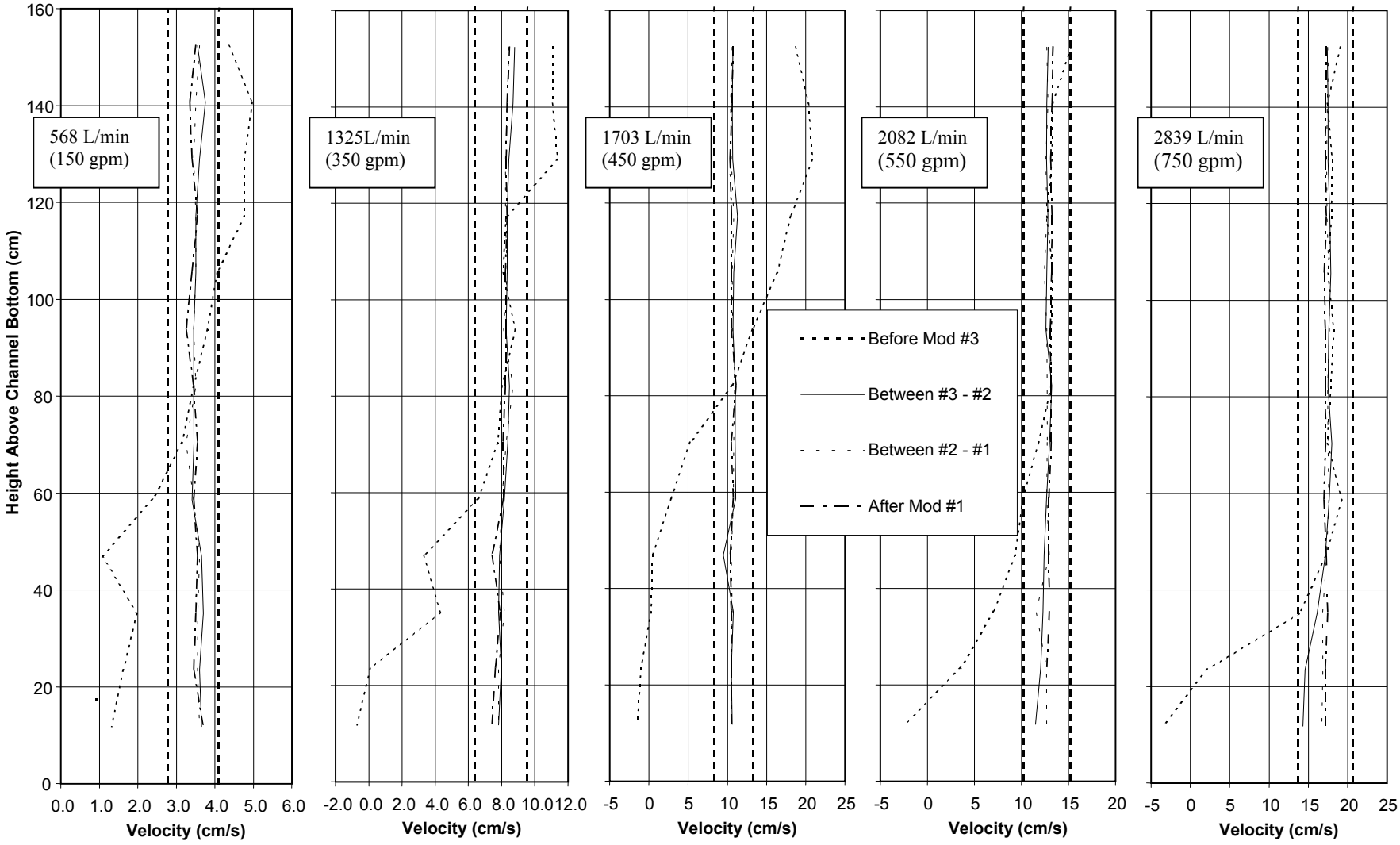

Figure 5-4. Flow velocity profiles for Aquaray® 10 HO VLS channel. (Velocity -cm/s, Height - cm).

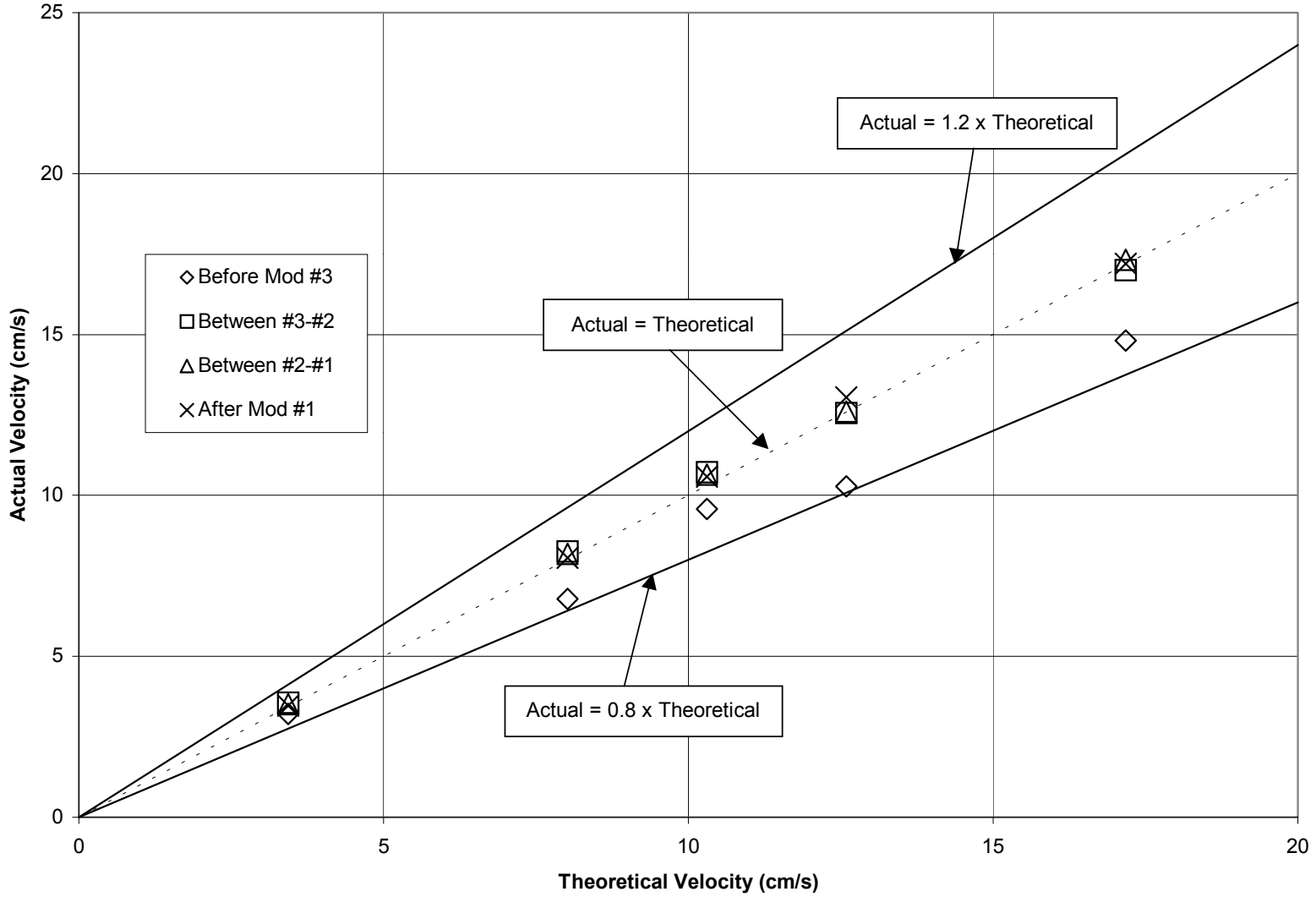

Figure 5-5. Comparison of actual and theoretical flow velocities at each channel position.

The data in Table 5-5 and Figure 5-4 show that the influent velocity profile at all flow rates had a significantly non-uniform character. In the other three downstream positions, the velocity profiles were quite uniform and are well within ± 20% of the theoretical flow rates. Figure 5-5 shows that the three downstream positions had average velocities that closely follow the theoretical expectations. In contrast, Figure 5-5 shows that the average velocity of the influent position was consistently low. Such a condition is not possible when mass balance considerations are made, but this probably reflects the difficulty of accurately measuring highly non-uniform profiles. A velocity profile measured with greater vertical resolution would likely have an average velocity that more closely follows the theoretical value.

The non-uniform influent velocity profile resulted from the inlet geometry of the test system where the water was piped into the bottom of the channel and then spilled over the short influent baffle. This introduced a large-scale rolling motion in the influent part of the channel, which manifested itself with low (or negative) velocities at the bottom and higher velocities at the top. This condition exists in disinfection systems with vertical lamps in narrow channels because the inlet water masses are not strongly coupled to the lamps in a vertical direction (as with horizontally oriented lamps). In effect, the water can "slide" vertically up or down the first row of lamps. This allows for the easy vertical movement of water, which can compromise the uniformity of the influent velocity profiles.

The influent velocity profiles are a key part of this verification test because they provide a reference condition for full-scale installations. It is the philosophy of the ETV and NWRI testing program, upon which this reuse verification test was designed, to simulate the worst-case scenario in terms of lamp fouling, lamp intensity, and transmittance for each application. Thus, the Aquaray® 10 HO VLS system design did not attempt to idealize the influent hydraulics of the test system used for validation. Because it is necessary to demonstrate that the Aquaray® 40 HO VLS full-scale systems will have hydraulic profiles that are equal to or better than the test system, it was the goal of this verification to complete the testing on a test system that has hydraulic profiles equal to or worse than those for the full-scale system.

The key performance effect of a non-uniform influent velocity profile should be to degrade the performance of the first reactor module. However, this did not appear to be the case for the Aquaray® 10 HO VLS system, as the dose delivery data showed. See Section 5.3.5.

5.2 MS2 Dose-Response Calibration Curve

5.2.1 Dose-Response Results

A total of 23 dose-responses were conducted during this verification test. Thirteen were considered valid, four were used for QA/QC validation purposes, and six were excluded for QA/QC purposes (see Section 6.2.2). All raw data are included Appendix C.

Data from the 13 valid dose-responses conducted on the MS2 bacteriophage batch used during this verification test are shown in Table 5-6. This valid data includes nine dose-response runs in 46%T challenge water, and four in 56%T challenge water. The greater number of dose-responses conducted in the 46%T challenge waters reflects the greater number of flow tests

conducted with the 46%T waters. This valid dose-response data set contains 48 valid dose-response measurements.

At some doses, the survival ratios at a given dose vary up to 0.5 log units. This variability is typical for such microbiological analyses. It highlights the need for several dose-response data sets to enhance the statistical confidence of the dose-response calibration curve. In this case, the variability is greatest at low doses (< 20 mJ/cm^2). See Section 6 for the QA/QC discussion.

5.2.2 Dose-Response Calibration Curve

The dose-response calibration curve used for the dose flow assays is based entirely on the 13 valid dose-response sequences conducted on challenge waters. 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 fitting a second-order polynomial, and allows the determination of a dose at arbitrary survival ratios.

$$Dose = 1.4822(Survival)^2 - 15.063(Survival) - 0.1633$$

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

N_0 = MS2 Concentration in Undosed Sample

N = MS2 Concentration in Dosed Sample

(5-3)

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

Table 5-6. Valid Dose-Response Data for MS2

Identifier	Flow Series (Day)	Nominal Dose[1]:		10	20	30	40	60	80	100
		%T (%/cm)	Matrix	Dose, Survival	Dose, Survival	Dose, Survival	Dose, Survival	Dose, Survival	Dose, Survival	Dose, Survival
DRS1	1	43.8	(2)	9.8, -0.72	19.6, -1.09	--	--	59.0, -2.97	78.7, -3.80	--
DRS5	5	46.7	(2)	9.9, -0.50	20.0, -1.23	--	39.9, -2.15	59.9, -3.01	79.8, -3.63	--
DRS6	6	54.4	(3)	--	20.1, -1.23	--	40.1, -2.25	--	80.1, -3.98	--
DRS7	7	44.4	(2)	--	19.9, -1.12	--	39.7, -2.16	--	79.5, -3.60	--
DRS8	8	57.0	(3)	10.0, -0.61	20.0, -1.29	--	40.0, -2.34	60.0, -3.12	--	--
DRS9	9	46.5	(2)	10.0, -0.67	20.0, -1.28	--	40.0, -2.21	60.0, -3.24	--	100.0, -4.52
DRS10	10	57.2	(3)	10.0, -0.51	--	30.0, -1.60	--	60.0, -2.95	--	--
DRS11	11	46.1	(2)	10.0, -0.90	--	--	--	59.8, -3.05	--	--
DRS13	13	46.2	(2)	10.1, -0.71	--	--	--	60.1, -3.04	--	--
DRS15	15	46.6	(2)	10.0, -0.29	--	29.8, -1.58	39.7, -2.11	--	79.5, -4.00	99.3, -4.52
DRS16	16	46.3	(2)	10.0, -0.95	--	30.0, -1.80	--	59.9, -2.93	--	--
DRS17	17	44.8	(2)	10.0, -0.65	19.9, -1.20	--	--	59.9, -2.99	80.0, -3.81	--
DRS18	18	55.5	(3)	10.0, -0.70	--	30.1, -1.76	40.2, -2.30	--	80.4, -4.08	100.5, -4.65

(1) Dose in mJ/cm^2; (2) Filtered Effluent + Coffee; (3) Potable water + Sodium Thiosulfate + Coffee.

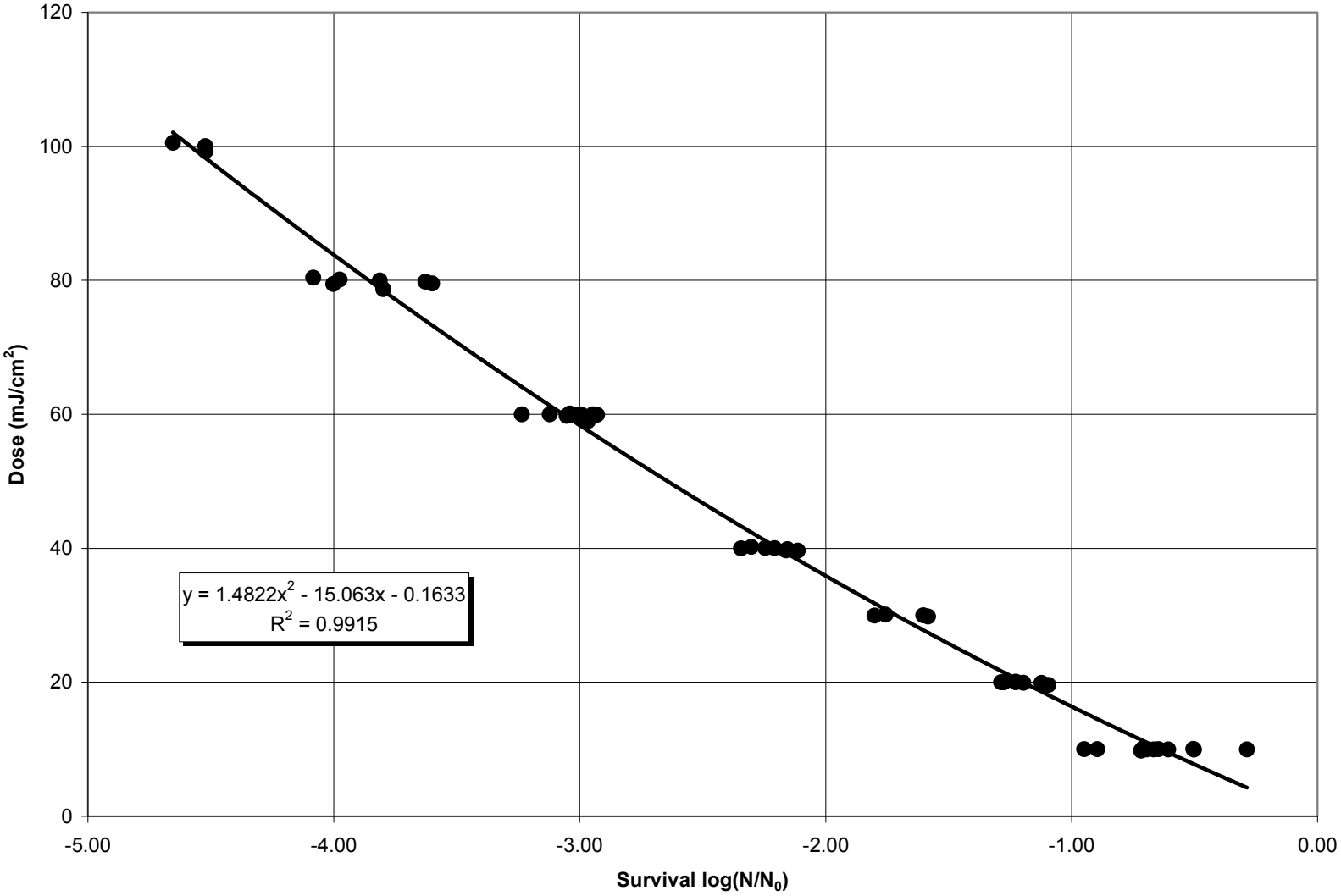

Figure 5-6. Dose-Response calibration curve for the MS2 batch used for this verification test.

5.3 Dose Flow Assays

5.3.1 Flow Test Summary

The flow rates tested in the Aquaray® 10 HO VLS reactor modules are summarized in Table 5-7, along with the equivalent flow rates for the reactor modules of the full-scale Aquaray® 40 HO VLS system. This verification test consisted of three independent bioassays: one at 65%T nominal (56%T actual) with three reactor modules, one at 55%T nominal (46%T actual) with three reactor modules, and one at 55%T nominal (46%T actual) with two reactor modules. For clarification, the two-module bioassay data in the following tables and graphs are designated with a suffix of "M."

Some early flow tests were conducted with samples collected in intermediate positions between the reactor modules with simultaneous effluent samples; thus, one set of actual flow conditions resulted in two or three dosed sample sets. For the following flow-inventory discussion, each set of dosed samples resulting in a survival ratio is defined as a "flow test."

A total of 115 flow tests were conducted during this verification test. The 71 valid flow tests were conducted over a period of 13 days and are summarized in Table 5-8. Forty-one flow tests were excluded for QA/QC reasons discussed in Section 6.3.3 or were initial shakedown experiments. Finally, three no-dose controls were also completed (see Section 6.3.2). All raw data and notes are included in Appendix C.

Table 5-7. Flow Rates for This Verification Test

Test Unit Aquaray® 10 HO		**Train of full-scale Aquaray® 40 HO**		
(L/min)	(gpm)	(L/min)	(gpm)	(MGD)
568	150	2,271	600	0.86
1,325	350	5,299	1,400	2.02
1,703	450	6,814	1,800	2.59
2,082	550	8,328	2,200	3.17
2,839	750	11,356	3,000	4.32

Table 5-8. Summary of Valid Bioassay Flow Tests

Date	Test Day	Target %T (%T/cm)	Actual %T (%T/cm)	N_0 (pfu/mL)	Flows (L/min)
11/7/02	1	46	44.0	$2.8x10^6$	568; 1,325; 1,703; 2,082; 2,839
12/10/02	5	46	46.9	$1.5x10^6$	568; 1,325; 1,703; 2,082; 2,839
12/15/02	6	56	55.0	$1.6x10^6$	568; 1,325; 1,325; 1,703; 2,082
12/15/02	7	46	44.9	$1.0x10^6$	568; 1,325; 568M, 1,325M; 1,703M
12/17/02	8	56	54.8	$1.6x10^6$	568; 1,325; 1,703; 2,082
12/17/02	9	46	46.5	$1.2x10^6$	1,703; 2,082; 568M; 2,082M; 2,082M; 2,839M
12/19/02	10	56	55.7	$1.3x10^6$	568; 1,325; 1,703; 2,082; 2,082; 2,839
12/19/02	11	46	46.4	$1.3x10^6$	2,839; 568; 568; 1,325M; 1,703M; 2,082M
12/21/02	13	46	46.8	$1.1x10^6$	1,325; 1,703; 568M; 1,325M; 2,839M; 2,839M
1/7/03	15	46	46.8	$1.7x10^6$	1,325; 2,839M; 568M; 1,325M; 1,703M; 1,703M
1/7/03	16	46	46.4	$1.2x10^6$	1,703; 2,082M; 2,839M; 568M; 1,325M; 1,703M
1/9/03	17	46	44.0	$1.4x10^6$	2,082; 2,839; 1,325; 2,082M; 2,818M
1/10/03	18	56	55.5	$1.5x10^6$	568; 1,325; 1,703; 2,082; 2,839; 2,839

Note: Flows designated with "M" were conducted with the farthest downstream reactor module (#1) turned off.

5.3.2 Data Reduction and Results

Table 5-9 shows the results for the valid flow tests, along with a statistical analysis. All raw data are included in Appendix C. Summary tables and calculations are presented in Appendix D.

For each flow test, the titers of three influent samples were geometrically averaged to calculate the undosed MS2 concentration (N_0). Then the titers of each of the three effluent samples (N) were used to calculate the three survival ratios, log (N/N_0). 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 approximately 12-15 delivered dose estimates (see Table 5-9). The Verification Protocol requires that these data be analyzed statistically for a 75% 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:

σ = Standard Deviation

$\alpha = 0.25$

n = Number of Measurements

$\upsilon = n - 1$

t = Students t - Test Distribution

(5-4)

The individual doses are plotted, along with the 75% confidence intervals, in Figures 5-7 through 5-9. In Section 5.3.5, the 55%T nominal data will be combined for a final 75% C.I. calculation. The data is summarized in Figure 5-10.

At the low flow rate (568 L/min), the data were generally more variable, as is often seen in such low-flow, high-dose bioassays. This flow rate is the lower design limit of the test unit.

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

Conditions	Day	Survival ($\log(N/N_0)$)	Dose (mJ/cm^2)	Dose Statistics (mJ/cm^2)	
568 L/min, 65%T (56%T Actual)					
(150 gpm)	Day 6	-3.68	75.3	STDEV:	7.34
		-3.61	73.5	MEAN:	74.26
		-3.59	73.0	75%C.I.:	2.57
	Day 8	-3.63	74.0	C.I. Hi:	76.83
		-3.41	68.4	C.I. Low:	71.69
		-3.55	72.0		
	Day 10	-3.26	64.7		
		-3.36	67.2		
		-3.37	67.4		
	Day 18	-4.03	84.6		
		-4.00	83.8		
		-4.12	87.1		
1,325 L/min, 65%T (56%T Actual)					
(350 gpm)	Day 6	-3.03	59.1	STDEV:	2.54
		-2.99	58.1	MEAN:	57.93
		-2.99	58.1	75%C.I.:	0.79
	Day 6	-2.76	52.7	C.I. Hi:	58.72
		-2.83	54.3	C.I. Low:	57.15
		-2.85	54.8		
	Day 8	-3.13	61.5		
		-3.12	61.3		
		-3.02	58.8		
	Day 10	-2.95	57.2		
		-3.07	60.0		
		-3.07	60.0		
	Day 18	-3.04	59.3		
		-2.94	56.9		
		-2.93	56.7		

1,703 L/min, 65%T (56%T Actual)					
(450 gpm)	Day 6	-2.57	48.3	STDEV:	2.19
		-2.73	52.0	MEAN:	50.31
		-2.78	53.2	75%C.I.:	0.77
	Day 8	-2.47	46.1	C.I. Hi:	51.08
		-2.64	49.9	C.I. Low:	49.54
		-2.67	50.6		
	Day 10	-2.76	52.7		
		-2.76	52.7		
		-2.65	50.2		
	Day 18	-2.64	49.9		
		-2.67	50.6		
		-2.53	47.4		
2,082 L/min, 65%T (56%T Actual)					
(550 gpm)	Day 6	-2.43	45.2	STDEV:	1.63
		-2.47	46.1	MEAN:	44.86
		-2.37	43.9	75%C.I.:	0.51
	Day 8	-2.30	42.3	C.I. Hi:	45.36
		-2.43	45.2	C.I. Low:	44.35
		-2.34	43.2		
	Day 10	-2.46	45.9		
		-2.47	46.1		
		-2.54	47.7		
	Day 10	-2.51	47.0		
		-2.41	44.7		
		-2.47	46.1		
	Day 18	-2.33	43.0		
		-2.32	42.8		
		-2.37	43.9		

2,839 L/min, 65%T (56%T Actual)					
(750 gpm)	Day 10	-2.02	36.3	STDEV:	1.11
		-2.00	35.9	MEAN:	35.20
		-2.06	37.2	75%C.I.:	0.46
	Day 18	-1.96	35.1	C.I. Hi:	35.65
		-1.98	35.5	C.I. Low:	34.74
		-1.90	33.8		
	Day 18	-1.94	34.6		
		-1.92	34.2		
		-1.92	34.2		
568 L/min, 55%T (46%T Actual)					
(150 gpm)	Day 1	-3.63	74.0	STDEV:	6.03
		-3.71	76.1	MEAN:	63.85
		-3.67	75.1	75%C.I.:	1.87
	Day 5	-3.23	64.0	C.I. Hi:	65.72
		-3.22	63.7	C.I. Low:	61.98
		-3.05	59.6		
	Day 7	-2.96	57.4		
		-3.12	61.3		
		-3.11	61.0		
	Day 11	-3.08	60.3		
		-3.11	61.0		
		-3.05	59.6		
	Day 11 rep	-3.13	61.5		
		-3.13	61.5		
		-3.14	61.7		

1,325 L/min, 55%T (46%T Actual)					
(350 gpm)	Day 1	-2.06	37.2	STDEV:	5.83
		-2.61	49.2	MEAN:	41.51
	Day 5	-2.38	44.1	75%C.I.:	1.69
		-2.46	45.9	C.I. Hi:	43.20
		-2.50	46.8	C.I. Low:	39.82
	Day 7	-2.54	47.7		
		-2.73	52.0		
		-2.54	47.7		
	Day 13	-2.22	40.6		
		-2.20	40.1		
		-2.11	38.2		
	Day 15	-2.12	38.4		
		-2.07	37.4		
		-2.15	39.1		
	Day 17	-1.96	35.1		
		-1.88	33.4		
		-1.86	33.0		
1,703 L/min, 55%T (46%T Actual)					
(450 gpm)	Day 1	-2.03	36.5	STDEV:	3.72
		-2.29	42.1	MEAN:	37.33
		-2.12	38.4	75%C.I.:	1.15
	Day 5	-2.27	41.7	C.I. Hi:	38.48
		-2.27	41.7	C.I. Low:	36.17
		-2.32	42.8		
	Day 9	-1.96	35.1		
		-2.12	38.4		
		-2.04	36.7		
	Day 13	-1.98	35.5		
		-2.08	37.6		
		-2.06	37.2		
	Day 16	-1.71	29.9		
		-1.81	32.0		
		-1.93	34.4		

2,082 L/min, 55%T (46%T Actual)					
(550 gpm)	Day 1	-1.87	33.2	STDEV:	4.15
		-1.94	34.6	MEAN:	33.76
		-1.87	33.2	75%C.I.:	1.45
	Day 5	-2.07	37.4	C.I. Hi:	35.21
		-1.98	35.5	C.I. Low:	32.31
		-2.00	35.9		
	Day 9	-2.09	37.8		
		-2.10	38.0		
		-2.01	36.1		
	Day 17	-1.41	24.0		
		-1.69	29.5		
		-1.71	29.9		
2,839 L/min, 55%T (46%T Actual)					
(750 gpm)	Day 1	-1.52	26.2	STDEV:	1.19
		-1.69	29.5	MEAN:	27.46
		-1.60	27.7	75%C.I.:	0.42
	Day 5	-1.60	27.7	C.I. Hi:	27.87
		-1.63	28.3	C.I. Low:	27.04
		-1.61	27.9		
	Day 11	-1.54	26.5		
		-1.58	27.3		
		-1.66	28.9		
	Day 17	-1.56	26.9		
		-1.47	25.2		
		-1.57	27.1		

568 L/min, 55%T (46%T Actual)					
(150 gpm)	Day 7	-2.69	51.1	STDEV:	8.44
(2 modules)		-2.73	52.0	MEAN:	43.26
		-2.79	53.4	75%C.I.:	2.62
	Day 9	-2.76	52.7	C.I. Hi:	45.88
		-2.64	49.9	C.I. Low:	40.65
		-2.63	49.7		
	Day 13	-2.04	36.7		
		-2.11	38.2		
		-2.11	38.2		
	Day 15	-2.51	47.0		
		-2.39	44.3		
		-2.35	43.4		
	Day 16	-1.68	29.3		
		-1.75	30.7		
		-1.82	32.2		
1,325 L/min, 55%T (46%T Actual)					
(350 gpm)	Day 7	-1.92	34.2	STDEV:	3.18
(2 modules)		-1.95	34.8	MEAN:	30.55
		-1.81	32.0	75%C.I.:	0.98
	Day 11	-1.92	34.2	C.I. Hi:	31.54
		-1.86	33.0	C.I. Low:	29.57
		-1.90	33.8		
	Day 13	-1.67	29.1		
		-1.71	29.9		
		-1.66	28.9		
	Day 15	-1.79	31.5		
		-1.74	30.5		
		-1.64	28.5		
	Day 16	-1.56	26.9		
		-1.51	26.0		
		-1.45	24.8		

1,703 L/min, 55%T (46%T Actual)					
(450 gpm)	Day 7	-1.57	27.1	STDEV:	3.40
(2 modules)		-1.56	26.9	MEAN:	26.07
		-1.64	28.5	75%C.I.:	1.05
	Day 11	-1.74	30.5	C.I. Hi:	27.12
		-1.78	31.3	C.I. Low:	25.02
		-1.85	32.8		
	Day 15	-1.38	23.4		
		-1.38	23.4		
		-1.49	25.6		
	Day 15 rep	-1.47	25.2		
		-1.40	23.8		
		-1.46	25.0		
	Day 16	-1.32	22.3		
		-1.34	22.7		
		-1.32	22.3		
2,082 L/min, 55%T (46%T Actual)					
(550 gpm)	Day 9	-1.29	21.7	STDEV:	2.93
(2 modules)		-1.34	22.7	MEAN:	21.97
		-1.44	24.6	75%C.I.:	0.91
	Day 9 rep	-1.37	23.3	C.I. Hi:	22.88
		-1.34	22.7	C.I. Low:	21.06
		-1.26	21.2		
	Day 11	-1.28	21.5		
		-1.24	20.8		
		-1.21	20.2		
	Day 16	-1.22	20.4		
		-1.20	20.0		
		-1.20	20.0		
	Day 17	-1.77	31.1		
		-1.17	19.5		
		-1.18	19.7		

2,839 L/min, 55%T (46%T Actual)					
(750 gpm)	Day 9	-1.01	16.6	STDEV:	0.98
(2 modules)		-1.09	18.0	MEAN:	17.55
		-1.06	17.5	75%C.I.:	0.27
	Day 13	-1.11	18.4	C.I. Hi:	17.83
		-1.15	19.1	C.I. Low:	17.28
		-1.11	18.4		
	Day 13	-1.04	17.1		
		-1.13	18.8		
		-1.07	17.7		
	Day 15	-1.07	17.7		
		-1.13	18.8		
		-1.01	16.6		
	Day 16	-1.02	16.7		
		-0.94	15.3		
		-1.02	16.7		
	Day 17	-1.10	18.2		
		-1.03	16.9		
		-1.07	17.7		

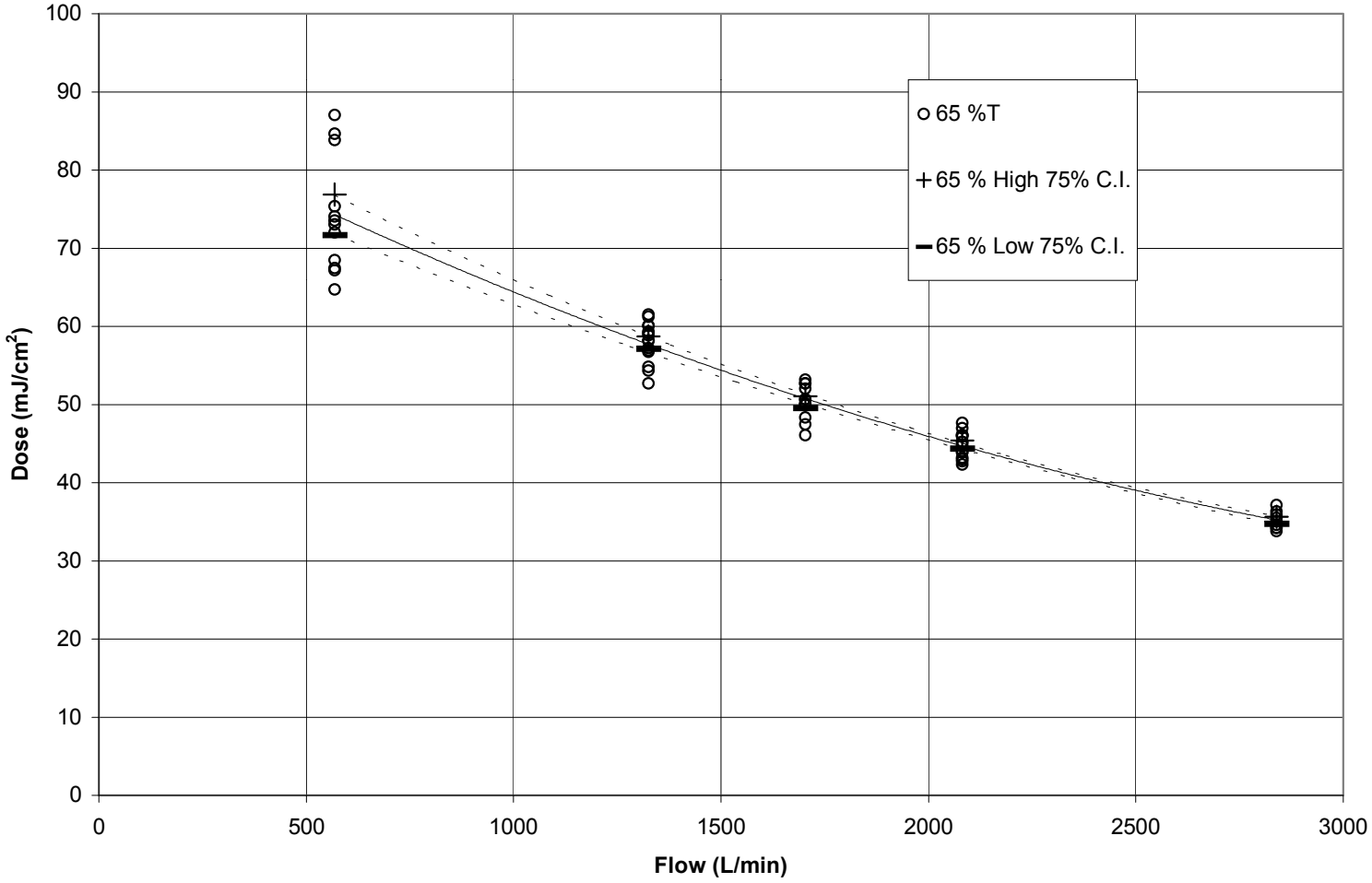

Figure 5-7. Dose delivery for 65%T (56%T actual), 3 Module Aquaray® 10 HO VLS system.

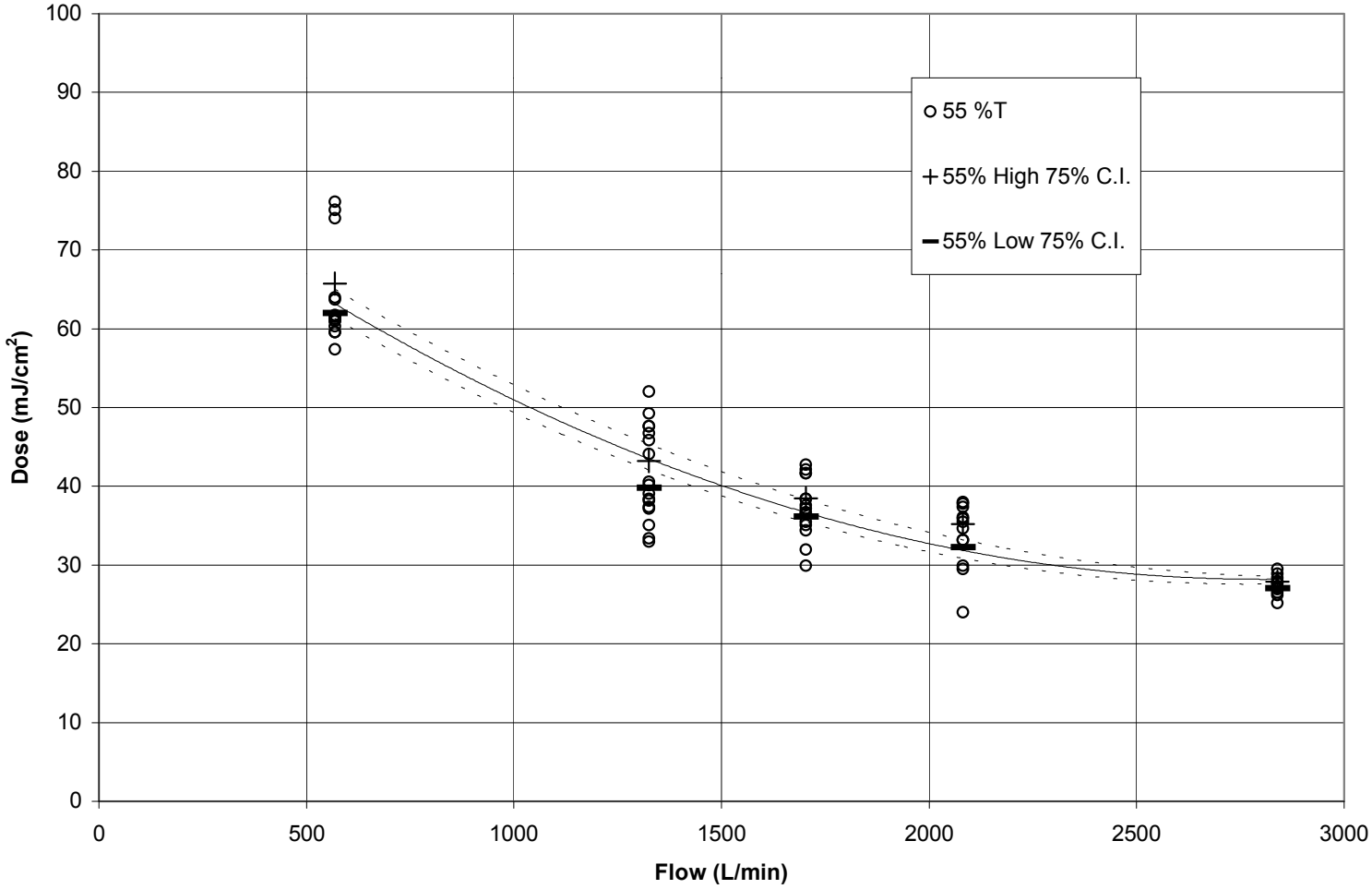

Figure 5-8. Dose delivery for 55%T (46%T actual), 3 Module Aquaray® 10 HO VLS system.

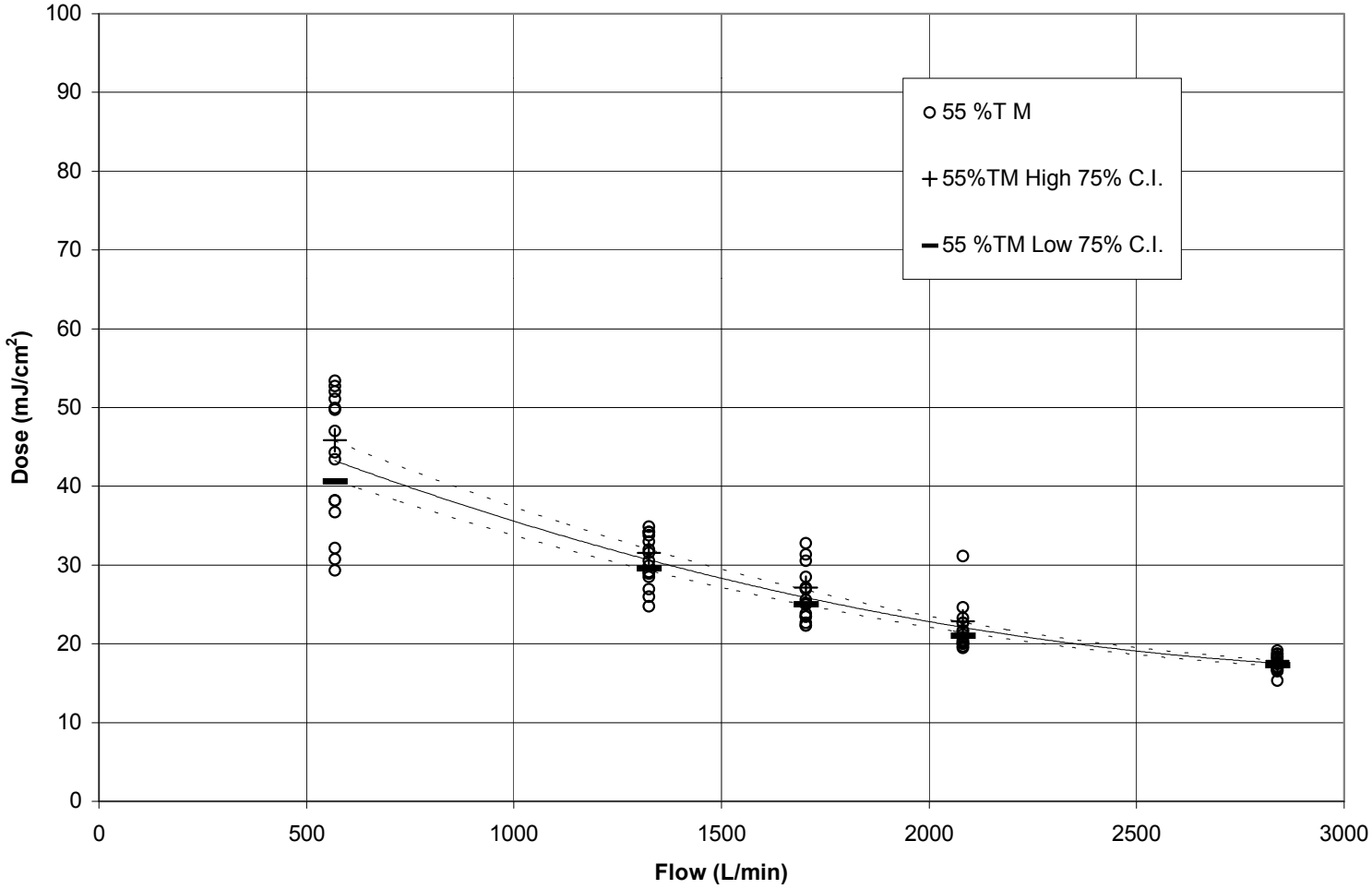

Figure 5-9. Dose delivery for 55%T (46%T actual), 2 Module Aquaray® 10 HO VLS system.

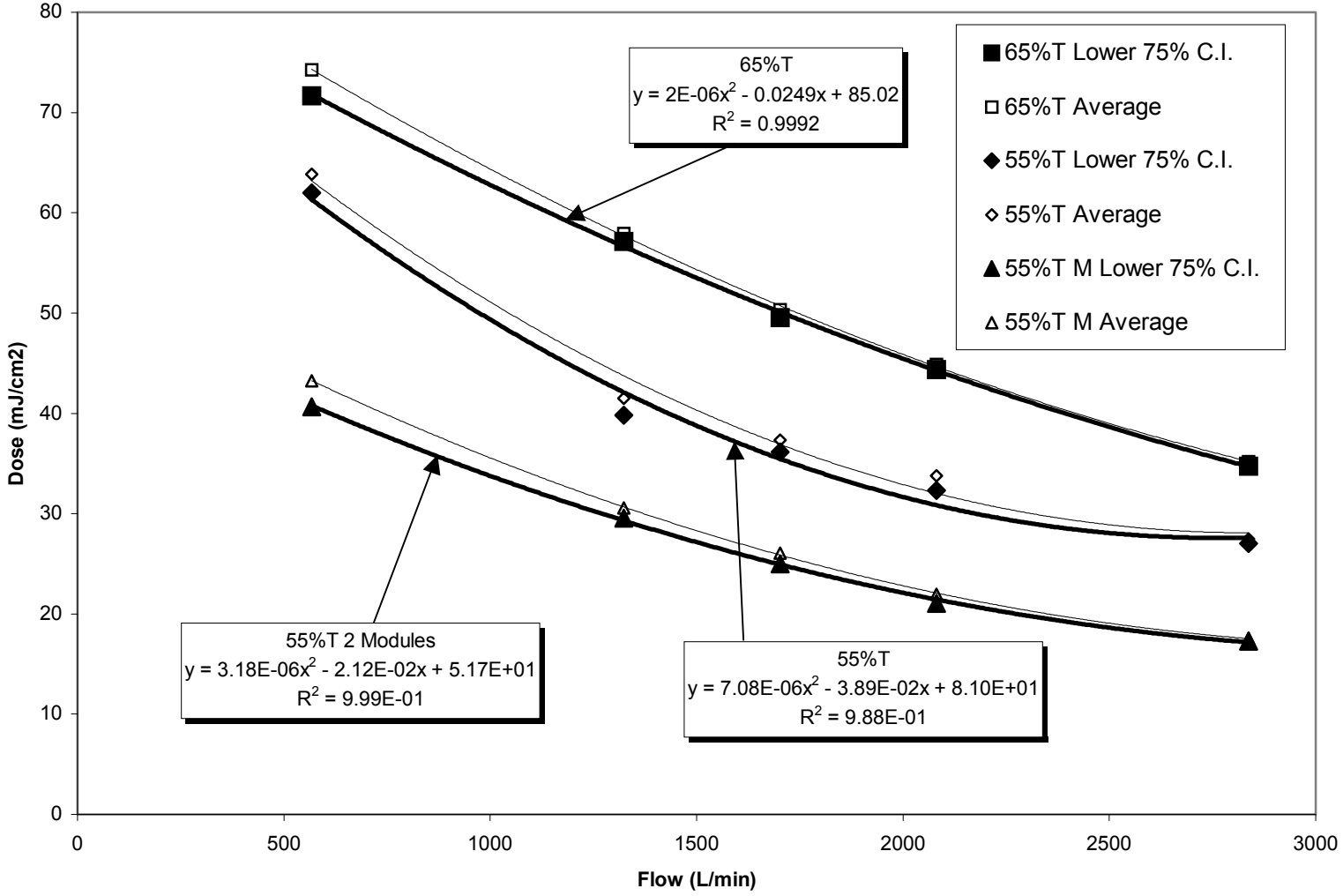

Figure 5-10. Dose delivery curves based on lower 75% confidence intervals.

5.3.3 Detector Measurements

Before sampling commenced for each flow test, the detector readings for all three modules were recorded. For each flow series ("Day"), the raw voltage of the detector readings was then averaged to give the results in Table 5-10. All raw data is in Appendix C. Table 5-10 also shows the conversion of this voltage output to the intensity, using the value of 4 mW/cm^2V.

For each nominal-transmittance data set, there are no significant correlations between the variations in actual transmittance and the detector readings. Most variance in the data is from intensity between reactor modules. For example, the intensity reading from module 1 is generally lower than the other two (see Table 5-10). Differences in intensity readings between the three modules likely results from small differences in detector positioning, variations in lamp-to-lamp intensity (see Section 3.1.2), and small variations in the quartz sleeves.

It is important to note that the detectors monitor the UV intensity of only a small portion of one lamp in each module. Thus, a low intensity reading for module 1 does not represent an overall lower UV dose from module 1.

To prevent a bias in the confidence interval calculations from the greater number of data for the 46%T flows, the average for each module was used in the 75% confidence interval calculation. See Section 5.3.2 for the confidence interval formula.

Table 5-10. Detector Readings During Flow Tests

Test Day	%T	Mod 1	Mod 2	Mod 3	Mod 1	Mod 2	Mod 3
		(Reading, Volts)			(Intensity, mW/cm^2)		
46 %T (nominal) Flow Series							
1	44.0	1.32	1.46	1.50	5.28	5.85	6.01
5	46.9	1.30	1.44	1.69	5.20	5.74	6.78
7	44.9	1.35	1.43	1.64	5.39	5.72	6.56
9	46.5	1.37	1.45	1.63	5.48	5.78	6.52
11	46.4	1.44	1.76	1.60	5.75	7.03	6.41
13	46.8	1.45	1.68	1.59	5.79	6.74	6.38
15	46.8	1.30	1.40	1.39	5.21	5.59	5.57
16	46.4	1.59	1.53	1.67	6.37	6.11	6.67
17	44.0	1.44	1.45	1.58	5.76	5.79	6.33
				Average	5.58	6.04	6.36
				Ave:	5.99	**Stdev:**	0.39
				75% C.I.	6.07	5.91	--
56 %T (nominal) Flow Series							
6	55.0	1.87	1.90	2.20	7.47	7.59	8.80
8	56.0	1.81	2.15	2.05	7.23	8.59	8.21
10	55.7	1.91	2.33	2.08	7.65	9.33	8.32
18	55.5	1.83	1.82	2.05	7.32	7.29	8.22
				Ave Mod	7.42	8.20	8.39
				Ave:	8.00	**Stdev:**	0.51
				75% C.I.	8.11	7.89	--

5.3.4 Flow Test Data Analysis

All of the data in Table 5-9 is presented in graphical form in Figures 5-7 to 5-9. Each of these figures shows one test condition (%T, number of modules) along with a second-order polynomial fit of the high 75% C.I., the low 75% C.I., and the mean.

A UV disinfection unit with ideal hydraulics should deliver a dose that is a function of 1/flow rate (Dose = k/(Flow Rate) and should fit a power function with an exponent of -1. However, this is often not the case because the mixing and the dose delivery efficiency change with different flow rates. The data shown in Figures 5-7 to 5-9 are better represented with second-order polynomials. Although this is somewhat arbitrary, the goal of this bioassay test is to allow the estimation of doses at arbitrary flow rates. This non-ideal hydraulic behavior is justification for conducting bioassay testing.

As described in the Verification Protocol (NSF, 2002), the final analysis of the flow test data was based upon the lower 75% confidence interval result for each flow condition (e.g., flow rate, %T). All subsequent discussion is based upon the lower 75% confidence interval, but the average dose delivery curve is included for comparison.

To summarize the data presented in Figures 5-7 to 5-9, the dose delivery data for all three, test conditions are shown in Figure 5-10. The lower 75% C.I. is shown with a bold line and the mean is shown with a thin line. In general, the lower 75% C.I. differs from the average by only a few percent.

5.3.5 Extension of Aquaray® 10 HO VLS Results to the Aquaray® 40 HO VLS System

In order to use the Aquaray® 10 HO VLS test system results for the practical application and design of Aquaray® 40 HO VLS systems, two main assumptions must be qualified and verified. (1) The flow rates for the Aquaray® 10 HO VLS system must be scaled up to the design flow rates for the Aquaray® 40 HO VLS systems. (2) The dose additive nature of modules in a train must be verified. These results are then recast into units and scales appropriate to allow flow pacing for a train of Aquaray® 40 HO VLS disinfection modules.

5.3.5.1 Scaling up of Flow Rates

The main goal of this verification test was to determine the disinfection performance of the full-scale Aquaray® 40 HO VLS system (with 40 lamps per module). These test results were generated from an Aquaray® 10 HO VLS test unit (with 10 lamps per module). The main flow scaling assumption is that the Aquaray® 40 HO VLS system has four times the flow capacity of the Aquaray® 10 HO VLS system. The assumptions that allow this extrapolation are that:

(1) The lamps, sleeves, ballasts, and lamp driving power of the Aquaray® 10 HO VLS system and the Aquaray® 40 HO VLS system are identical.

(2) The lamp array geometry and the depth of lamp submersion of the Aquaray® 10 HO VLS system and the Aquaray® 40 HO VLS system are identical.

(3) The full-scale Aquaray® 40 HO VLS system complies with the channel width and baffle considerations discussed in Section 3.2.2.

(4) The Aquaray® 10 HO VLS system I_{AVE} is equal to or smaller than the Aquaray® 40 HO VLS system I_{AVE}.

(5) The flow velocities for the Aquaray® 10 HO VLS system and the Aquaray® 40 HO VLS system are identical.

(6) The influent velocity profile for a full-scale Aquaray® 40 HO VLS system is equal to or better than the influent velocity used for the Aquaray® 10 HO VLS system for this verification test.

Based on the validity of these assumptions, the performance of the Aquaray® 40 HO VLS system is determined simply by multiplying the flow rates for the Aquaray® 10 HO VLS system verification test by a factor of four.

5.3.5.2 Evaluation of the Additive Nature of Downstream Modules

Part of the operational philosophy of the Aquaray® 40 HO VLS system is based on the application of a multiple-module train to meet the dose delivery requirements of reuse applications. Additional reactor modules in the train are brought online as disinfection requirements increase due to increased flow rate or to decreased transmittance. Thus, one of the goals of this verification test was to evaluate the dose-additive nature of downstream modules.

The first approach to evaluating this assumption compared two-thirds of the three-module dose delivery with the two-module dose delivery for the 55%T data. These results are shown in Figure 5-11. The two-thirds curve of the three-module dose delivery agrees quite closely with the curve of the two-module dose delivery. This is interpreted to support the additive nature of the dose delivery in a reactor train.

The second approach to evaluating the additive nature of the modules is intended to have a more general applicability and is based upon a complete analysis of the whole bioassay data set.

In general, the dose delivery in the Aquaray® 40 HO VLS UV disinfection system is proportional to the number of modules and the average intensity (see section 4.4.5.1). The inverse proportionality relationship of the dose delivery to the flow is not linear. The rate of decrease of the UV dose diminishes with increasing flows. As the flow increases through the vertical lamp reactors, mixing improves and the most efficient dose delivery depends on dosing every parcel of water "just enough"; overdosing the water in a low velocity flow wastes energy. Thus, an empirical relation or "Performance Factor" (*PF*) is introduced. The *PF* primarily takes into account the non-linear effect that changes in hydraulics (e.g., mixing and velocity distributions) have on the measured, effective, dose distribution. This is based upon the following relationship:

$$Dose = \frac{I_{AVE}}{Q}(\#Modules)(PF)$$

Where:

Q = Aquaray® 40 HO VLS system flow rate (L/min)

Dose = Bioassay Delivered Dose (mJ/cm^2)

#Modules = Number of Modules in a reactor train

I_{AVE} = Average intensity in reactor from the LSI method (mW/cm^2)

PF = Performance factor as a function of flow (L/60#modules)

The equation can then be solved for *PF*:

$$PF = \frac{(Dose)(Q)}{(I_{AVE})(\#Modules)} \tag{5-5}$$

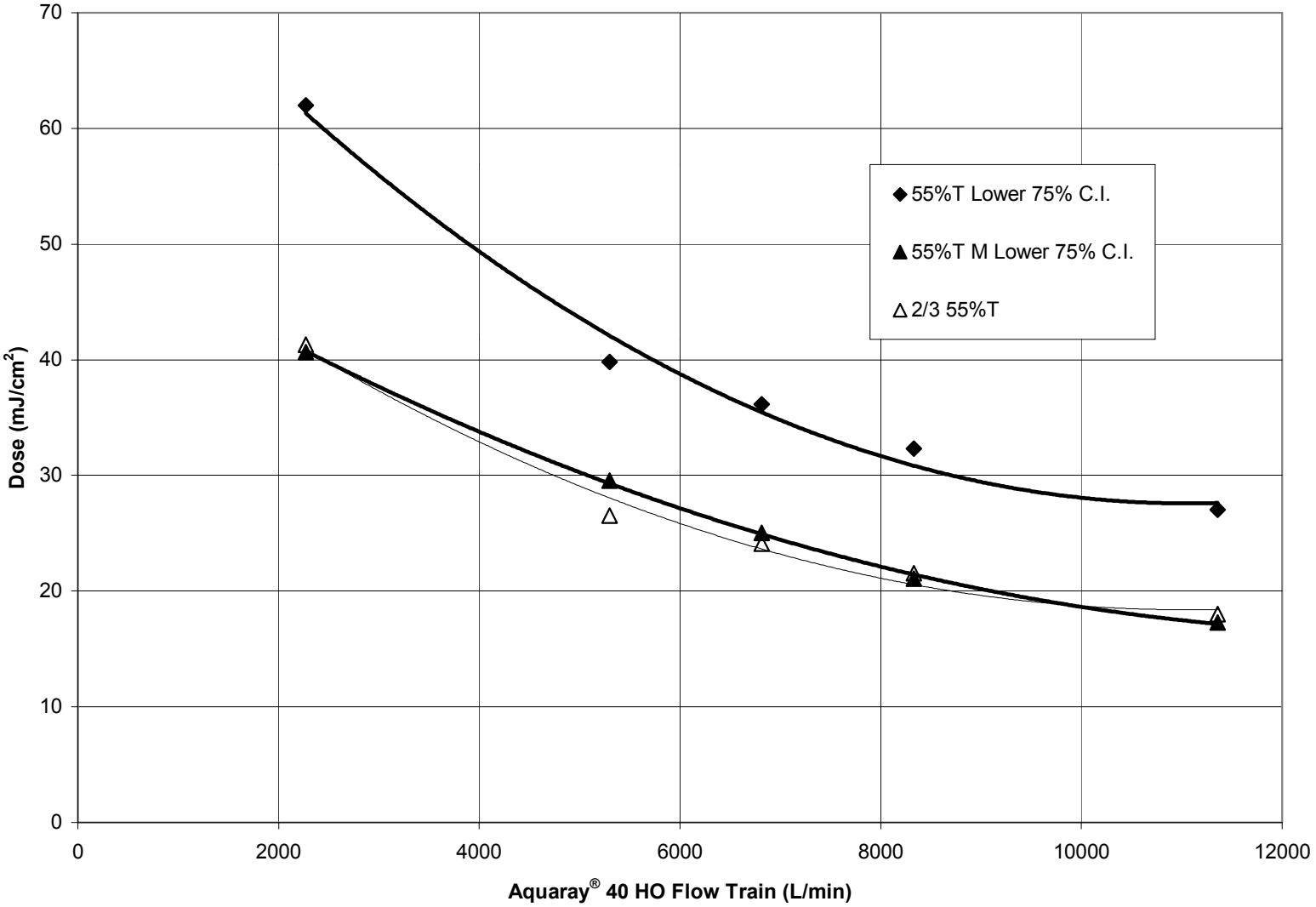

Figure 5-11. Comparison of 55%T data for 3 modules, 2 modules, and two-thirds of 3 modules.

Essentially, the three bioassays performed in this verification test were tests to vary all four variables in the above equation. This allows the empirical determination of *PF* as shown in Figure 5-12, where the *PF* data are fitted with a second-order polynomial. *PF* is a function of the flow rate:

$$PF = -1.151\times10^{-4}(Flow)^2 + 2.790(Flow) + 3503 \quad (5\text{-}6)$$

The dose delivery of the Aquaray® 40 HO VLS system can be calculated empirically for arbitrary values of flow (Q), transmittance (I_{AVE}), and module number. However, the validity of this relationship must first be tested to determine if the original bioassay dose delivery determined during this verification test can be reproduced accurately with the empirically calculated dose. These results are presented in Table 5-11 and graphically in Figure 5-13. In all but two cases, the empirical dose calculation is within 5% of the bioassay dose.

The first deviation is for the 65%T flow at 2271 L/min, where the empirically calculated dose is 12% higher than the bioassay dose. An examination of Figure 5-10 shows that the curve for the 65%T flows is somewhat more linear than the curves for the 55%T and the 55%T M flows. In fact, the 65%T curve approaches the 55%T curve most closely at the low flow rate. This suggests that the bioassay dose measured at this low flow rate may have been slightly low, and the calculated empirical dose may actually be more accurate.

The second deviation is for the 55%T M flow at 5299 L/min, where the empirically calculated dose is 7.1% lower than the bioassay dose. The doses are, respectively, 27.47 and 29.57 mJ/cm^2. A difference of 2.00 mJ/cm^2 is quite minor and is clearly within the natural variability of the bioassay process. All other comparisons between the bioassay dose and the calculated empirical dose agree within less than 5%.

This good empirical estimate of dose delivery with the above approach, based upon a linear function of the number of modules, again, supports the assumption that the number of modules adds to the dose in a linear fashion.

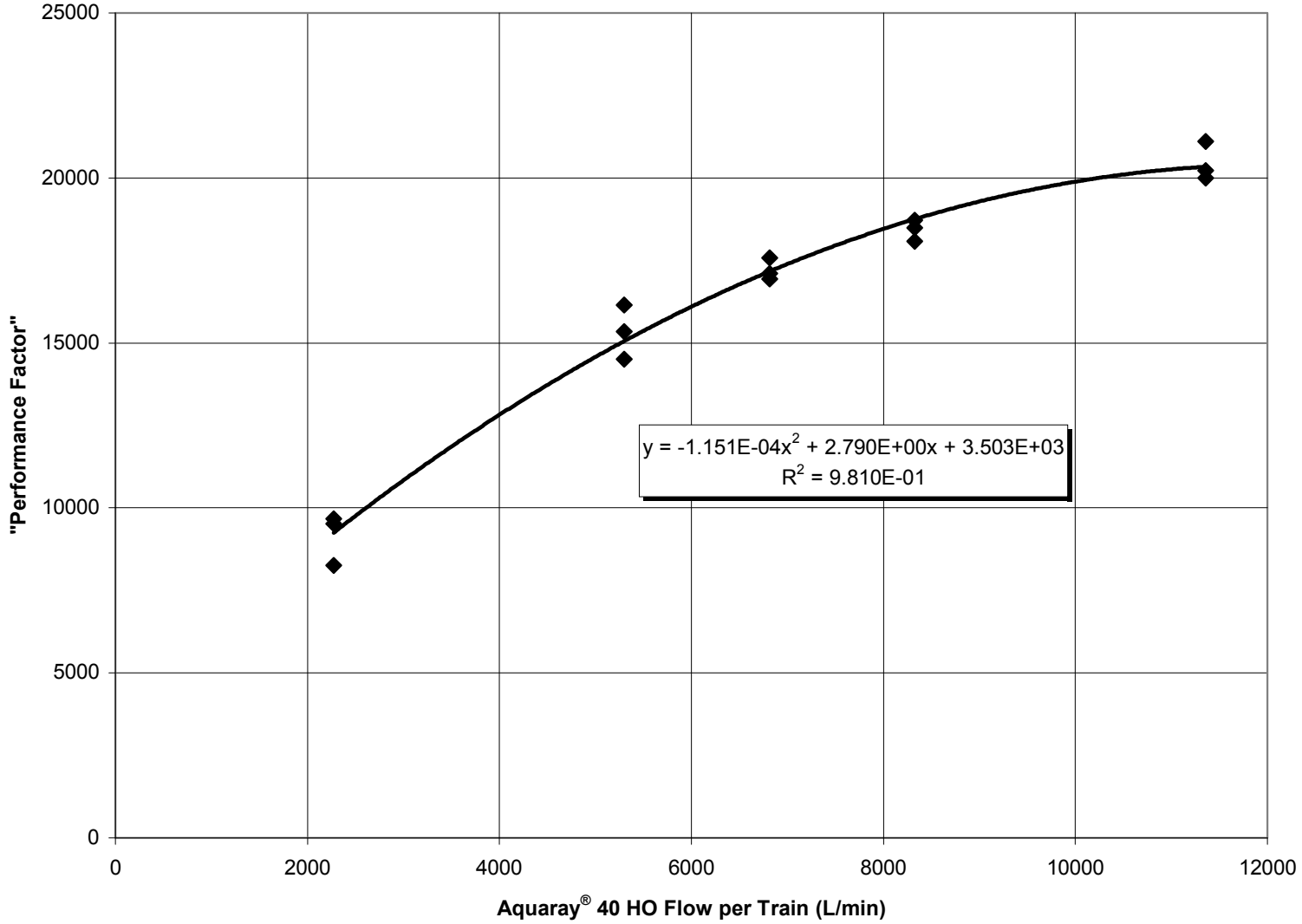

Figure 5-12. "Performance Factor" curve for all three bioassays.

Table 5-11. Comparison of Bioassay Dose and Empirically Calculated Dose

Flow (L/min)	Bioassay Dose (mJ/cm^2)	I_{AVE} (mW/cm^2)	# Modules (n)	PF (L/60#mod)	PF from Curve (L/60#mod)	Calculated Dose (mJ/cm^2)	Dose Difference (%)
65%T Lower 75% C.I.							
2,271	71.69	6.577	3.00	8,251	9,217	80.08	11.70
5,299	57.15	6.577	3.00	15,348	15,006	55.88	-2.23
6,814	49.54	6.577	3.00	17,108	17,104	49.53	-0.02
8,328	44.35	6.577	3.00	18,719	18,669	44.23	-0.27
11,356	34.74	6.577	3.00	19,994	20,203	35.10	1.04
55% Lower 75% C.I.							
2,271	61.98	4.850	3.00	9,674	9,217	59.05	-4.73
5,299	39.82	4.850	3.00	14,502	15,006	41.20	3.47
6,814	36.17	4.850	3.00	16,939	17,104	36.52	0.97
8,328	32.31	4.850	3.00	18,493	18,669	32.62	0.95
11,356	27.04	4.850	3.00	21,104	20,203	25.89	-4.27
55%T M Lower 75% C.I.							
2,271	40.65	4.850	2.00	9,517	9,217	39.37	-3.16
5,299	29.57	4.850	2.00	16,154	15,006	27.47	-7.11
6,814	25.02	4.850	2.00	17,576	17,104	24.35	-2.68
8,328	21.06	4.850	2.00	18,081	18,669	21.74	3.25
11,356	17.28	4.850	2.00	20,230	20,203	17.26	-0.13

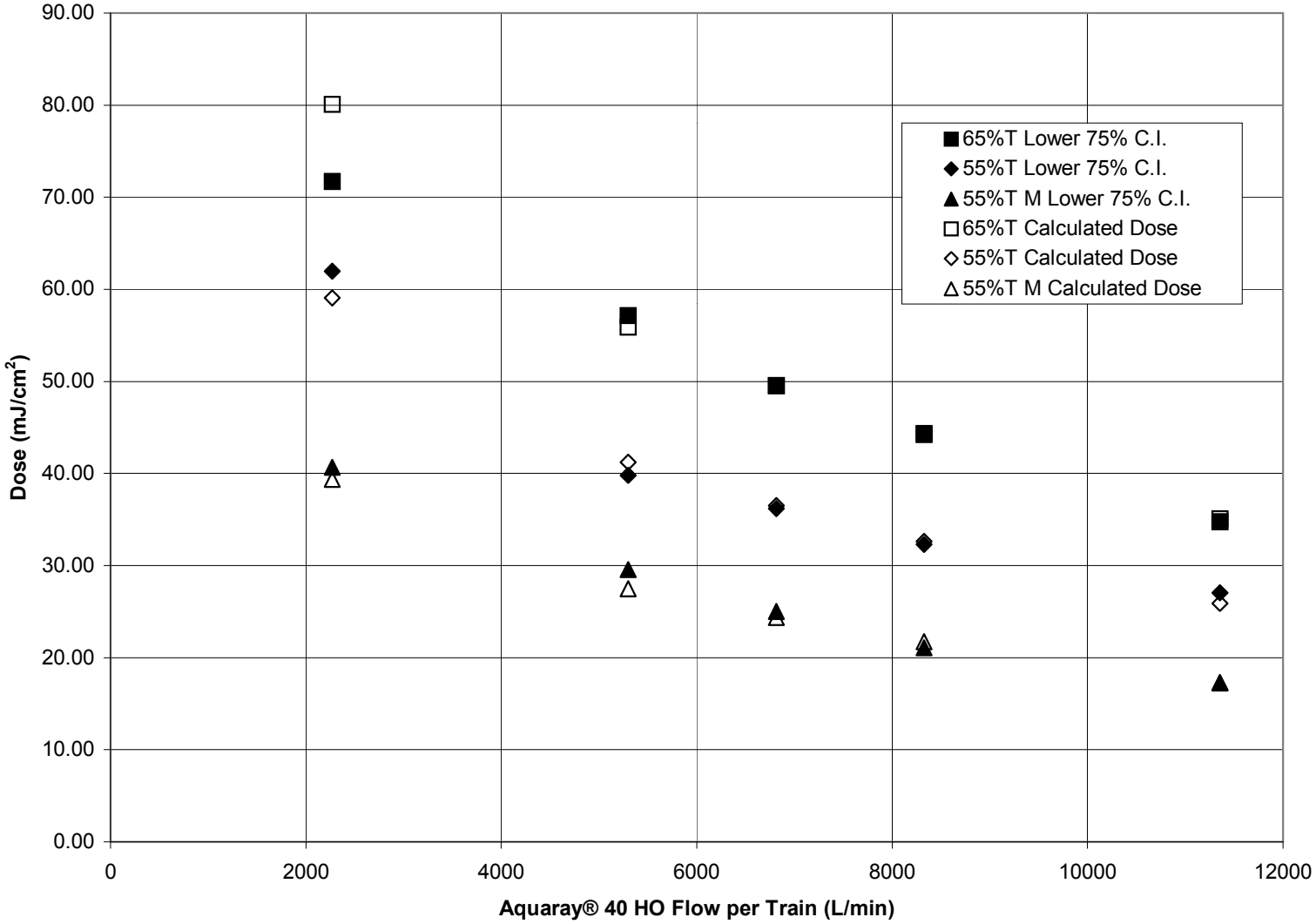

Figure 5-13. Comparison of bioassay dose to empirically calculated dose.

5.3.5.3 Dose Delivery per Aquaray® 40 HO VLS Module

Although the empirical calculated dose is a fairly accurate estimate of the dose delivery, the Verification Protocol (NSF, 2002) requires that the dose delivery be based on the actual verification test data. As such, the dose delivery per Aquaray® 40 HO VLS module was calculated with the data in Table 5-9. The lower 75% confidence intervals for the 65%T dose delivery per module calculation were based on one-third of the doses in Table 5-9 (see Figure 5-14). The lower 75% confidence intervals for the 55%T dose delivery per module are based upon the composite data set of one-half of the 2-module 55%T data and one-third of the 3-module 55%T data in Table 5-9 (see Figure 5-15). The relevant statistics are summarized in Table 5-12.

Table 5-12. Single Aquaray® 40 HO VLS Module Dose Delivery Statistics

Flow (L/min)	**Flow** (MGD)	**n**	**Average Dose** (mJ/cm^2)	**Standard Deviation** (mJ/cm^2)	**75% C.I.** (mJ/cm^2)	**High 75% C.I.** (mJ/cm^2)	**Low 75% C.I.** (mJ/cm^2)
65%T (56%T Actual)							
2,271	0.86	12	24.75	2.45	0.86	25.61	23.90
5,299	2.02	15	19.31	0.85	0.26	19.57	19.05
6,813	2.59	12	16.77	0.73	0.26	17.03	16.51
8,327	3.17	15	14.95	0.54	0.17	15.12	14.78
11,355	4.32	9	11.73	0.37	0.15	11.88	11.58
55%T (46%T Actual)							
2,271	0.86	30	21.46	3.25	0.70	22.16	20.76
5,299	2.02	32	14.51	1.90	0.39	14.91	14.12
6,813	2.59	30	12.74	1.49	0.32	13.06	12.42
8,327	3.17	27	11.10	1.41	0.32	11.42	10.78
11,355	4.32	30	8.93	0.49	0.10	9.03	8.82

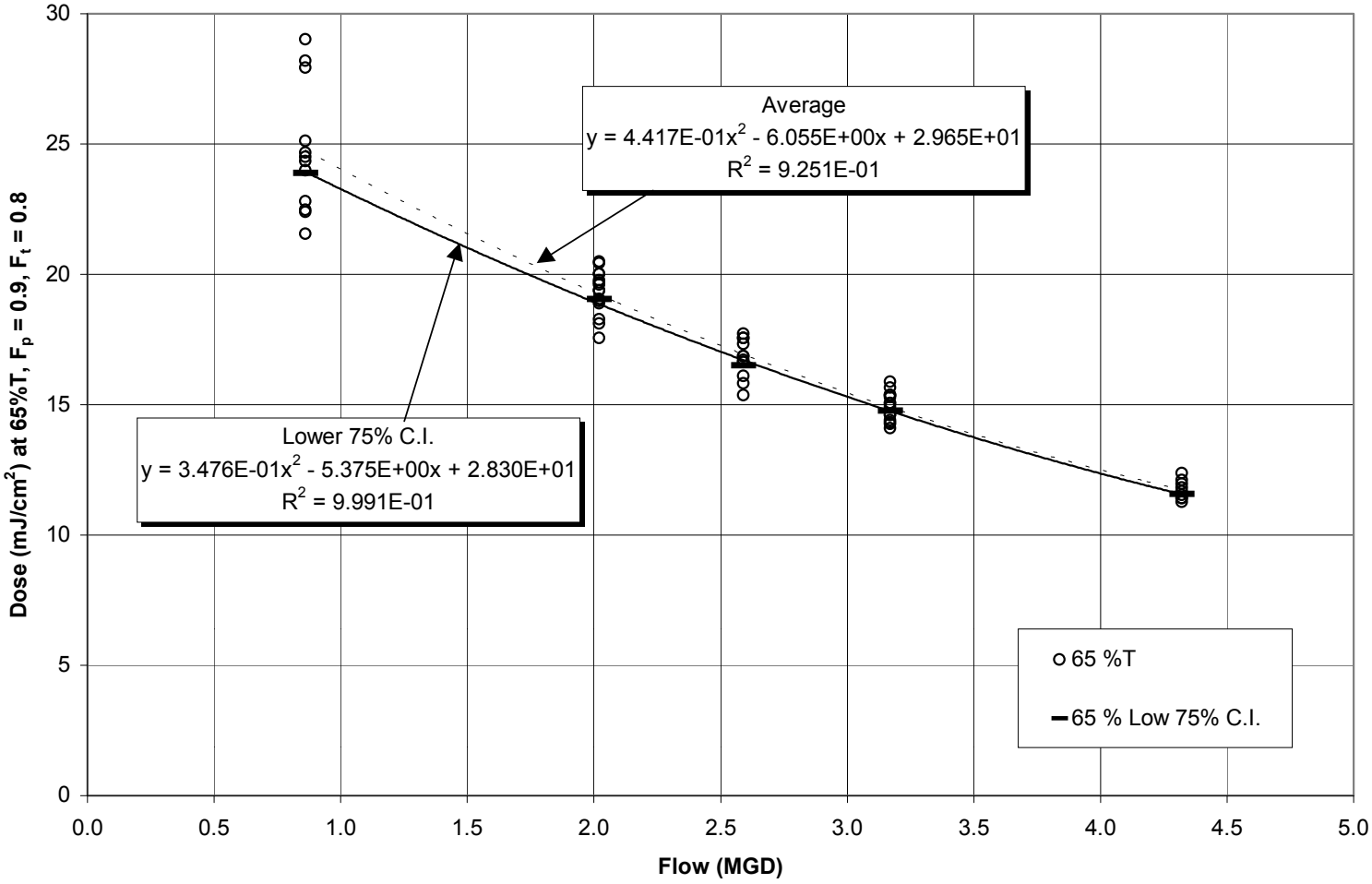

Figure 5-14. Dose delivery per Aquaray® 40 HO VLS module in membrane filtered water (65%T).

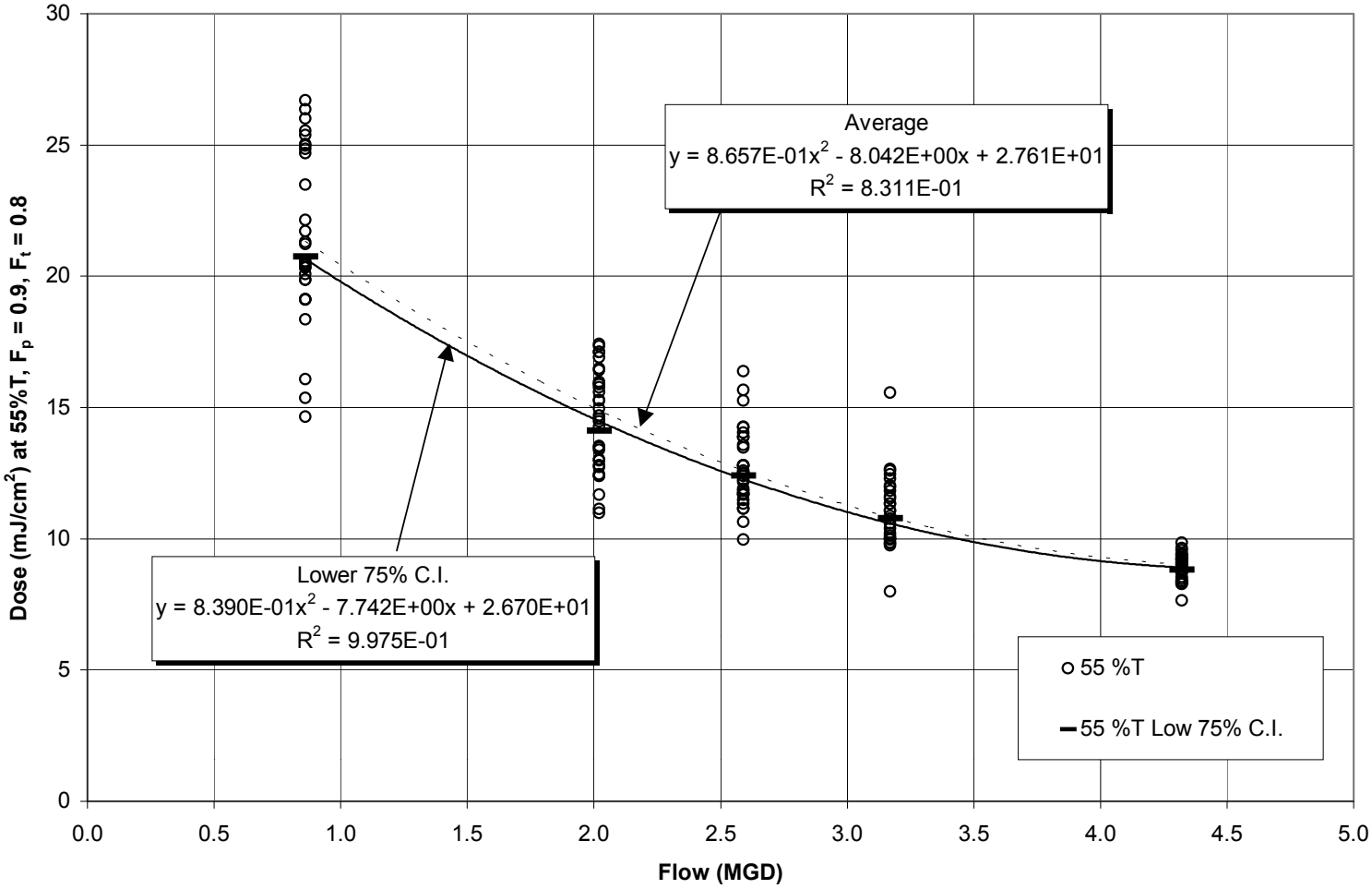

Figure 5-15. Dose delivery per Aquaray® 40 HO VLS module in media filtered water (55%T).

The empirical relationships derived from Figures 5-14 and 5-15 are as follows:

For 65%T membrane filtered water:

$$D_B = 0.3476 \cdot (Q_{train})^2 - 5.375 \cdot Q_{train} + 28.30$$

For 55%T media filtered water:

$$D_B = 0.8390 \cdot (Q_{train})^2 - 7.742 \cdot (Q_{train}) + 26.70$$

Where:

Q_{train} = Flow per train of full-scale Aquaray® 40 HO VLS system (MGD)

D_B = Dose delivery per module or dose per bank (mJ/cm^2)

(5-7)

5.3.5.4 Temperature Correction of Dose Delivery

The dose delivery performance of a train of Aquaray® 40 HO VLS modules derived above is based on the verification test bioassays conducted at temperatures very close to 15 ºC. As described in Section 4.4.5.2, the intensity correction for optimum temperature has already been included in the degraded transmittance calculation. Because typical water temperatures at full-scale Aquaray® 40 HO VLS module installations may vary from the optimum temperature of 22.8 ºC, it may be necessary to correct for the temperature-dependent lamp intensity change.

The following empirical correction factor is based on the data presented in Section 3.1.3. In addition, this correction factor assumes that dose delivery will be linearly related to changes in intensity. This assumption is justified in light of the empirical analysis of the dose delivery as a function of the I_{AVE} (see Section 5.3.5.2.).

The temperature correction is an adjustment of intensity from that at 22.8 ºC:

$$TF = \frac{I(T)}{I(22.8^\circ C)}$$

Where:

TF = Temperature Correction Factor (5-8)

$I(T)$ = Lamp Intensity at Operating Temperature

$I(22.8^\circ C)$ = Lamp Intensity a 22.8° C (Maximum Intensity)

Thus, operating a system at 22.6 ºC will result in TF = 1, and dose delivery need not be corrected from the values determined in this verification test. At other temperatures, an equation derived from Figure 3-6 is to be used:

$$TF = \frac{-0.00163T^2 + 0.0742T + 0.591}{-0.00163(22.8)^2 + 0.0742(22.8) + 0.591}$$

Where:

T = Operating Water Temperature

Or to simplify:

$$TF = \frac{-0.00163T^2 + 0.0742T + 0.591}{1.435}$$

Where:

T = Operating Water Temperature

(5-9)

It is important to note that the temperature dependence of the lamp intensity limits the extension of these test results. Operating conditions must be in systems where the water temperature is in the range of 15-30 ºC. In addition, it must be noted that the temperature correction presented above is based on data acquired by ODI; it is not derived from results collected during this verification test.

5.4 Example of Application

5.4.1 Background

For two years, ODI has used the Dose per Bank method in combination with the 2001 bioassay results (performed by HydroQual) to size and control the flow for Aquaray® 40 HO VLS disinfection systems with primary, secondary, and reused wastewaters. For wastewater reuse applications, the Dose per Bank sizing method needs to be updated to include the results of this verification test.

With the Dose per Bank sizing method, the plant design peak flow is inserted in the bioassay dose flow equation. By doing so, the resulting number of modules for the Aquaray® 40 HO VLS system will account for the mixing and hydraulic condition specific to the design peak flow. Scaling the results from this verification test, using the Dose per Bank method, assumes the following:

(1) The lamps, sleeves, ballasts, and lamp driving power of the Aquaray® 10 HO VLS system and the Aquaray® 40 HO VLS system are identical.

(2) The lamp array geometry and the depth of lamp submersion of the Aquaray® 10 HO VLS system and the Aquaray® 40 HO VLS system are identical.

(3) The full-scale Aquaray® 40 HO VLS system complies with the channel width and baffle considerations discussed in Section 3.2.2.

(4) The Aquaray® 10 HO VLS system I_{AVE} is equal to or smaller than the Aquaray® 40 HO VLS system I_{AVE}.

(5) The flow velocities for the Aquaray® 10 HO VLS system and the Aquaray® 40 HO VLS system are identical.

(6) The influent velocity profile for a full-scale Aquaray® 40 HO VLS system is equal to or better than the influent velocity employed for the Aquaray® 10 HO VLS system for this verification test.

(7) The UV delivered dose is additive with the number of modules in series. Each module contributes equally to the total delivered dose of a train.

(8) The UV delivered dose is the same, where multiple parallel trains of Aquaray® 40 HO VLS modules in one are used to accommodate higher flows. For example, x trains of Aquaray® 40 HO VLS modules in one channel (a channel of x modules wide) will deliver the same UV dose of a single train but with x times more flow (refer to Section 3.2.2).

5.4.2 Example of Reuse Application Conditions for the Aquaray® 40 HO VLS System

In the present application example, the following conditions are to be addressed.

(1) Proper disinfection for a maximum day flow of 12 MGD, with multiple, parallel channels.

(2) Delivered dose to target should be 100 mJ/cm^2 at 55% UVT with lamps at EOL and fouled sleeves in media filtered water.

(3) Yearly average temperature of the water is 17 ºC.

5.4.2.1 Reuse Calculations

The modular nature of the Aquaray® 40 HO VLS system allows many scenarios to be considered for this example application. Each reactor train could have multiple numbers of modules, and parallel reactor trains in one channel can be considered.

The procedure to determine the system's delivered dose with N_c channels containing N_m Aquaray® 40 HO VLS modules wide (parallel trains in one channel), with B Aquaray® 40 HO VLS modules in series per train, is detailed in this section.

The following calculations are based on the results of this verification test, and the data has been linearly scaled (i.e. test flow to full-scale flow) to represent the Aquaray® 40 HO VLS System.

Table 5-13. System Design Parameters

Peak Plant Flow Rate (MGD)	Q
Peak Flow Rate in Each Train	Q_{train}
Number of Channels	N_c
Number of Modules Across	N_m
Number of Banks in Series (Train)	B
UV Transmittance (%)	UVT
Operating Water Temperature (ºC)	T

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

One train is defined as being a single row of modules. The total flow is divided equally between each channel and equally between each row of modules in each channel.

$$Q_{train} = \frac{Q}{N_C \cdot N_m} \qquad \text{With 0.86 MGD} < Q_{train} < \text{4.3 MGD} \tag{5-10}$$

(2) Dose per Bank (D_b).

At given UVT, D_b is based on the Dose Delivery per Module curves of Section 5.3.5.3. For media filtered water at 55% UVT (with Fp=0.9 and Ft=0.8).

$$D_B = 0.8390(Q_{train})^2 - 7.742 \cdot Q_{train} + 26.70 \tag{5-11}$$

(3) Temperature Factor (TF).

TF is the temperature factor obtained from Figure 3-6 and the following equation developed in Section 5.3.5.4.

$$TF = \frac{-0.00163T^2 + 0.0742T + 0.591}{1.435} \tag{5-12}$$

(4) Total Dosage ($Dose$).

Total dosage is calculated by multiplying the dose-per-bank by the number of banks in each train and the temperature correction factor (TF).

$$Dose = D_b \times B \times TF \tag{5-13}$$

(5) Power Consumption (P).

The total power consumption is 166 W per lamp.

$$P = 0.166kW \times Number\ of\ Modules \times 40 \tag{5-14}$$

(6) Headloss.

Total headloss through the system is the amount of headloss per module multiplied by the number of modules in a train (B).

$$Total\ Headloss\,(in) = B \times \left(0.0514(Q_{train})^2 - 0.133(Q_{train}) + 0.0787\right) \tag{5-15}$$

5.4.2.2 Applied Reuse Calculations

For the flow per train (Q_{train}) to remain below the limit of 4.3 MGD, two configurations are possible (see Table 5-14):

- Case 1: Three channels with one train (one module wide). Twelve Aquaray® 40 HO VLS Modules per train for a total of 36 modules.
- Case 2: Two channels with two trains (two modules wide per channel). Ten Aquaray® 40 HO VLS Modules per train for a total of 40 modules.

Table 5-14. System Design Results

Design Parameter	Case 1	Case 2
Q_{train}	4.00 MGD	3.00 MGD
B	12	10
N_C	3	2
N_m	1	2
Number of Modules	36	40
Number of Lamps	1440	1600
D_b	9.16 mJ/cm^2	11.03 mJ/cm^2
TF	0.962	0.962
Dose	105.8 mJ/cm^2	106.2 mJ/cm^2
Power	239 kW	265 kW
Headloss per Module	0.369 in	0.142 in
Total Headloss per train	4.43 in	1.42 in

Case 2 requires 4 additional modules to achieve a dose similar to that of Case 1. Clearly, Case 1 has a much higher Q_{train}, which improves mixing and, therefore, lowers the total number of reactors needed to achieve the required disinfection. In addition, Case 1 consumes 26 kW less power than Case 2. Headloss considerations show that both cases have headlosses less than or equal to 4.43 inches and are both, depending on plant requirements, acceptable. Based on this assessment, Case 1 appears to be the optimum design.

Chapter 6
Quality Assurance/Quality Control

6.1 Calibrations

6.1.1 Flow Meter Calibration

The flow rate through the test unit is a critical variable that controls the UV dose delivery. Therefore, before testing, the 6-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. Summary data and calculations are presented in Appendix D.

The calibration procedure was repeated for three flow rates between 568 L/min and 2,839 L/min (150 gpm and 750 gpm). Calibration of the flow meter by tank drawdown resulted in good agreement between the reading on the magnetic flow meter and the flow rate calculated by drawdown. Table 6-1 shows the results of the calibration procedure. The average ratio of flow meter to drawdown flow rates is 100.3%, verifying the accuracy of the flow meter.

Table 6-1. Flow Meter Calibration

Drawdown (gpm)	Flow Meter (gpm)	Flow Meter (L/min)	Ratio Flow/Drawdown (%)
145	150	568	103.4
461	450	1,703	97.6
751	750	2,839	99.9
		Average:	100.3

6.1.2 Radiometer Calibration

UV irradiances were measured during dose-response test procedures using an IL-1700 radiometer with SED240 detectors that included a quartz wide-eye diffuser and an NS254 filter. International Light, Inc. performed the detector calibrations. The first detector was calibrated on August 22, 2002, and on January 29, 2003, with a responsivity change of 0.53%. The second detector was calibrated on March 28, 2002, and on September 10, 2002, with a responsivity change of 2.59%.

6.2 Dose-Response Data

This section includes only a discussion of the QA/QC for the 13 valid dose-responses conducted in field challenge waters and the four dose-responses conducted for QA/QC purposes. All dose-response data, including the invalid data, are included in Appendix C.

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 29 complete mapping events were completed. On three occasions, the field was only mapped far enough to assure that the intensity was the same as at the start of the dose-response series.

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 0.91 and 1.05.

6.2.1.2 Initial and Final Control Similarity

Each dose-response series was bracketed at the beginning and the end with undosed control samples. The geometric mean of the 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:

$$Similarity = \log\left(\frac{Inital\ Control(pfu/mL)}{Final\ Control(pfu/mL)}\right) \tag{5-16}$$

For the 13 valid and the four QA/QC dose-response series' completed during this verification test, the similarities are shown in Figure 6-1. One series, DRS9, did not have a valid final control, so there are a total of 16 similarity values. The similarities between the control titers are generally less than 0.15, but range up to 0.23, which is still less than the acceptable value of 0.32.

6.2.2 Excluded Data

Six dose-response data sets and four individual data points are excluded from the valid data set for various QA/QC considerations. Table 6-2 lists the data, along with a justification for exclusion. All raw data is included in Appendix C. Dose-responses on challenge waters for invalid flow series' are also excluded.

Table 6-2. Excluded Dose-Response Data

Series	Doses	Justification
DRS2	All	Wrong %T, non-ETV configuration (shakedown).
DRS3	All	Wrong %T, non-ETV configuration (shakedown).
DRS4	All	Flow tests not valid.
DRS8	100	Counts too low.
DRS11	30	Anomalous result.
DRS13	30	Anomalous result.
DRS14	All	Flow tests not valid.
DRS17	40	Scatter.

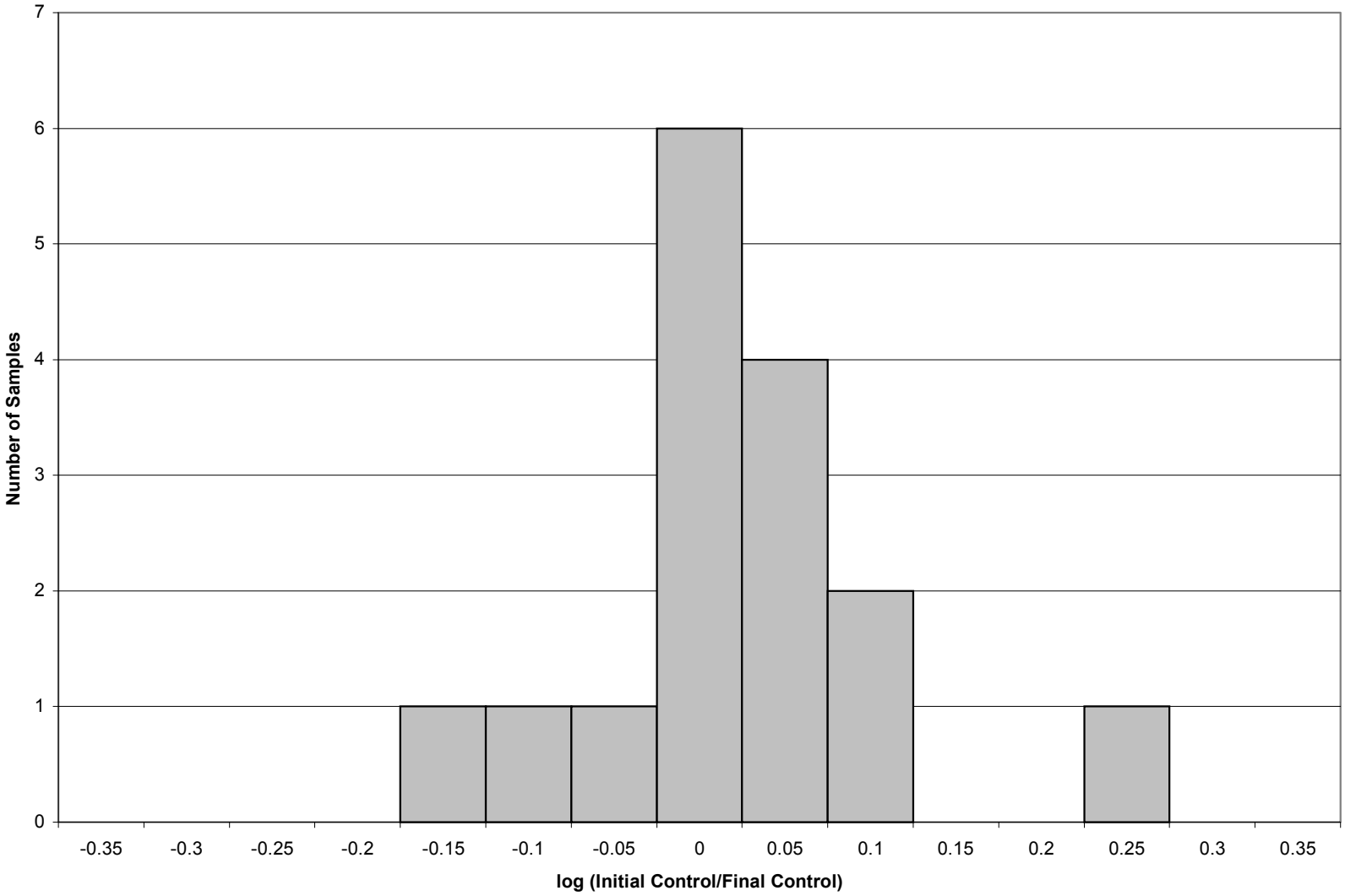

Figure 6-1. Similarity between initial and final dose-response controls.

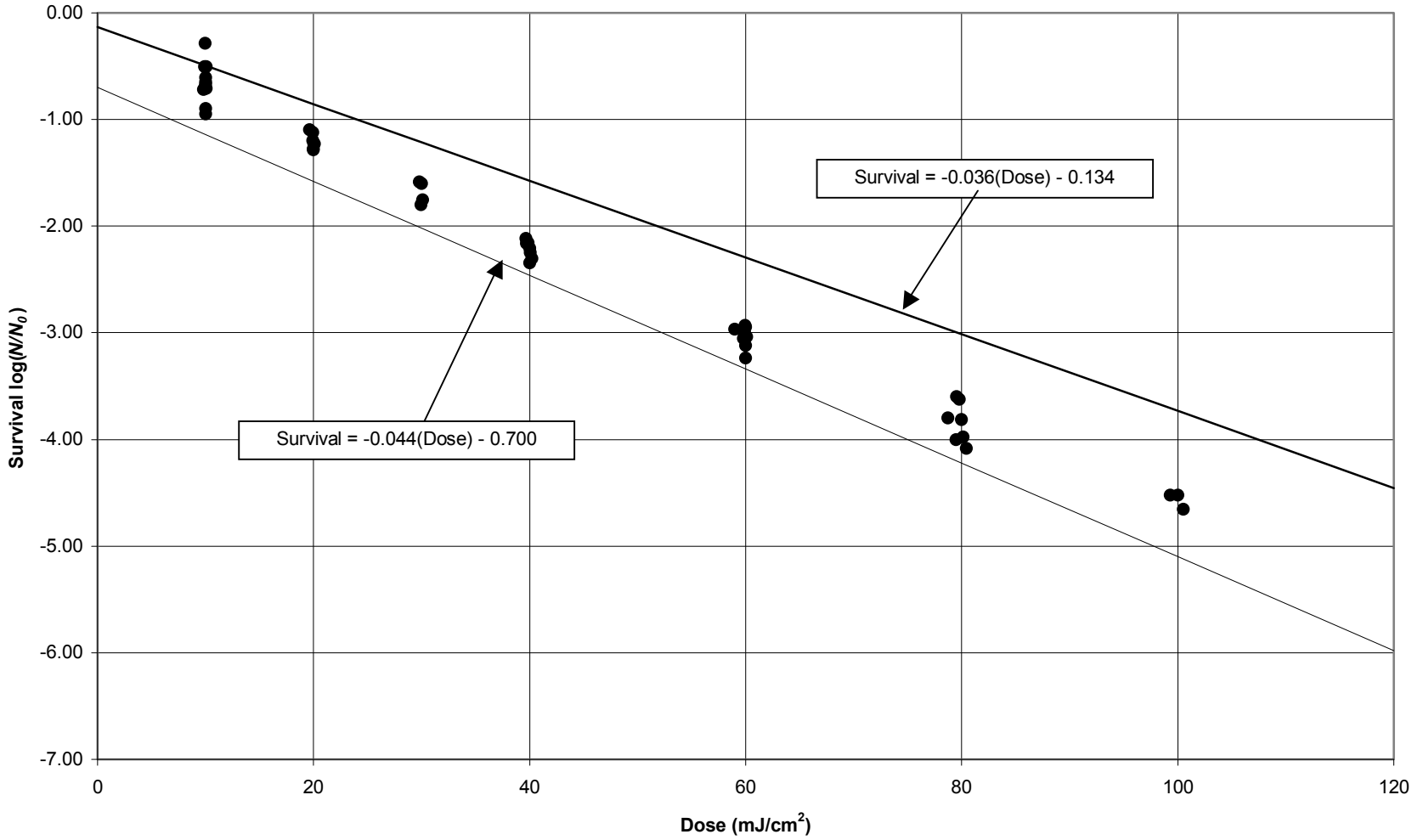

Figure 6-2. Dose-Response data and QA/QC boundary lines.

6.2.3 Compliance with QC Boundaries

The QC criteria for the acceptance of the dose-response data is described in the Verification 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 test. Of the 48 valid data points used for the dose-response calibration curve, 47 (98%) lie within the specified QC boundary lines. Thus, the valid dose-response data generated for this verification test is accepted as valid behavior for MS2 bacteriophage.

6.2.4 Collimator Verification and MS2 Sensitivity

Additional dose-response runs were conducted to verify the depth and intensity correction in the dosing sample containers and to determine the sensitivity of the MS2 bacteriophage to the challenge water and modifiers. Four dose-response tests were conducted in solutions prepared in the laboratory; two doses were conducted in 0.85% saline solution and two were conducted in potable water from the site with the modifying agents added. The data for these QA/QC dose-response runs are in Table 6-3.

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

Identifier	**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	99.0	(2)	10.0, -0.71	19.9, -1.28	39.7, -2.12	--	79.4, -3.72	99.3, -4.29
DR2	99.0	(2)	10.0, -0.70	19.9, -1.35	39.8, -2.20		79.8, -3.69	99.8, -4.70
DRV1	99.0	(3)	10.1, -0.67	20.0, -1.15	40.2, -2.31	--	80.3, -3.96	100.5, -4.92
DRV3	44.0	(3)	9.9, -0.48	20.0, -1.16	39.9, -2.02	59.9, -3.11	79.9, -3.71	--

(1) Dose in mJ/cm^2; (2) 8.5% Saline Solution; (3) Potable water + Sodium Thiosulfate + Coffee.

This analysis results in three data sets for comparison: (1) The 13 valid, seeded, challenge water dose-responses; (2) Two 8.5% saline dose-responses; and (3) Two verification run dose-responses. The three data sets are presented graphically in Figure 6-3 with second-order polynomial fits to allow dose estimates at arbitrary survival ratios.

Table 6-4 shows the calculated doses resulting 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 saline data 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 for survival ratios of -1.0, the calculated doses are within

10%. The differences are greater for the -1.0 survival ratio, reflecting the greater sensitivity of the calibration curves at low survival ratios.

The favorable comparison of the dose-response curves conducted in different matrices and transmittances indicates that the intensity and depth correction was correct, and that the potable water and additives did not have a significant effect on the response of the MS2 bacteriophage to the UV dose.

Table 6-4. Dose-Response Verification Calculations

	Calculated Doses			Comparison to Saline	
Survival ($\log(N/N_0)$)	**Saline** (mJ/cm^2)	**Seeded Challenge** (mJ/cm^2)	**Verification** (mJ/cm^2)	**Seeded Challenge** (% diff)	**Verification** (% diff)
-1.0	14.7	16.4	17.5	11.1	18.7
-1.5	25.7	25.8	26.9	0.4	4.7
-2.0	37.0	35.9	36.6	-3.0	-1.0
-2.5	48.7	46.8	46.7	-4.0	-4.1
-3.0	60.8	58.4	57.2	-4.0	-5.9
-3.5	73.3	70.7	68.1	-3.6	-7.1
-4.0	86.2	83.8	79.3	-2.8	-8.0
-4.5	99.5	97.6	90.9	-1.9	-8.6

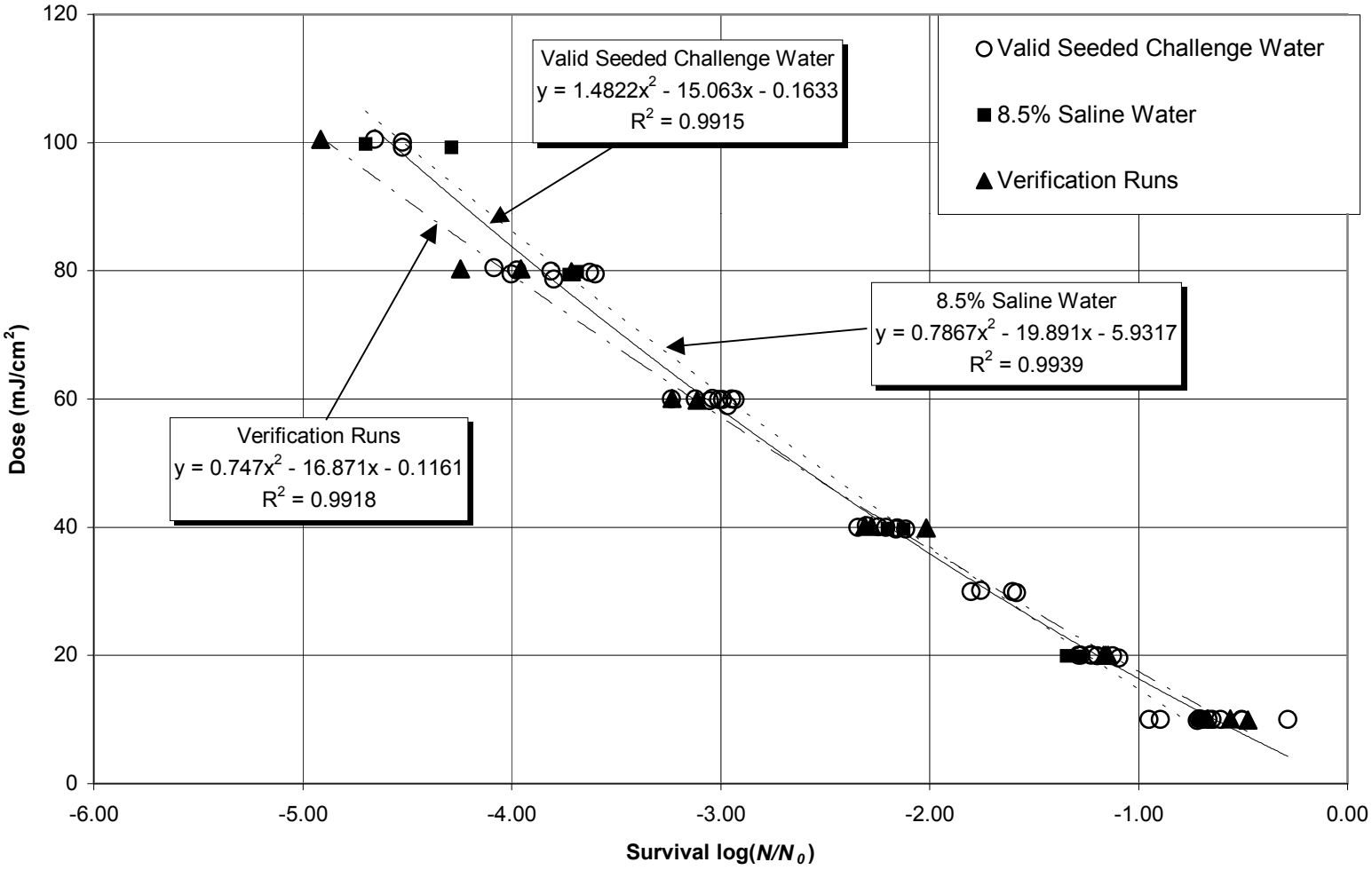

Figure 6-3. Dose-Response validation data.

6.3 Flow Test Data

The QA/QC analysis of the 71 valid flow tests is presented here. All raw flow test data are included in Appendix C, along with excluded data. Supporting data summaries and spreadsheets are included in Appendix D.

6.3.1 Quantitative QC Criteria

6.3.1.1 Flow Test Sample Replicates

The VTP (see Appendix A) includes a schedule of samples that were analyzed for each flow test series, including samples that are plated in replicate for MS2 bacteriophage enumeration. Generally, two samples were plated in replicate each test day for a total of 25 replicate platings. The similarity of these titers allows a quantitative evaluation of the plating procedure's repeatability.

The titers are compared by calculating the similarity:

$$Similarity = \log\left(\frac{SampleTiter1\left(pfu/mL\right)}{SampleTiter2\left(pfu/mL\right)}\right) \quad (6\text{-}1)$$

Figure 6-4 shows a distribution of the replicate similarity data. For the 25 samples plated in replicate during this verification test, the similarities ranged from -0.16 to 0.27 log units. All were within the acceptable limit of 0.46 log units (a factor of three).

6.3.1.2 Duplicate Flows

During each of seven flow series, a flow test was duplicated (i.e., using 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, is shown in Table 6-5.

Table 6-5. Results From Flow Test Duplicates

Day	Flow	Survival Flow A	Survival Flow B	Similarity
Day 6	1,325	-2.99	-2.82	-0.17
Day 9	2,082M	-1.35	-1.33	-0.03
Day 10	2,082	-2.49	-2.46	-0.03
Day 11	568	-3.08	-3.14	0.06
Day 13	2,839	-1.13	-1.08	-0.05
Day 15	1,703	-1.38	-1.45	0.06
Day 18	2,839	-1.95	-1.92	-0.03

The maximum similarity is 0.17 log units, which is well 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 this verification test, each influent sample was analyzed for percent T at 254 nm at the laboratory. In 24 cases, a sample was analyzed in replicate to determine the repeatability of the transmittance measurement. The samples are compared, using the relative percent difference (RPD):

$$RPD = \frac{Analysis1 - Analysis2}{Average(Analysis)} \times 100\% \quad (6\text{-}2)$$

Figure 6-5 shows the RPD of the 24 transmittance measurements that were replicated. In all cases, the replicate measurements are in agreement within the 5% allowed by the test plan.

6.3.2 No Dose Flows

No dose flows were conducted on three occasions with a standard flow condition duplicated but with the lamps turned off. These no dose flows were conducted to determine if there was any "memory" effect from dosed MS2 collecting on the reactor surfaces or to detect any residual dosed water in dead spots.

The results of these tests are shown in Table 6-6. These tests were conducted at the end of their respective daily flow test series'; the standard flush time was allowed after the lamps were turned off.

Table 6-6. Results from No Dose Flow Tests

Day	Flow	Survival	Dose
	(L/min)	($\log(N/N_0)$)	(mJ/cm^2)
Day 7	568	0.04	-0.8
Day 8	568	0.03	-0.6
Day 8	2,839	0.00	-0.2

The maximum survival ratio of these three flow tests was 0.04, which was typical of samples that have identical titers. There was no difference between the influent and effluent titers. In addition, the calculated doses are all less than 1.0 mJ/cm^2, further indicating the lack of systematic error from any operational conditions related to the system.

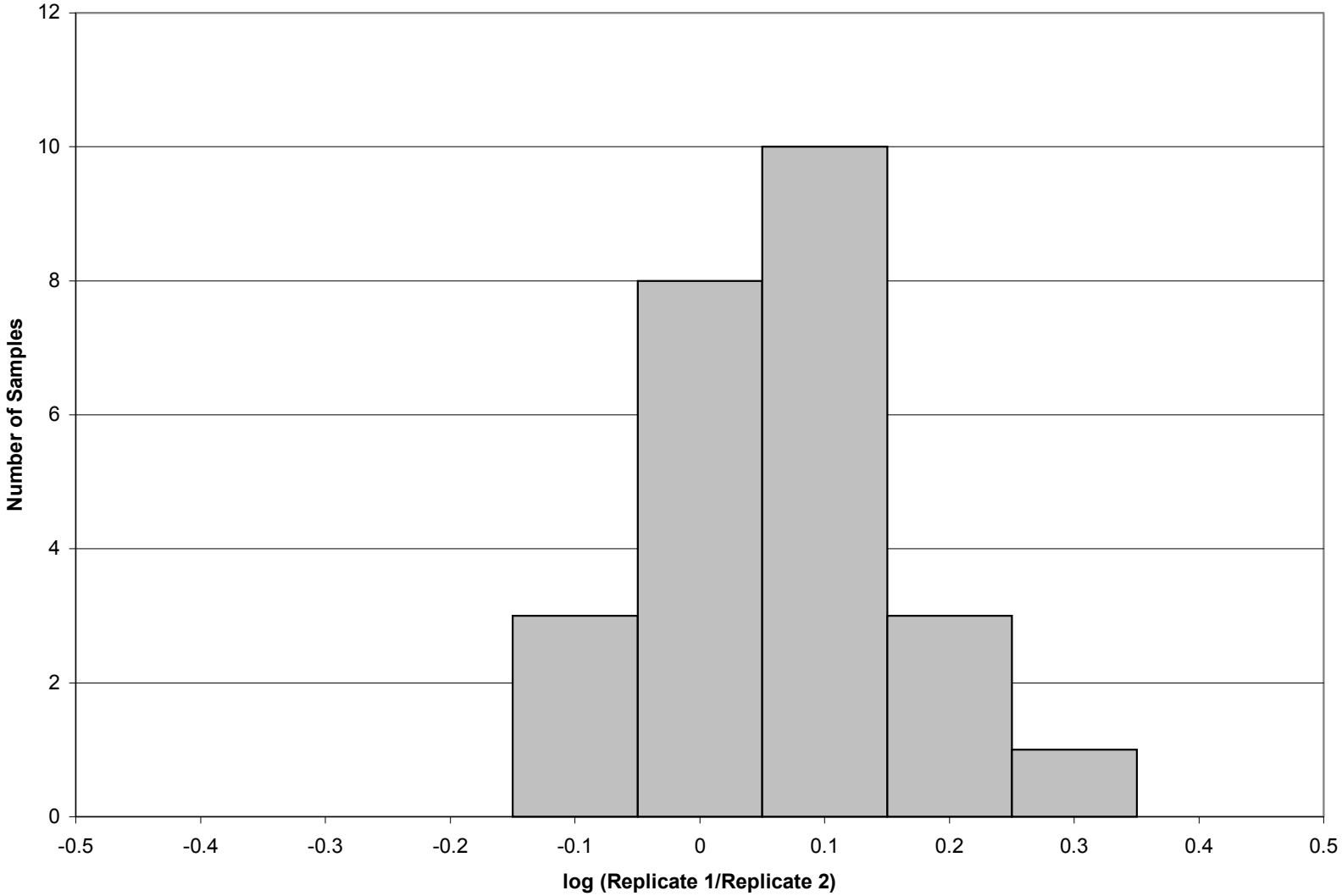

Figure 6-4. Similarity among replicate flow test samples.

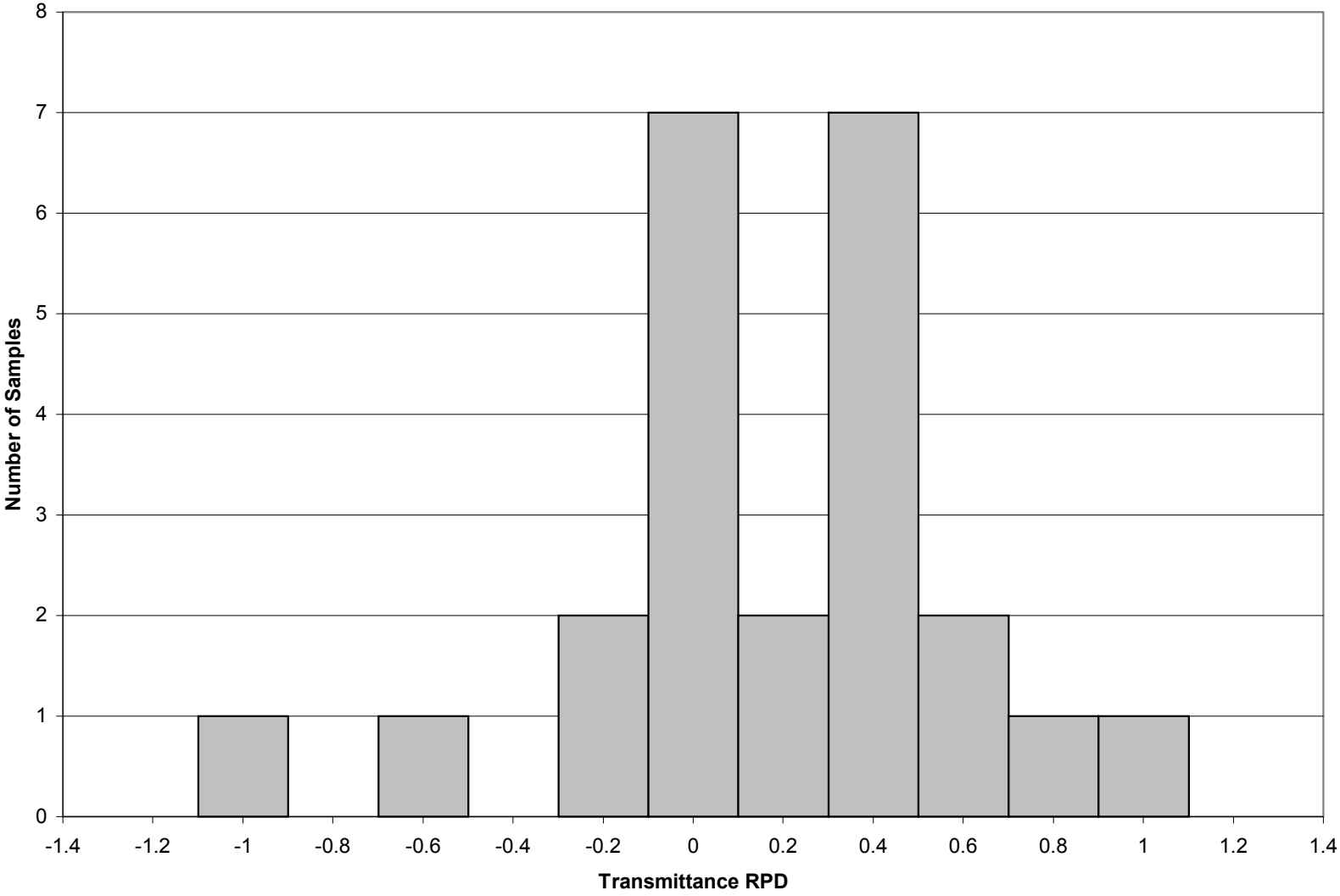

Figure 6-5. Relative percent difference for %T replicates.

6.3.3 Excluded Data

Of the 115 flow tests conducted during this verification test, 41 were excluded because they were shakedown flows or did not meet some QA/QC criterion. The individual flow tests are shown in Table 6-7, with the justification for exclusion. The data for these flows is included in Appendix C.

Table 6-7. Excluded Flow Test Data

Day	Flow	Justification
Day 1	6 Flows	Non-ETV single-module sampling scheme.
Day 2	11 Flows	Non-ETV single-module sampling scheme; different %T.
Day 3	5 Flows	Non-ETV single-module sampling scheme; different %T.
Day 4	5 Flows	Difficulty due to extreme cold.
Day 6	2839	Anomalous result, bad dilution?
Day 8	2839	Anomalous result, bad dilution?
Day 12	6 Flows	Bad %T, bacterial contamination.
Day 14	6 Flows	Lamp burned out

6.3.4 Power Monitoring and Datalogging

Appendix C contains printouts from the dataloggers, 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. For example, the power consumption data identified the loss of a lamp at the start of the Day 14 series, which invalidated the data.

Chapter 7
Mixer Additional Data

Experiments were performed before the start of the verification program to examine the effect of different influent configurations. One experiment involved the comparison of the influent velocity profiles, both with and without the mixer in place (see Section 3.2.1). This experiment was performed by acquiring velocity profiles at the minimum, median, and maximum flow rates, using the method described in Section 4.2.4 at position (1). Note that the velocity profiles were not measured in triplicate.

Table 7-1 shows the velocity profile data at the three flow rates. Note that the velocity at each height position and condition reflects the average of two measurements at that height. The data are presented graphically in Figure 7-1.

In general, the mixer had no measurable effect on the influent velocity profile. A minor exception exists at the lower part of the 568 L/min profile (see Figure 7-1) where some negative velocities were brought into the positive region with the action of the mixer.

Table 7-1. Influent Velocity Profiles With and Without Mixer

Conditions	Height (cm)	Influent with Mixer (cm/s)	Influent without Mixer (cm/s)
568 L/min	152.4	6.86	6.71
(150 gpm)	140.7	7.32	7.32
	129.0	7.01	7.01
	117.2	6.25	6.40
	105.5	5.64	5.64
	93.8	4.11	4.27
	82.1	5.64	5.64
	70.3	2.74	3.51
	58.6	0.76	-0.15
	46.9	1.07	1.07
	35.2	0.61	-0.61
	23.4	0.46	-0.76
	11.7	-0.15	-0.15
	Average:	3.72	3.53
1,703 L/min	152.4	18.14	17.83
(450 gpm)	140.7	20.27	21.49
	129.0	20.57	20.57
	117.2	19.20	19.20
	105.5	18.29	18.14
	93.8	9.91	9.75
	82.1	13.72	13.56
	70.3	8.53	7.01
	58.6	5.64	5.64
	46.9	3.35	3.35
	35.2	3.20	1.22
	23.4	0.00	0.00
	11.7	-1.52	-0.46
	Average:	10.71	10.56

2,839 L/min	152.4	35.81	30.94
(750 gpm)	140.7	36.88	37.03
	129.0	35.51	35.51
	117.2	37.34	37.34
	105.5	30.48	30.63
	93.8	17.98	17.98
	82.1	18.90	18.90
	70.3	12.50	12.50
	58.6	8.23	8.23
	46.9	6.55	2.74
	35.2	-0.76	-1.37
	23.4	-1.52	-1.52
	11.7	-3.35	-2.59
	Average:	18.04	17.41

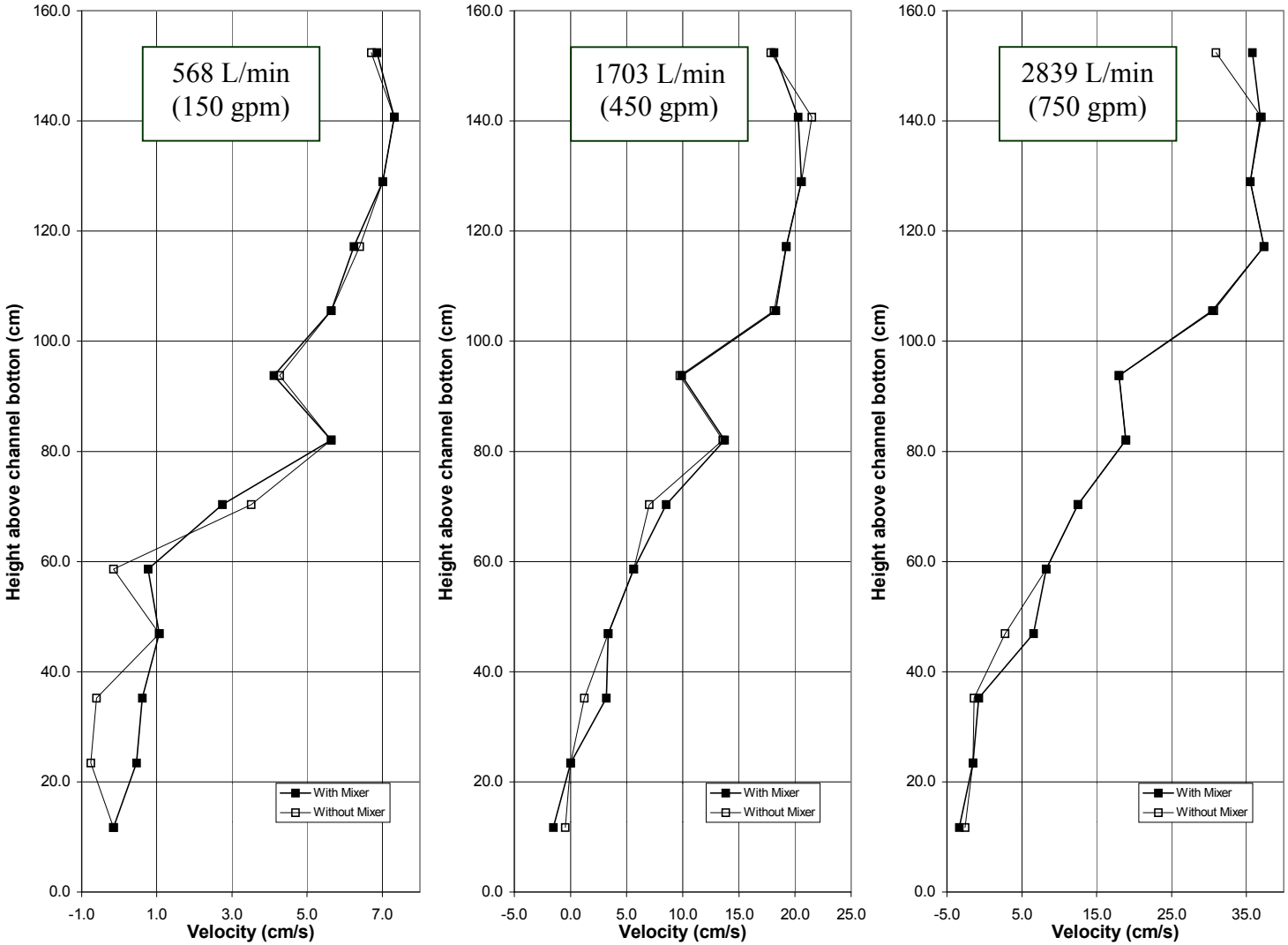

Figure 7-1. Influent velocity profiles with and without mixer.

Appendices

A Verification Test Plan for the Ondeo Degremont, Inc. UV Aquaray® 40 HO Disinfection System Reuse Applications, V 3.1.

B Operation and Maintenance Manual for the Aquaray® 40 HO UV Disinfection System, and Operation and Maintenance Manual for the Aquaray® 10 HO VLS Title-22 Test Channel.

C Master Data Volumes 1 and 2: ODI Aquaray® 10 ETV Reuse Testing Program.

D Spreadsheets, Data Summaries, and 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) - 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.

Field Testing Organization (FTO) - An organization qualified to conduct studies and testing of induction mixers in accordance with the Verification Protocol.

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 an undosed 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.

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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