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Environmental Technology Verification Report

UV Disinfection of Secondary Effluent

SUNTEC *environmental*, Inc.
LPX200 UV 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 SECONDARY EFFLUENT**
TECHNOLOGY NAME:	**LPX200 UV DISINFECTION SYSTEM**
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NSF International (NSF) manages the Water Quality Protection Center (WQPC) under the U.S. Environmental Protection Agency's Environmental Technology Verification (ETV) Program. The WQPC evaluated the performance of the SUNTEC *environmental*, Inc. (SUNTEC) LPX200 UV Disinfection System (LPX200) for use with secondary wastewater effluent at UV transmittances of 55 and 65 percent. HydroQual, Inc. (HydroQual) performed the verification testing.

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

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

Technology Description

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

The LPX200 uses high-output, low-pressure ultraviolet (UV) lamps, oriented horizontally and parallel to the direction of water flow. Each lamp has a UV output rating of approximately 68 W at 254 nm and a total power draw of 210 W. The lamps have an effective arc length of 162.6 cm. The quartz sleeves are test-tube type, with one sealed end and an outer diameter of 23 mm. The sleeves are composed of Type 214 clear fused quartz with a wall thickness of 1.50 mm, resulting in a UV transmittance of approximately 90 percent. SUNTEC supplies the UV lamps in modules that can be linked together to form systems based on the design flow requirements.

The lamp modules supplied for the verification test consisted of two columns of five lamps each. Two modules were mounted parallel in the channel for a 20-lamp, 5 by 4 matrix configuration. The resulting lamp array had a uniform lamp spacing of 8.9 cm. Each lamp had a dedicated electronic ballast that was enclosed in a round, stainless steel housing at the head end of the quartz sleeve assembly and was submerged in the wastewater for cooling. Each lamp module was equipped with an automatic sleeve cleaning system designed to simulate its effect on the hydraulic behavior of the standard module assembly. In accordance with the testing protocol, the wipers were not actively operational during the verification testing, and the sleeves were cleaned manually before each flow series.

The LPX200 system was controlled with the standard Power Distribution Center (PDC) computerized control. The PDC system, enclosed in a NEMA 4X enclosure, had a user interface and display and contained a control card (microprocessor) that monitored individual lamp status, elapsed time, and detector inputs for controlling the disinfection process. The power supply to the system was 120/240V single-phase AC. The PDC contained Lamp Rack Control Modules (LRCM). Each LRCM controlled five ballasts and was interfaced with the control card, to allow adjustment of lamp ballast power from 60 to 100 percent.

The LPX200 modules were housed in a 6.5 m long, open, stainless steel channel. The effective disinfection zone was approximately 0.36 m wide and 1.62 m long. The channel was fitted with a 1.07 m square influent approach box with a flow diverting baffle, a 2.4 m straight approach before the UV reactor, and a 1.0 m straight exit after the reactor and before the weir. An automatic level control gate regulated the water level in the channel with a pivoting weight system that operated over a wide range of flow rates.

Verification Test Description

Test Site

The test site was located at the Parsippany-Troy Hills Wastewater Treatment Plant (PTRH) in Parsippany, New Jersey. The test site had two, 80,000-Liter tanks for preparation of challenge water and a 71 hp centrifugal pump to provide challenge water to the LPX200 at flow rates up to 7,600 L/min or recirculation flow rates of 1,100 L/min for mixing in the tanks. Flow to the LPX200 was metered using a magnetic flow meter, which was calibrated before testing using the tank drawdown method.

Methods and Procedures

All methods and procedures followed the *ETV Verification Protocol for Secondary Effluent and Water Reuse Disinfection Applications* (protocol), dated October 2002. The LPX200 was tested under Element 1, dose delivery verification of the protocol for secondary effluent at transmittances of 55 and 65 percent.

HydroQual installed the LPX200 at the test site in conjunction with SUNTEC. Before dose delivery verification testing began, the lamps were aged for 100 hours to allow the lamp intensity to stabilize. One lamp was replaced during the initial startup before burn-in. The burn-in period spanned five days, during which the lamps were not turned off or restarted. There were no further lamp failures.

Power consumption for the LPX200 system was measured separately from the dose delivery tests. The power measurements included: (1) overall power consumption, as measured by a kilowatt-hour meter connected to the main power supply; (2) power consumption after the power was stepped down through the transformer; and (3) discrete power readings of voltage, current, and power to each of the four ballast boards.

Headloss measurements were determined by monitoring the channel depth at seven locations that were spaced before and after the LPX200. Hydraulic behavior of the LPX200 was also characterized using a UV absorbing tracer to perform the step-feed tracer method.

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 lamp racks were lifted from the channel, manually cleaned, and inspected. The lamp racks were returned to the channel and kept on overnight at 100 percent power with water flowing. The lamps were turned down to the target intensity (end-of-lamp life) of 70 percent by adjusting the control panel and were allowed to stabilize for a minimum of 30 minutes. Finally, the wiping system was manually activated for one cleaning cycle to remove any accumulated debris or lint and to ensure that the wiper assembly was returned to its proper, idle position.

A batch of challenge water was prepared immediately before each flow test series by filling the tank with potable water 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 of either 55 or 65 percent. 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. Flow testing was conducted by pumping the water through the channel at the specified flow rate with the lamp intensity set at the simulated end-of-lamp life condition of 70 percent. Each of the five flow conditions was replicated at least four times for each transmittance tested. Flow rates for the 55 percent transmittance test were 379, 757, 1,890, 3,030, and 4,160 L/min**.** Two runs were also made at 5,680 L/min. Flow rates for the 65 percent transmittance test were 757, 1,890, 3,030, 4,160 and 5,680 L/min.

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 SUNTEC system was monitored while operating at the 100 percent power setting, which represents the unit's maximum power consumption level. Power consumption measured at the 480 V three-phase service was 4,860 W; power consumption at the 120/240 V supply was 4,560 W.

This indicates a transformer and transmission efficiency of 94 percent. The total power draw of the four LRCMs was 4,360 W. (The additional 200 W represents power consumed by the enclosure heater and other circuitry in the control box.)

Headloss though the lamp modules exists at any non-negligible flow rate, arising from the hydraulic resistance of obstacles such as lamps and mounting hardware. In ideal, turbulent systems, the headloss increases as a function of the square of flow velocity. For the LPX200 system used in this test, the headloss (cm) as a function of flow velocity (cm/s) is approximated by the relation:

$$headloss = 3.91 \text{ X } 10^{-4} \, (velocity)^2 + 0.0242 \, (velocity) + 0.475$$

The headlosses were measured in the range of velocities used for the bioassay validations in this verification. They cannot be extrapolated to different velocities or channel configurations. The flow velocity through a full-scale system must be determined before these headloss data can be applied.

The hydraulic parameters derived from the step-response behavior of the SUNTEC unit were within accepted engineering limits, as determined by five typical methods of analyzing the tracer data. These methods are detailed in the verification report. One exception was for the ratio of mean residence time to theoretical residence time for the higher flow rates. However, additional parameters representing the mean detention time were well within accepted limits, and the detention times were generally within accepted limits. While these data showed no evidence of short-circuiting or significant dead spots, it is important to realize that the tracer test was conducted in the central part of the lamp array. Non-idealities in the water flow near the channel walls would not have been identified in these tests.

Dose-Response Calibration Curve

Thirteen, valid, dose-response tests were conducted during this verification test. The delivered doses were corrected for 2.5 percent reflectance at the surface of the sample. The calibration curve for the MS2 bacteriophage stock was:

$$Dose = 1.6191(survival)^2 - 12.782(survival) + 1.6009$$

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

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

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

The calibration curve was validated using QC criteria for the acceptance of the dose-response data 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 providing 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 that reaches the fluid as well as the exposure time to an organism. Therefore, the MS2 bacteriophage log survival ratios measured on samples from the field, and presented in the final report for the LPX200 reactor, are converted to an effective delivered dose using the calibration curve from the dose response data. MS2 bacteriophage is used for the testing as 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 test flow data is based on the lower 75 percent confidence interval (C.I.) results. The results for the 20-lamp system are shown in Figure 1, where they are fitted with a power function. For comparison, the average dose delivery curve is also shown, and it tracks closely with the lower 75 percent C.I curve.

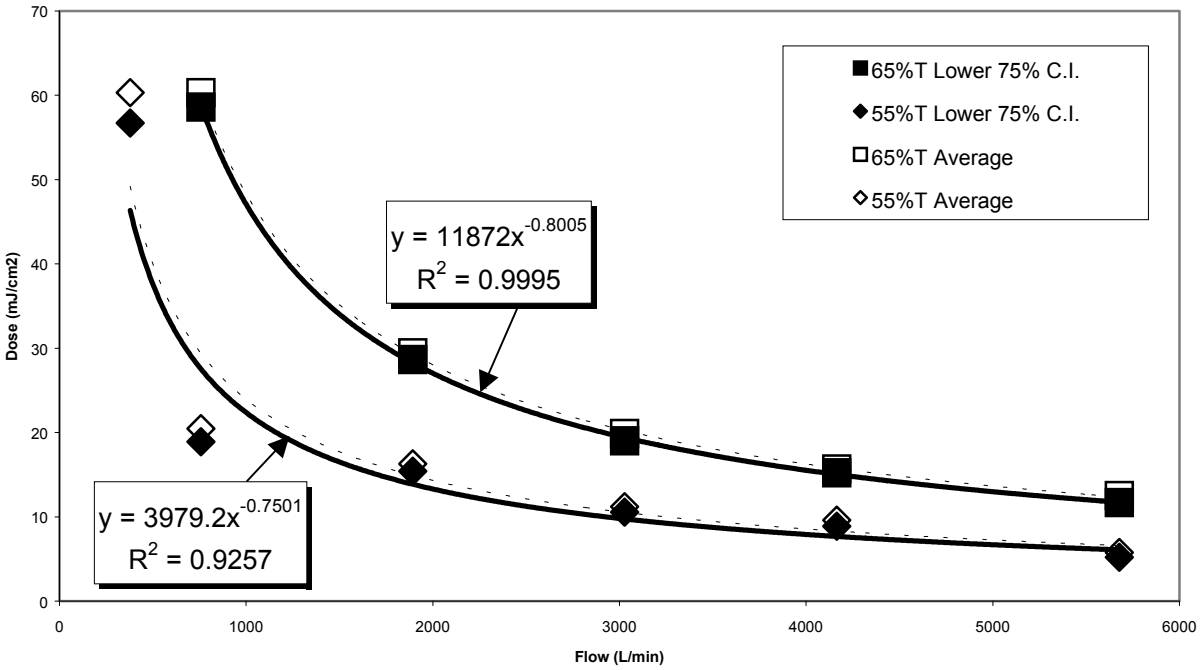

Figure 1. Dose Delivery Curves Based on Lower 75 Percent Confidence Intervals.

A second approach to understanding the dose delivery in the LXP200 is to relate it to lamp power. The power used in these calculations was for lamps at full power at the end-of-lamp life (70 percent). The data were rescaled and the relationship of flow per unit of power consumed (L/min/kilowatt) to the average dose delivery was determined using a power function. The relationships derived for the end-of-lamp life at 55 and 65 percent transmittance are:

For 55% Transmittance: $power\ usage(L/\min/kW) = 11163(dose)^{-1.2341}$

For 65 % Transmittance: $power\ usage(L/\min/kW) = 28721(dose)^{-1.2485}$

An alternative way to view the results from these dose delivery verification tests is to normalize the dose delivery to L/min per lamp. This allows a potential UV disinfection system user to estimate the number of lamps that would be needed for a certain application. The data are analyzed in the same manner as in Figure 1, except the vertical (y) axis is rescaled to reflect the hydraulic loading per lamp. The relationships derived for the end-of-lamp life for 55 and 65 percent transmittance are:

For 55% Transmittance: $hydraulic\,loading\,(L/\min\,/lamp) = 2422.3(dose)^{-1.2341}$

For 65 % Transmittance: $hydraulicloading\,(L/\min\,/lamp) = 6134.8(dose)^{-1.2485}$

Further discussion on these equations is included in the verification report.

Scalability

The protocol identifies the elements of UV system design that are critical for designing larger systems based on the data obtained from the verification. The appropriate data for these design elements were obtained during the verification and are reported in detail in the verification report. The report also provides a further discussion on application of the data.

Quality Assurance/Quality Control

NSF performed QA/QC audits of the test site at PTRH and HydroQual during testing. These audits included: (1) a technical systems audit to assure the testing was in compliance with the test plan, (2) a performance evaluation audit to assure that the measurement systems employed by HydroQual were adequate to produce reliable data, and (3) a data quality audit of at least 10 percent 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 International, EPA QA personnel conducted a quality systems audit of NSF International's QA Management Program, and accompanied NSF during audits of the HydroQual facilities.

Original Signed by	
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Availability of Supporting Documents

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

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

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

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.)

September 2003

Environmental Technology Verification Report

Verification of Ultraviolet (UV) Disinfection For Secondary Effluent

SUNTEC *environmental*, Inc. LPX200 UV 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 EPA is charged by Congress with protecting the nation's land, air, and water resources. Under a mandate of national environmental laws, the EPA 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 provides 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 technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication was produced as part of the NRMRL'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

C	Celsius
CFD	Computational fluid dynamics
C.I.	Confidence interval
cm	Centimeter (10^{-2} meters)
EOL	End-of-life
EPA	United States Environmental Protection Agency
ETV	Environmental Technology Verification
gpm	Gallons per minute
Hg	Mercury
hp	Horsepower
HydroQual	HydroQual, Inc.
I	Intensity
ISO	International Standards Organization
kg	Kilogram
kW	Kilowatt
LRCM	Lamp rack controller module
L	Liter
L/min	Liters per minute
log	Base 10 logarithm
m	Meters
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	Milliwatt per square centimeter
nm	Nanometers (10^{-9} meters)
NRMRL	National Risk Management Research Laboratory
NSF	NSF International
O&M	Operation and maintenance
PDC	Power Distribution Center
pfu	Plaque forming units
pfu/mL	Plaque forming units per milliliter
PLC	Programmable Logic Center
PTRH	Parsippany-Troy Hills Wastewater Treatment Plant
QA	Quality assurance
QC	Quality control
RPD	Relative percent difference
SAG	Stakeholder Advisory Group
Sec	Second

SUNTEC	SUNTEC *environmental* Inc.
SWP	Source water protection area, Water Quality Protection Center
T	Transmittance
TO	Testing organization
UV	Ultraviolet
UVC	Ultraviolet radiation in the range of 230 nm to 280 nm
V	Volt
VTP	Verification test plan
W	Watts
WQPC	Water Quality Protection Center

Chapter 1
Introduction and Background

1.1 The ETV Program

1.1.1 Concept of the ETV Program

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

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

A technology panel formed through NSF oversaw the development of the *Verification Protocol for Secondary Effluent and Water Reuse Disinfection Applications* (NSF, 2002). 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 SUNTEC environmental, Inc. UV Disinfection System for Secondary Effluent 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 (T) 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% T
  - 65% T
  - 75% T

- Reuse Application test conditions (National Water Research Institute and American Waste Water Association Research Foundation, 2000):
  - Granular or Fabric Media 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 system 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 for the technology verification. As 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 the applications of the 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 SUNTEC environmental, *Inc. (SUNTEC) ETV*

This verification test of the SUNTEC LPX200 UV disinfection unit focused on the dose delivery, which is the most critical operational behavior and is evaluated within Test Element 1. SUNTEC chose not to verify the technology against Test Elements 2 and 3 of the protocol.

The test consisted of dose delivery verification for secondary effluent applications at 55% and 65% water transmittance with a lamp-aging factor of 70%. It involved using transmittance-adjusted, potable, challenge waters for bioassay testing, headloss measurements, and detention time analysis using a step-response method.

1.2 Mechanism of Ultraviolet (UV) Disinfection

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

Medium-pressure lamps operate between 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 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 than 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, watts/cm^2) and the exposure time (t, seconds) experienced by a population of organisms. The effective intensity of the radiation is a function of the lamp output and of the factors that attenuate the energy as it is deposited into the

water. Such attenuating factors include 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 ameliorates 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 prevented 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 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 the verification tests, the bacteriophage MS2 was used. The survival ratio of the organism is calibrated to a well-controlled UV dose in the laboratory with a dose-response procedure. The same organism is then used to field-challenge the actual disinfection system under specified conditions. 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 average germicidal UV exposure of all parcels of water.

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;
- Preparation and dissemination of the Verification Statement.

Key contacts at NSF relating to this VTP include:

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2.2 EPA's Role

EPA Office of Research and Development, through the Urban Watershed Management Branch, Water Supply and Water Resources Division, NRMRL, provided administrative, technical, and quality assurance guidance and oversight on all WQPC activities. In addition to disseminating the Verification Report and Verification Statement, EPA had review and approval responsibilities for these documents:

- Verification Test Plan
- Verification Report
- Verification Statement

The key EPA contact for the WQPC is:

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

2.3 TO's Role

The selected TO, HydroQual, Inc., 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 was the project microbiologist. 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 and 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;
- Reviewing, approving and/or assisting with activities that affect the plant, such as electrical connections from the plant's main feed.

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
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 Wastewater Treatment Plant (PTRH) 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;
- 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 PTRH 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 to be verified was provided by SUNTEC; it represented a scalable version of their LPX200 UV disinfection system. SUNTEC's responsibilities included:

- Providing the test unit for verification, along with all ancillary equipment, instrumentation, materials, and supplies necessary to operate, monitor, maintain and repair the system;
- Providing documentation and calculations necessary to demonstrate the system's conformity to commercial systems, hydraulic scalability, and to the requirements of the protocol;
- Providing descriptive details of the system, its operation and maintenance, and its technical capabilities and intended function in secondary effluent applications;

- Providing technical support for the installation and operation of the UV system, including designating 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 SUNTEC is:

Dr. Elliott Whitby
SUNTEC *environmental*, Inc.
106 Rayette Road – Unit #1
Concord, Ontario
CANADA L4K 2G3
(905) 669-4450
(905) 669-4451 (fax)
Email: ewhitby@suntecuv.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 SUNTEC. 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 SUNTEC *environmental* UV Disinfection System

The O&M manual (see Appendix B) describes the LPX200 UV disinfection system supplied by SUNTEC.

3.1.1 Lamps and Sleeves

The LPX200 UV unit uses high-output, low-pressure GXO74T5LS lamps that are oriented both horizontally and parallel to the direction of flow (see Figure 3-1). Each lamp has a UV output rating of approximately 68 W at 254 nm and a total power draw of 210 W. The lamps have an effective arc length of 162.6 cm.

The quartz sleeves are test-tube type, with one sealed end and an outer diameter of 23 mm. The sleeves are composed of Type 214 clear fused quartz with a wall thickness of 1.50 mm, resulting in a UV transmittance of approximately 90%. Figure 3-1 shows a diagram of the lamp rack assembly. Figure 3-2 shows the channel in which the two lamp racks were installed.

3.1.2 Lamp Aging

SUNTEC conducted a lamp-aging test at the wastewater treatment plant in Horse Cave, Kentucky. This testing was not completed as part of the ETV testing program, but provides important input for the testing conditions under this ETV. SUNTEC used an LPX200 system with 24 of the same, GXO74T5LS, lamps and ballasts used for the verification testing presented here. The system was operated nearly continuously with few on/off cycles. Testing was conducted from May 2001 to September 2002.

Lamp intensity was measured with the lamps removed from the disinfection system and installed in an LPX200 quartz sleeve inside a laboratory-scale, water-cooled, test apparatus. Recirculated deionized water at 15° C was used as the cooling medium, and the lamps were allowed 24 hours to stabilize before the readings were taken. The intensity was measured with an IL-1700/SUD-240 radiometer through a quartz window mounted halfway along the length of the lamp. The lamps were driven with ballasts identical to those used in the full-scale system.

At the start of operation, the outputs of six lamps were measured after a 100-hour burn-in to establish a baseline for lamp degradation. At 5,925 hours, the output of six lamps was measured. At 11,338 hours, the output of 18 lamps was measured.

Figure 3-3 shows the lamp aging data acquired during the Horse Cave experiment. While the final outputs average approximately 85% of the starting outputs, the lowest intensities are at approximately 70%. Based on these results, SUNTEC requested the verification tests be conducted at 70% lamp output. This level is more conservative than the requirements in the Verification Protocol and is intended to be a worst-case scenario.

3.1.3 Lamp Intensity vs. Temperature

The UV radiation output of a low-pressure mercury discharge lamp varies with the operating temperature of the lamp. This can change the effective germicidal dose delivered to the wastewater stream, depending on the operating conditions. To address this operating variable, SUNTEC conducted tests to determine the relative lamp output as a function of temperature. This testing was not completed as part of the ETV testing program, but provides important input in selection of the ETV testing conditions.

While the operating temperature of the lamp is the main control on this variability, the temperature of the water in which the lamp and sleeve assembly is submerged is the practical operational variable to be quantified. As a result, SUNTEC performed the lamp intensity experiments in a chamber in which the water temperature could be controlled. The experiments were performed in the same test rig previously described in the lamp aging test in Section 3.1.2, however, the water temperature was set to different values in the range of 5 °C to 30 °C. The lamp was allowed to stabilize before measurements were taken.

Eight lamps were used and were driven by two different ballasts. The lamp intensity data is shown in Figure 3-4. While there is some variability in the behavior of the lamp and ballast configurations, it is clear that there is a maximum intensity in the range of 15 °C to 20 °C. The data set for each lamp was normalized to the maximum intensity and calculated as a percent of intensity. The average behavior of all eight lamps is shown in Figure 3-5.

As shown in Figure 3-3, the maximum lamp output occurs when the water temperature is approximately 17 °C. Further, water temperatures in the range of 10 °C to 23 °C result in a reduction of lamp output intensity to only 95%. Thus, the temperature range of the challenge waters employed during this test (~ 12-13 °C) resulted in a reduction of efficiency of less than 5%.

3.1.4 Lamp Modules

The lamp modules supplied for this verification test consisted of two columns of five lamps each (see Figure 3-1). Two such modules were mounted parallel in the channel for a 20-lamp, 5 x 4 matrix configuration (see Figure 3-2). The resulting lamp array had a uniform lamp spacing of 8.9 cm.

Each lamp was driven by a single electronic ballast. This ballast was enclosed in a round, stainless steel housing at the head end of the quartz sleeve assembly and was submerged in the wastewater for cooling. The ballast was concentric with the quartz sleeve and was attached with an o-ring compression fitting for a watertight seal.

Each vertical column of lamp and ballast assemblies was supported by two, thin, vertical, stainless steel supports. The wiring conduits supplying the ballasts were in line with each lamp column to produce a minimal hydraulic cross section (see Figure 3-1).

3.1.5 Sleeve Cleaning System

Each lamp module was equipped with an automatic sleeve cleaning system that simultaneously cleans all the sleeves on a lamp rack. The system consists of stainless steel spring-type sharpened wires that are driven the full length of the quartz sleeve with a motor and lead-screw drive (see Figure 3-1). The control panel allows a cleaning interval of 1 to 999 hours; it also permits manual cycling of the wipers.

The standard wiping system was present on the test unit to simulate its effect on the hydraulic behavior of the standard module assembly. The wipers were not actively operational during the verification testing because the sleeves were cleaned manually before each flow series. However, the wipers were tripped once after manual cleaning to dislodge any possible lint or debris and to ensure that the wiper assembly was returned to its proper idle position.

3.1.6 Electrical Controls

The LPX200 system supplied for this verification test was controlled and driven with the standard Power Distribution Center (PDC) computerized control offered by SUNTEC (see Appendix B). This PDC system was enclosed in a NEMA 4X enclosure with a user interface and display. It contains a programmable logic controller (PLC) that monitors individual lamp status, elapsed time counters, and detector inputs that control the disinfection process. The power supply to the system was 240/120V single-phase AC.

The PDC contains Lamp Rack Controller Modules (LRCM), each of which controls five ballasts. The failure of one lamp or ballast does not interfere with the operation of the other four lamps. The LRCM's were interfaced with the control card to allow adjustment of lamp ballast power from 60-100%.

3.1.7 UV Sensors

The disinfection system used for the verification was not supplied with a UV intensity sensor, because a sensor is not necessary for the secondary effluent verification test. However, the control card allows the interface of two UV sensors to monitor the disinfection performance as the water properties change and as the lamp and sleeve condition deteriorates.

3.1.8 Design Operational Envelope

The system verified in this test was designed for operation at flow rates of up to 5678 L/min (1500 gpm). This corresponds to a scalable flow rate of up to 284 L/min (75 gpm) per lamp. Higher flow rates create too large a headloss to keep the lamps properly covered. This verification program simulated a lamp output of 70%, which is slightly more conservative than the 75% specified in the Verification Protocol. This condition was chosen to simulate intensity reduction due to lamp aging and quartz fouling.

Because the LPX200 disinfection system is used for a variety of wastewater disinfection applications, various operational scenarios can be used. A system such as the unit tested in this

verification test can be operated without UV detectors. This scenario requires a regular maintenance schedule involving sleeve cleaning and lamp replacement at the manufacturer's recommended intervals.

Another operational scenario, which was not evaluated in this verification test, could employ an intensity feedback system that can monitor and adjust the lamp power and dose delivery based on lamp intensity and the flow rate of the wastewater. Full validation of this operational scenario would require completion of Test Element 2 of the Verification Protocol.

3.2 UV Test Unit Specifications

3.2.1 Test Channel

The reactors were housed in a 6.5 m long, open, stainless steel channel (see Figure 3-2). The effective disinfection zone was approximately 0.36 m wide and 1.62 m long. The channel was fitted with a 1.07 m square influent approach box with a flow diverting baffle, a 2.4 m straight approach before the UV reactor, and a 1.0 m straight exit after the reactor and before the weir. An automatic level control gate regulated the water level in the channel with a pivoting weight system that operated over a wide range of flow rates. This controlled the level of the water so that the effluent end of the lamps were submerged under 1-2 cm of water.

3.2.2 Scaling Considerations

The 20-lamp LPX200 system tested under this verification program is one possible configuration offered by SUNTEC. Larger disinfection needs can be met by expanding the lamp matrix in both vertical and horizontal directions. The lamp modules are offered in configurations containing up to 16 lamps in two, eight-lamp columns (the present unit contains two, five-lamp columns). Adding parallel lamp modules can expand each lamp bank in the horizontal direction.

The scalability of these ETV results is predicated on the assumption that certain operating conditions are identical in a full-scale system. The full-scale system must use the same lamps, sleeves, ballasts, driving circuitry, lamp and sleeve mounting hardware, and sleeve cleaning system. Geometric conditions that must be similar between the test system and full-scale systems are: lamp spacing, distance between the lamps and the walls, and submersion of the upper lamp row. Full-scale systems must be operated in the same range of wastewater flow velocities and/or detention times as those evaluated in this verification test.

These verification results cannot be used on smaller systems, but can be extended to systems up to ten times the capacity of the test unit evaluated in this verification test. Thus, the maximum-sized system in a single channel could have up to 200 lamps. Multiple, parallel channels must be used to achieve greater flow capacities.

3.3 Verification Test Claims

The overall objective of this verification test was to validate the performance of the SUNTEC LPX200 UV disinfection system for secondary effluent applications. Transmittances of the test

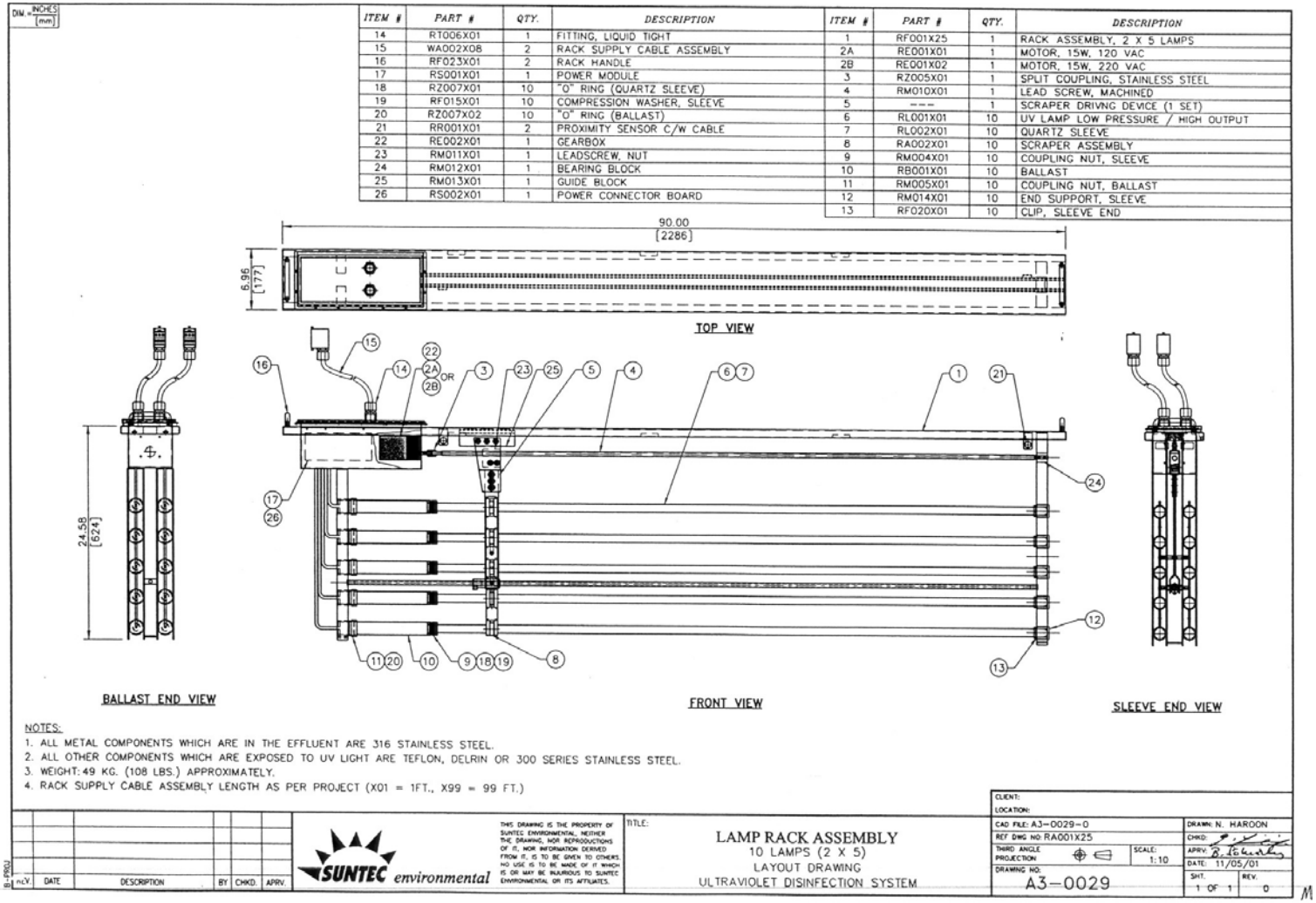
waters were adjusted to simulate secondary effluent applications. Lamp intensity was reduced to simulate a dose delivery reduction to 70% due to fouled sleeves and aged lamps. Within this objective, the test fulfilled three specific goals:

1) The test quantified the flow-dose relationship for secondary effluent applications with wastewaters that have UV transmittances of 65% at 254 nm.

2) The test quantified the flow-dose relationship for secondary effluent applications with wastewaters having UV transmittances of 55% at 254 nm.

3) The test measured the hydraulic characteristics of the system by using hydraulic tracer analysis and headloss.

As allowed by the Verification Protocol, and at the discretion and decision of SUNTEC, the performance of this disinfection system in wastewaters with a transmittance of 75% was not validated in this test program.



ITEM #	PART #	QTY.	DESCRIPTION
14	RT006X01	1	FITTING, LIQUID TIGHT
15	WA002X08	2	RACK SUPPLY CABLE ASSEMBLY
16	RF023X01	2	RACK HANDLE
17	RS001X01	1	POWER MODULE
18	RZ007X01	10	"O" RING (QUARTZ SLEEVE)
19	RF015X01	10	COMPRESSION WASHER, SLEEVE
20	RZ007X02	10	"O" RING (BALLAST)
21	RR001X01	2	PROXIMITY SENSOR C/W CABLE
22	RE002X01	1	GEARBOX
23	RM011X01	1	LEADSCREW, NUT
24	RM012X01	1	BEARING BLOCK
25	RM013X01	1	GUIDE BLOCK
26	RS002X01	1	POWER CONNECTOR BOARD

ITEM #	PART #	QTY.	DESCRIPTION
1	RF001X25	1	RACK ASSEMBLY, 2 X 5 LAMPS
2A	RE001X01	1	MOTOR, 15W, 120 VAC
2B	RE001X02	1	MOTOR, 15W, 220 VAC
3	RZ005X01	1	SPLIT COUPLING, STAINLESS STEEL
4	RM010X01	1	LEAD SCREW, MACHINED
5	---	1	SCRAPER DRIVNG DEVICE (1 SET)
6	RL001X01	10	UV LAMP LOW PRESSURE / HIGH OUTPUT
7	RL002X01	10	QUARTZ SLEEVE
8	RA002X01	10	SCRAPER ASSEMBLY
9	RM004X01	10	COUPLING NUT, SLEEVE
10	RB001X01	10	BALLAST
11	RM005X01	10	COUPLING NUT, BALLAST
12	RM014X01	10	END SUPPORT, SLEEVE
13	RF020X01	10	CLIP, SLEEVE END

Figure 3-1. Diagram of Lamp Rack Assembly Used for Test System.

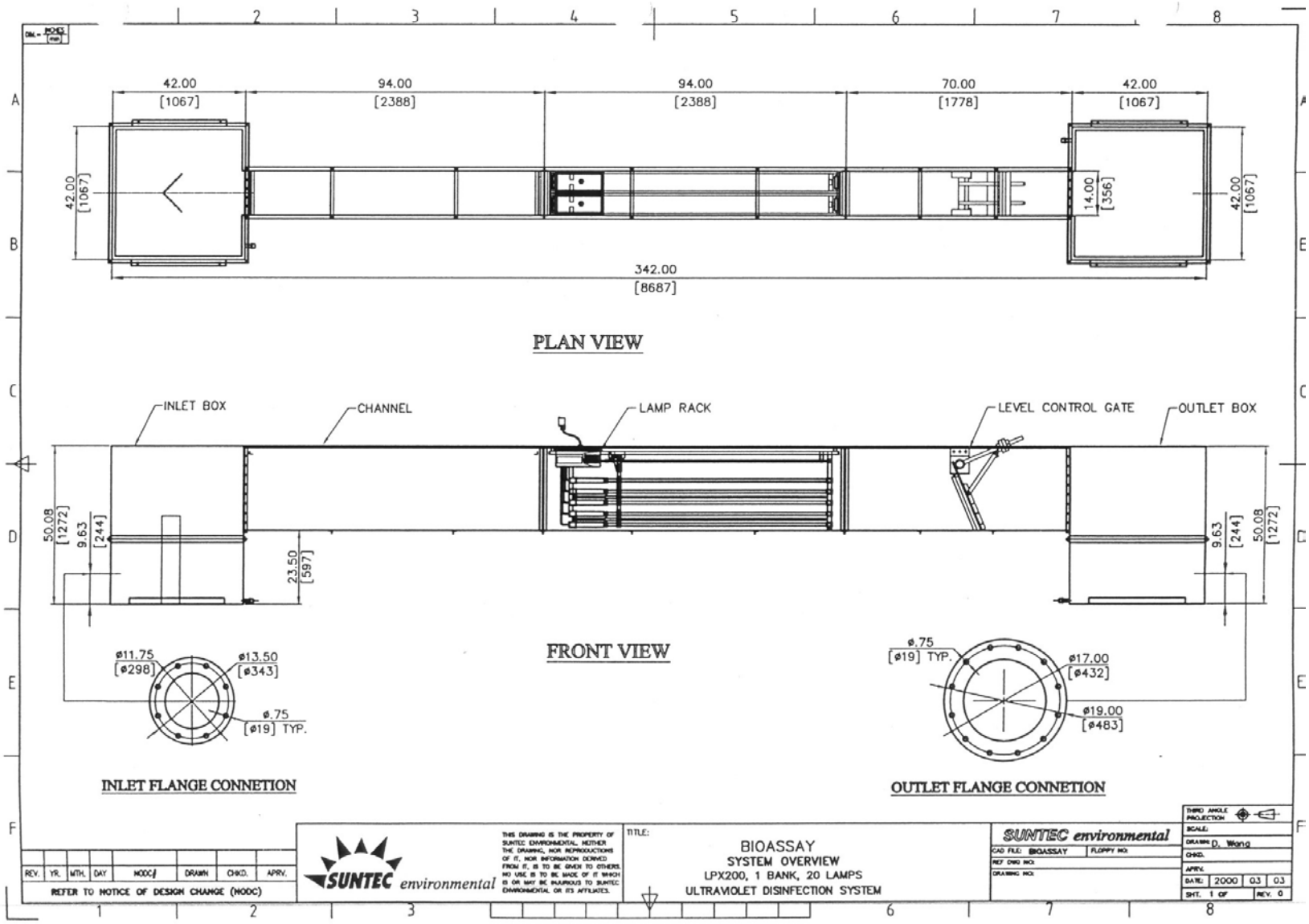


Figure 3-2. Schematic of SUNTEC Test Unit.

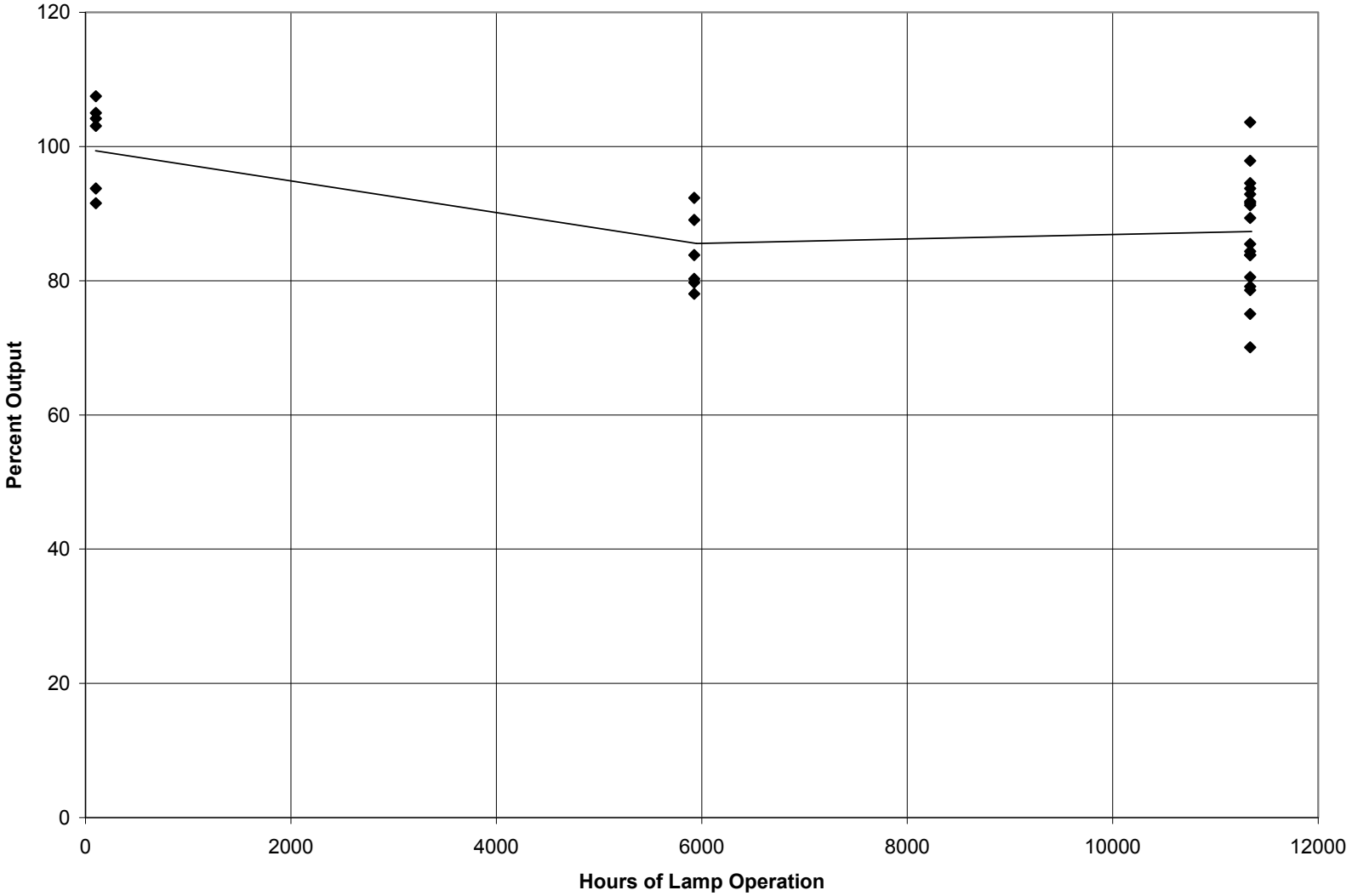


Figure 3-3. Lamp Intensity vs. Operational Age.

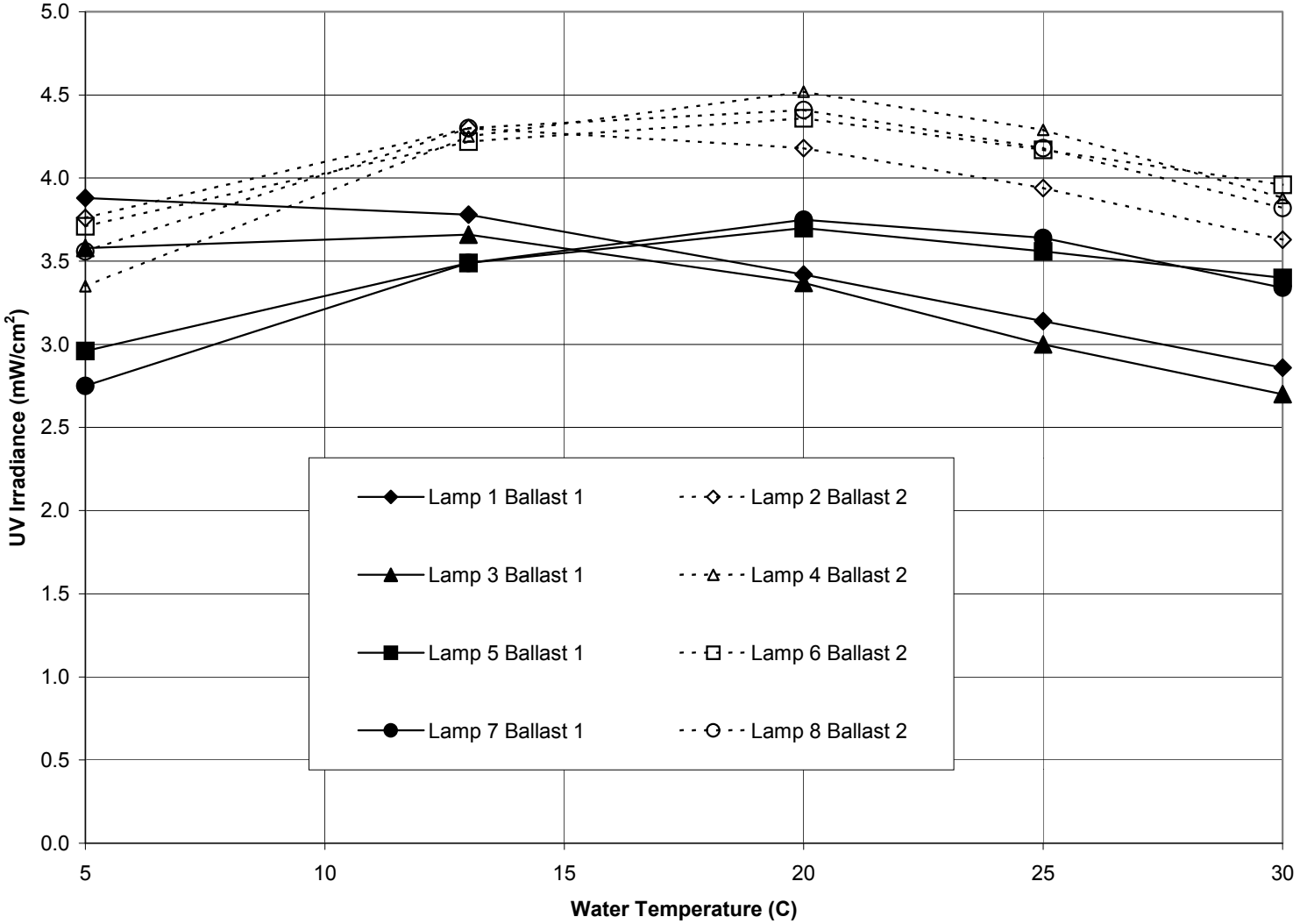


Figure 3-4. Lamp Intensity vs. Temperature for 8 Lamps.

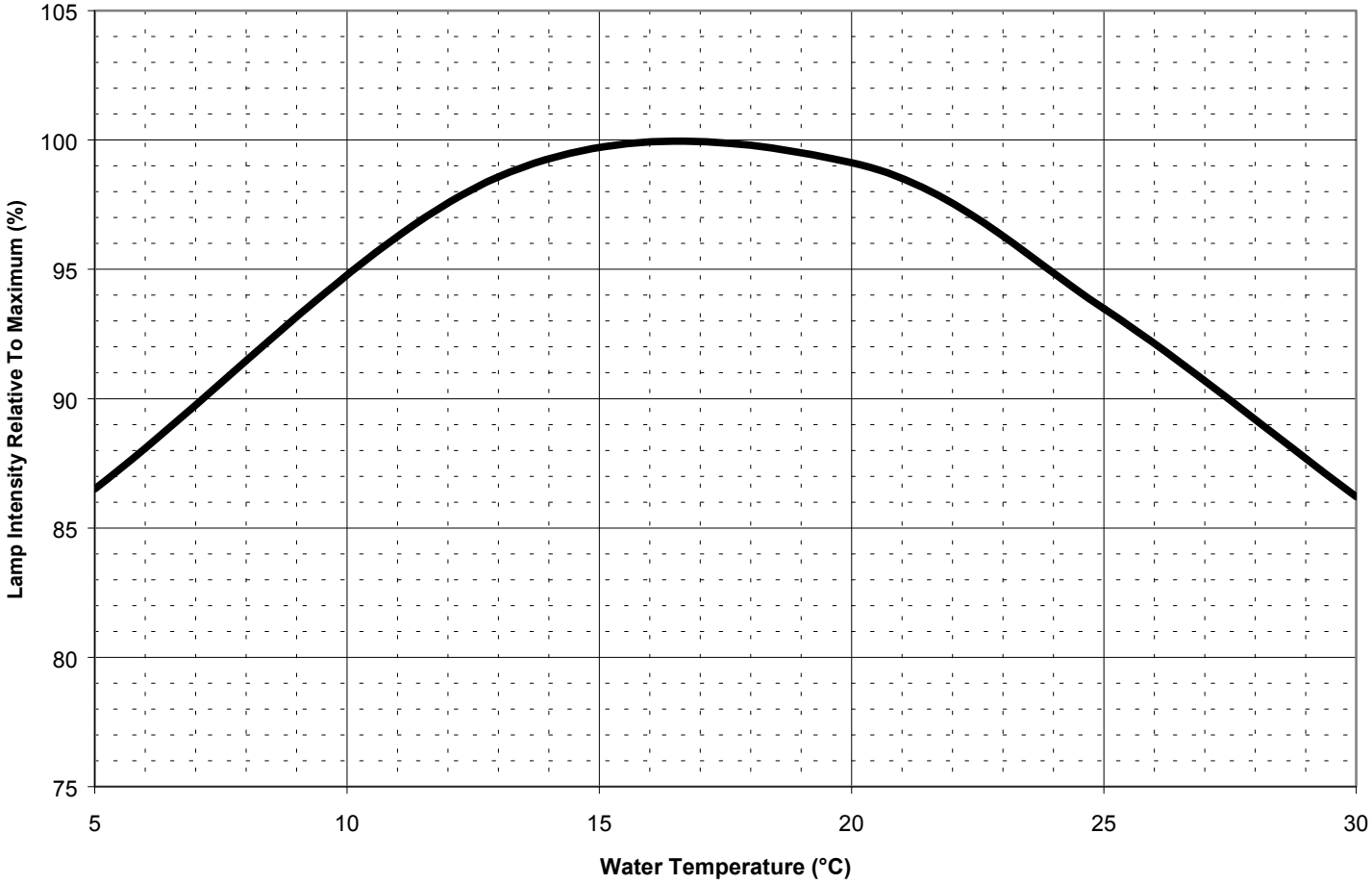


Figure 3-5. Average Percent Lamp Intensity as a Function of Temperature.

Chapter 4
Procedures and Methods Used During Verification Testing

4.1 Test Site Setup

4.1.1 General Description

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

The ETV installation occupied an area approximately 30 feet by 120 feet located between the main chlorine contact chamber and the primary clarifier for the old plant (see Figure 4-1). The south end of the test site was adjacent to an aeration tank, which was used to dispose of treated and untreated challenge waters. The test site included a semi-permanent structure for housing the test 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 SUNTEC disinfection unit. In brief, 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 allowed to flow out of the UV unit into the adjacent aeration tank. Power from PTRH's electrical supply was used for the test unit.

4.1.2 Water Source

The water for these bioassay tests was taken from a hydrant that provides potable water at PTRH. It was piped into the challenge water tanks where modifying agents such as sodium thiosulfate, instant coffee, and MS2 bacteriophage were added. The water was supplied at a rate of approximately 1100 L/min; it had a discharge temperature of 12-13 °C. Total chlorine, before the addition of modifying agents, was typically 1.0 mg/L.

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 tanks were supplied with a fresh coat 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.

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 1100 L/min to the rear of both tanks to enable mixing. The tanks were valved so that they could be isolated or operated in tandem.

4.1.4 Pump

The test challenge waters were pumped to the test 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 71 hp motor to provide flow rates up to 7600 L/min in the test configuration.

A ball valve on the discharge pipe of the pump was used as a sample port for the test challenge waters while the test batches were being mixed and prepared. Samples were drawn for total chlorine, pH, and 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 105 cm before and 70 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).

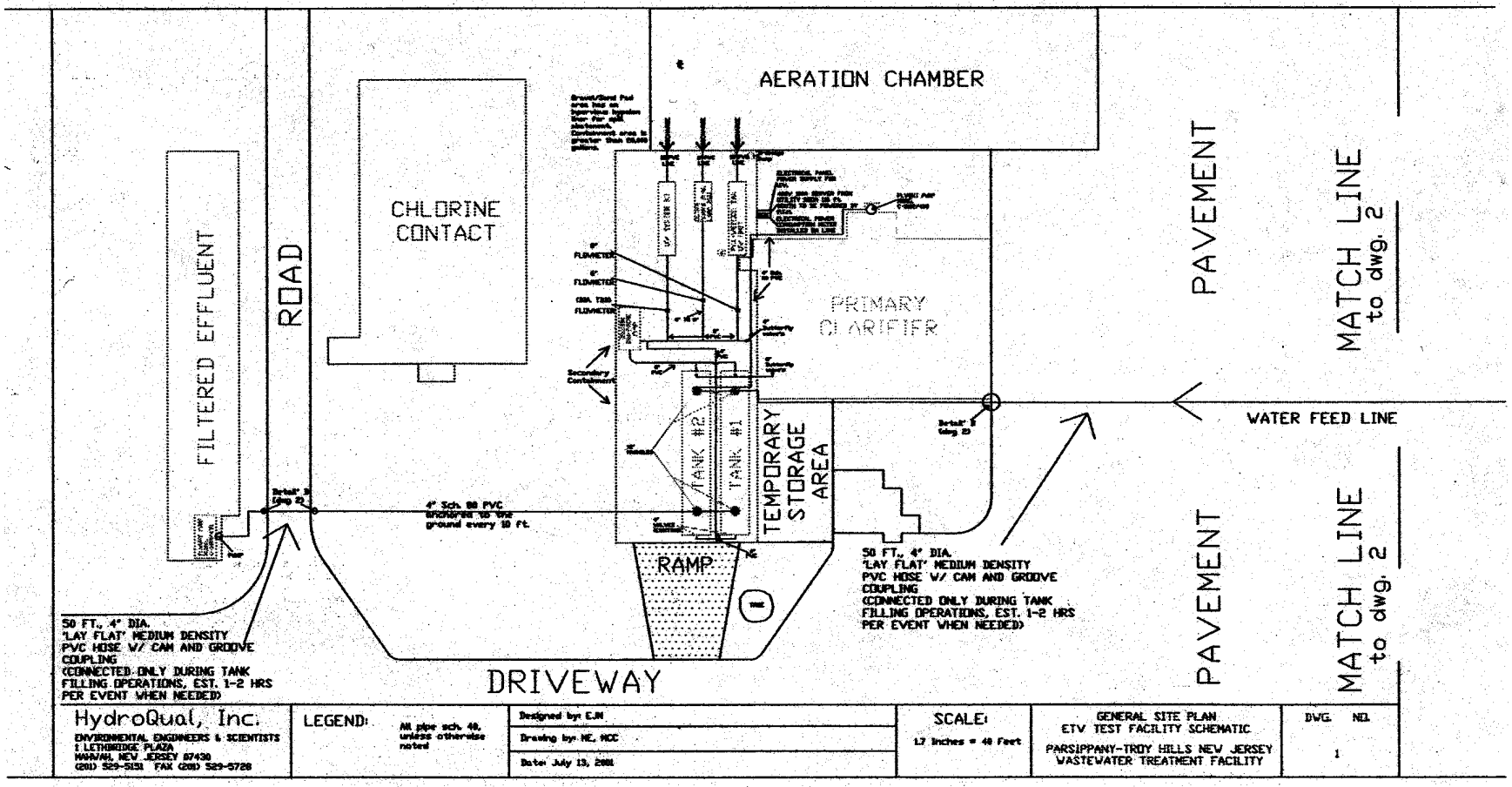


Figure 4-1. General Site Plan of the ETV Test Facility at the Parsippany-Troy Hills WWTP.

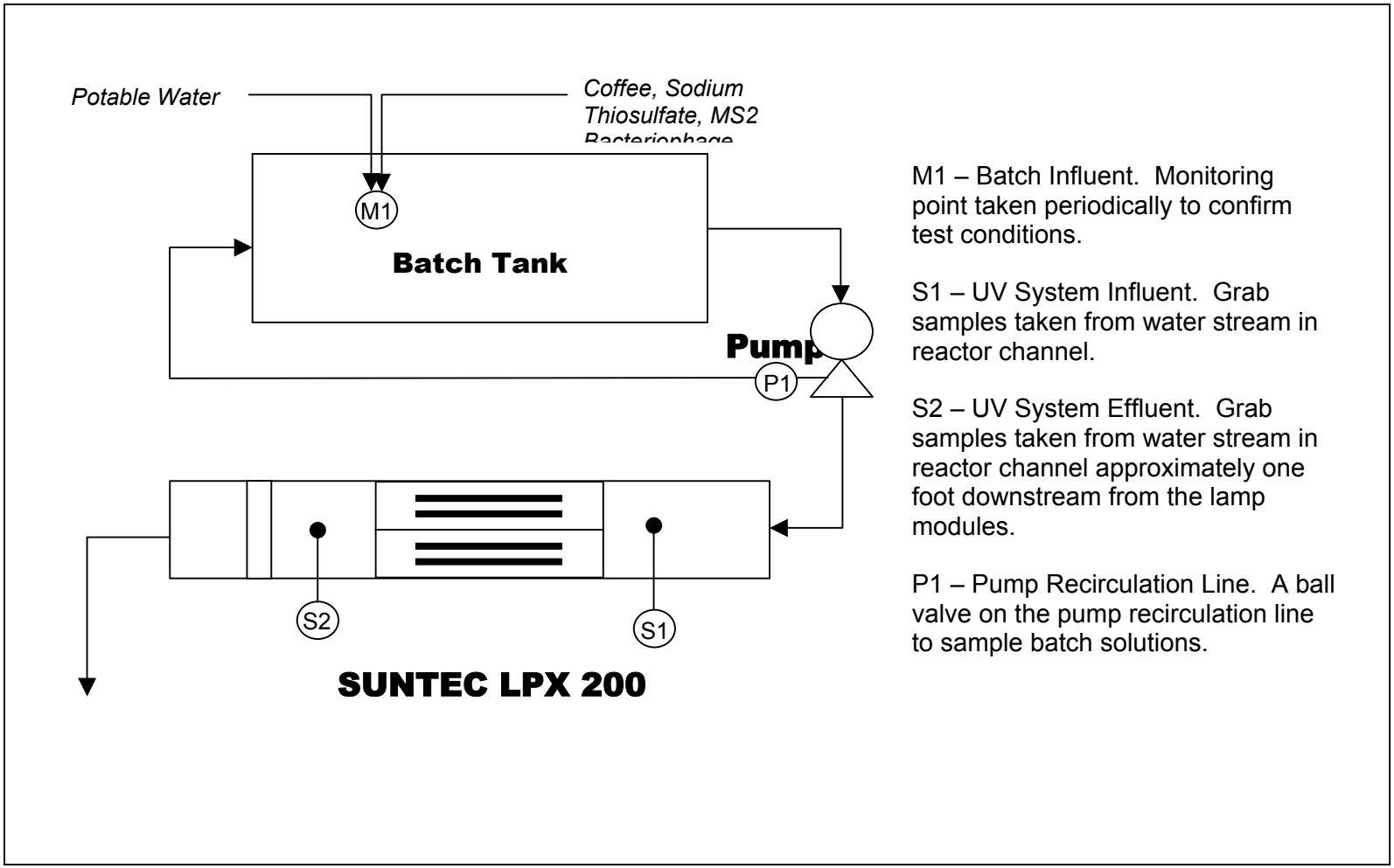


Figure 4-2. Flow Schematic and Sampling Points for Conducting This ETV.

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. Both HydroQual personnel and a technician from SUNTEC monitored this process. The lamps were turned on at 100% power with secondary effluent flowing through the channel at a rate of approximately 379 L/min (100 gpm) to prevent the lamps from overheating.

One lamp was replaced during the initial startup before burn in. The burn-in period spanned five days, during which the lamps were not turned off or restarted. No additional lamps failed.

4.2.2 Power Consumption and Intensity Turndown Characterization

4.2.2.1 Power Consumption Measurement

For this test program, the measurement of power consumption during the bioassay testing would not give representative results because the lamps were first operated at a lower power level to simulate reduced-output, end-of-life (EOL) conditions. Thus, the power consumption of the system was measured at three stages.

(1) The overall power consumption of the system was measured with a kilowatt-hour meter connected inductively to the main 480 V, 3-phase power supply of the test unit, inclusive of the transformer and the circuitry in the control panel.

(2) Power consumption was measured after the power had been stepped down through a transformer to the 120/240 V single-phase supply to the test unit's PDC.

(3) Additional discrete readings were taken by measuring the voltage, current, and power supplied to each of the four ballast control boards using a Fluke Model 39 power meter.

4.2.2.2 UV Output Intensity Measurement

The UV output intensity of the lamp module was measured with an International Light IL-1700 radiometer connected to a submerged SUD 240 UV detector that was mounted on a support located approximately 10 cm from one of the lamps. Once the detector was in place, it was not moved for the remainder of the monitoring period. Only relative readings can be acquired with a detector mounted in such a position because of the geometry of the lamp UV emission pattern and the input optic of the detector.

Readings for the lamp intensity were taken while potable water with a transmittance greater than 98% was flowing through the unit at a rate of 757 L/min (200 gpm).

4.2.2.3 Turnup and Turndown Behavior

The lamp output intensity of the SUNTEC LPX200 test unit can be adjusted on the PLC panel via a current percentage adjustment between 50% and 100% relative current, with 1% steps. Because the bioassay test flows were conducted under a simulated EOL condition, intensity adjustment was necessary. Thus, the behavior of the system with varying power settings was evaluated during the characterization of the unit.

With potable water flowing through the channel, the output of the lamps was correlated with the power settings on the control panel. The lamps were allowed to stabilize for two hours. Then the control panel was taken through several turndown steps and through the same steps back to 100% lamp current. Each adjustment was allowed to stabilize for 10 minutes, intensity readings were taken with the IL-1700 radiometer and SUD detector, and voltage and current to all four LRCM's were measured.

4.2.2.4 Intensity Stability

With potable water flowing through the channel, the lamps were turned on from a cold start and the intensity, voltage, and current were measured at 15-minute intervals for 2 hours. Then the lamps were taken through a turndown/turnup cycle (Section 4.2.2.3). Finally, the lamps were adjusted to the 55 percent power setting that was used for the ETV flows (resulting in 70 percent relative intensity) and monitored for one hour.

4.2.3 Headloss Measurements

Measurements of headloss were achieved by attaching measuring scales to the inside of the reactor channel. The channel was leveled within 0.5 cm before the start of the testing. The accuracy of the measurements was achieved by assuring level installation of the measuring scales with stationary water in the channel.

For this verification, the water level was measured at seven positions. The positions were located at 0.30 m, 0.85 m, 1.40 m, 2.44 m, 3.44 m, 6.04 m, and 6.49 m from the front end of the influent box. The 3.44 m location was approximately 30 cm in front of the integral ballasts; the 6.04 m location was approximately 30 cm after the end of the lamp sleeve.

The vertical datum was the bottom of the channel under the UV unit, thus these measurements represent the depth of water in the channel. Measurements in the influent box were taken from the same datum, for example a measurement of 41.0 cm in the influent box represents a water level 41.0 cm above the bottom of the channel. The actual water depth was greater because the influent box extended below the depth of the channel.

4.2.4 Hydraulic Detention Time Analysis

4.2.4.1 Experimental Apparatus

The hydraulic behavior of the test unit was characterized with a step-feed tracer method (U. S. EPA, 1986). A UV absorbing tracer (rhodamine dye) was slowly injected into the flowing water in the channel with a peristaltic pump at a rate approximating the flowing water. The injection point was located at the beginning of the lamp unit, approximately even with the ballast wires; this location was maintained in the center of the channel at mid-depth with an aluminum support rack.

The SUD 240 detector was located at the effluent end of the rack and used the lamp output as the light source for the relative transmittance measurements. The SUD 240 was connected to an IL-1700 radiometer and the output was recorded on paper charts. The distance to the lamps was minimized (~2 cm), and the intensity ratio was maintained at approximately 0.5 for the absence or presence of the dye. These two adjustments were made to operate the IL-1700 output at a nearly linear relationship with the rhodamine concentration.

The tracer was introduced into the reactor under steady state conditions for several volume changeovers to get a relative baseline transmittance of the tracer-spiked water. The tracer pump was shut off, and the chart was marked simultaneously. The step function was then recorded as the remaining tracer flushed from the lamp rack. This step-feed detention time measurement was repeated in triplicate for each flow rate.

4.2.4.2 Data Reduction

These step-feed tracer curves represent the advection-diffusion behavior of the water flowing through the central lamp rack assembly. The curves were digitized, and the function of concentration versus time, $C = f$ (t), was evaluated mathematically for various statistical parameters. In addition, the theoretical detention time is included for reference; this was calculated as the time it takes for a given flow rate to flush the volume of the channel minus the displacement of the submerged lamp assembly. The interpretation of these calculations is described in Section 5.1.3.

$$T = \text{Theoretical Residence Time:} \quad T = \frac{(ChannelVolume - LampModuleVolume)}{Flow\,Rate}$$

$$\theta = \text{Actual Residence Time:} \quad \theta = \frac{\sum C}{\sum tC}$$

t_p = Time of Peak Change in Tracer Level.

t_{10} = Time of 10% Tracer Concentration.

t_{50} = Time of 50% Tracer Concentration.

t_{90} = Time of 90% Tracer Concentration.

d = Dispersion Number : $d = 2\dfrac{\left(\sum t^2 C \Big/ \sum C - \theta^2\right)}{\theta^2}$

E = Dispersion Coefficient: $E = \dfrac{d\left(Length^2\right)}{\theta}$ (4-1)

4.2.5 Shakedown Flows

Before the verification test flow series began, three shakedown flows were conducted. The targeted transmittance was 65% and the flow rates were 5679 L/min, 3028 L/min, and 757 L/min. This allowed an initial calibration run of the test unit and allowed the dilutions for the microbiological enumeration to be determined. This also allowed a "test run" to enable the technicians to familiarize themselves with the equipment operation and sampling scheme. The flows were conducted using the methodology described in Section 4.4. The results are in Appendix C.

4.3 MS2 Production and Calibration

4.3.1 MS2 Propagation

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

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

Briefly, the host strain (*E. coli*) was grown at 37 °C in Trypticase, yeast-extract, glucose broth until the log-growth phase was reached. This time was determined by previously completing three growth curves of the same host-strain working culture. When the optimum log-growth phase was reached, the MS2 stock solution was pipetted into the bacterial growth culture to start the infection, which was allowed to continue overnight. During the following day, the culture media was filtered through 0.45 μm 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. Typically, sub-batches were prepared in 1.5 L volumes each day.

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 laboratory dose responses in 0.85% saline water, and field influent samples collected from the field-challenge batch solutions for flow tests. 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 calculations.

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: $$Time = Dose \times I \qquad (4\text{-}2)$$

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).

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

For this verification test, 15 dose-response runs were conducted. Nine were in 0.85% saline solution, four were conducted with 55% T seeded influent solution, and two were conducted with 65% T seeded influent solution.

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 sponges and an acidic cleaning solution (e.g., Lime Away). The lamp racks were placed in the channel, water was allowed to flow, and the lamps were kept on overnight at 100% power.

Before the daily flow test series, the lamps were turned down to the target intensity (to simulate EOL conditions) via a power adjustment on the control panel and allowed to stabilize for a minimum of 30 minutes. Finally, the wiping system was tripped manually for one cleaning cycle to remove any accumulated debris or lint and ensure that the wiper assembly was returned to its proper, idle position.

4.4.2 Challenge Water Batch Preparation

The bioassay flow tests were conducted on a mixture of potable water, instant spray-dried coffee, sodium thiosulfate, and MS2 bacteriophage. A batch of challenge water was prepared immediately before each flow-test series, either in a volume of 80,000 liters for one tank or 160,000 liters for two tanks, depending on the exact daily flow scheme. During the double-tank flow test series, the amounts of the modifying agents (coffee, sodium thiosulfate, and MS2 bacteriophage) were doubled.

First, the tank was filled approximately ¾ full with potable water, the total chlorine was checked, and 1.5 kg of sodium thiosulfate was added; this was approximately 6 times the amount required for neutralization of the chlorine. With the pump running, the tank was configured with a recirculation loop to provide mixing. 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 (55% or 65%), with frequent transmittance checks made. Finally, 0.5-1 liter of MS2 bacteriophage was added and allowed to circulate for 30 minutes to mix fully.

4.4.3 Flow Testing

Flow testing was conducted by pumping the water through the channel at the specified flow rate with the lamp intensity set at SUNTEC's simulated EOL condition of 70%. Enough time was allowed for at least five volume changeovers in the lamp assembly, 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 mid-channel, mid-depth, approximately 30 cm in front of the lamp bank. Effluent samples were collected at mid-channel, mid-depth, just upstream from the level control gate. 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 least four times for a total of 47 valid flow tests.

4.4.4 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 cell with a path-length of 1 cm. The zero reference was Grade 2 laboratory deionized water (ISO, 1987).

4.4.5 MS2 Enumeration

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

To summarize, 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 employed 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:

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

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

$$N = \text{MS2 Concentration in Dosed Sample} \qquad (4\text{-}3)$$

4.4.6 Delivered Dose Determination

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

Chapter 5
Results and Discussion

5.1 Disinfection Unit Startup and Characterization

5.1.1 Power Consumption and Intensity Turndown Characterization

5.1.1.1 Power Consumption

The power consumption of the SUNTEC system was monitored, while operating at the 100% power setting. Because the flow tests were conducted under a simulated EOL condition with reduced power draw, data used to characterize power consumption were acquired separately from the flow-test events. Thus, the data below represents the unit's operation at maximum power consumption levels.

Power consumption measured at the 480 V 3-phase service level was 4863 W; power consumption at the 120/240 V supply level was 4560 W, resulting in a transformer and transmission efficiency of 94%. The total power draw of the four LRCM's was 4358 W; the additional 202 W represents power consumed by the enclosure heater (200 W) and other control circuitry in the control box.

5.1.1.2 Lamp Output Stability

The lamp output intensity and power consumption were monitored through a characterization sequence consisting of a cold start, warm up, turnup and turndown adjustments, and the final turndown adjustment. Table 5-1 shows the elapsed time, intensity, and total LRCM power. The data are also presented in graphic form in Figure 5-1. Note that the data discontinuity in Figure 5-1 at 130-140 minutes represents the interval during which the turnup and turndown adjustments were made. See Table 5-1 for the actual times.

Table 5-1. Power and Intensity Stability Data.

Conditions	Elapsed Time (min)	Intensity SUD (mW/cm^2)	Total Power To LRCMs (W)
Cold Start 100% Power	0	0	0
	10	1.520E-06	4368
	25	1.597E-06	4332
	40	1.658E-06	4326
	55	1.715E-06	4319
	70	1.750E-06	4319
	85	1.793E-06	4338
	100	1.826E-06	4316
	115	1.832E-06	4351
Begin Turnup/Down	130	1.828E-06	4341
Return to 100%	265	1.760E-06	4340
	280	1.242E-06	2828
	295	1.267E-06	2848
	310	1.256E-06	2856
	325	1.279E-06	2853

Figure 5-1 shows that, beginning with a cold start, the lamps reach 83% of their maximum intensity in 10 minutes and reach a stable maximum intensity output after two hours. Cycling the control panel through the turnup and turndown cycle (as described in Section 5.1.1.3) and returning to 100% brings the lamps to within 3.7% of their original, warmed-up intensity. After an adjustment to 55% power, the lamp output intensity stabilizes quickly. For this particular power and intensity monitoring test, a power setting of 55% results in a relative intensity of 71.3% of the warmed-up 100% intensity value.

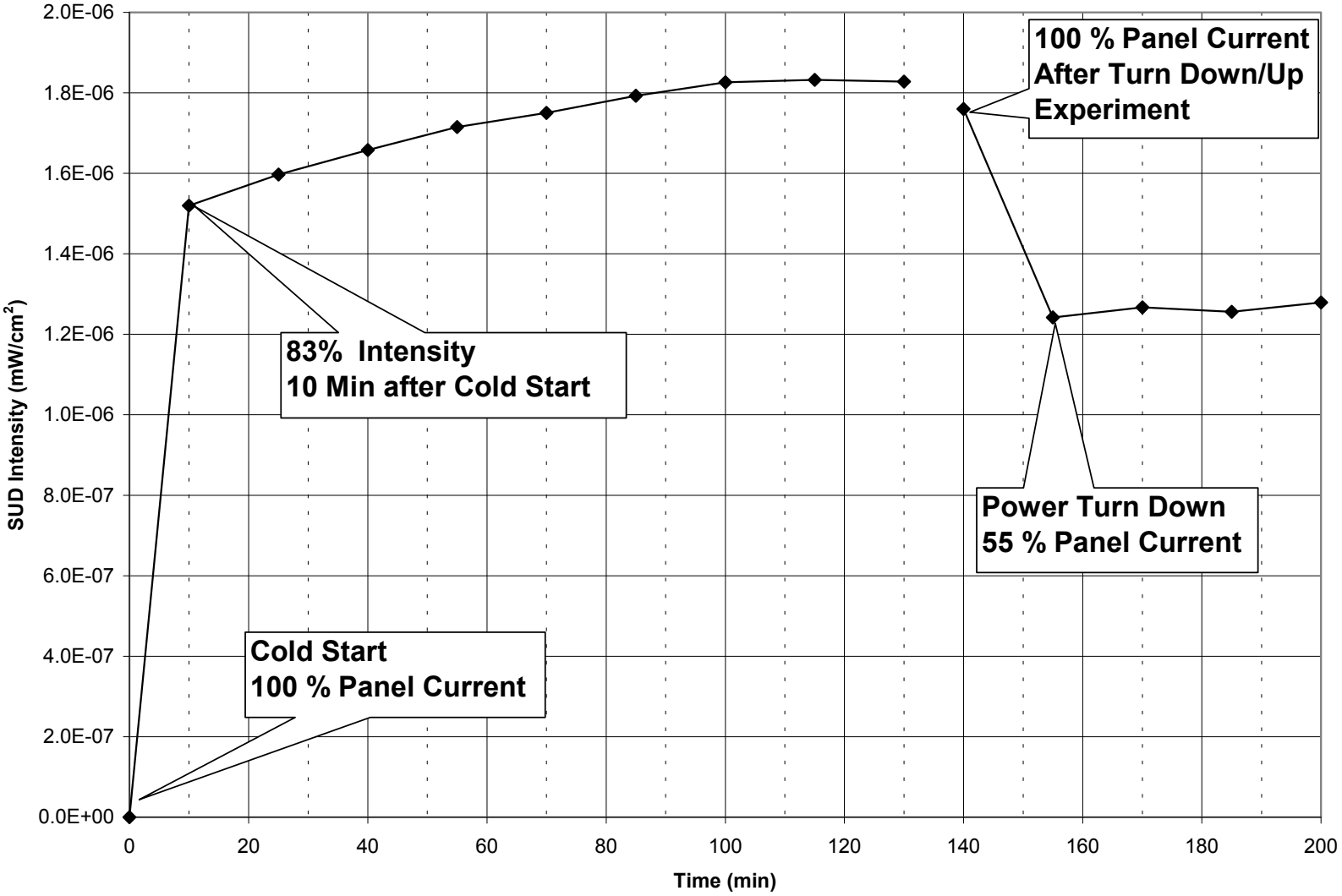


Figure 5-1. Warm Up and Intensity Stability Data.

Bioassay flow tests were conducted after the lamps had warmed up at 100% for approximately 12-15 hours to assure a complete warm-up cycle and re-equilibration after module movement. Then the intensity was turned down to the target EOL intensity, using the radiometer and potable water, and the bioassay flows were allowed to commence. Power settings of 55-57% were used on the bioassay flow tests to simulate the 70% relative intensity for the EOL condition. The power setting varies slightly from day to day because the turndown intensity value determined each day likely represents slight variation in the operation of the reactor.

5.1.1.3 Turnup and Turndown Cycle

The lamps were taken through a turndown and turnup cycle to characterize the operating parameters of the system and to determine the power turndown for the simulation of the EOL lamp condition. Data collected during this adjustment experiment is shown in Table 5-2. The time the data was collected corresponds to 130-265 minutes in the test.

Interpreting the absolute SUD 240 intensity reading would require analysis of the detector position, the lamp emission geometry, the input optic geometry, and the water transmittance. Thus, in this case, the SUD 240 intensity is interpreted only as a relative intensity reading. The I/I_0 value in Table 5-2 is the relative intensity at each condition as compared to the average of the two readings at 100%. Because the ballasts are supplied with single-phase power, the power factor is assumed to be 1.0, which agrees closely with the power factor of 0.99 supplied by SUNTEC.

Table 5-2. Intensity Response to Power Adjustments.

Panel Current (%)	Intensity SUD (mW/cm^2)	I/I_0 (%)	Average LRCM Voltage (V)	Average LRCM Current (A)	Total Power To LRCMs (W)
100	1.828E-06	101.9	119.0	9.12	4341
95	1.760E-06	98.1	119.0	8.61	4099
90	1.690E-06	94.2	120.2	8.16	3922
75	1.532E-06	85.4	119.9	7.13	3416
60	1.360E-06	75.8	120.4	6.16	2964
55	1.310E-06	73.0	120.2	5.94	2855
50	1.272E-06	70.9	120.8	5.67	2737
55	1.320E-06	73.6	119.8	5.93	2843
60	1.383E-06	77.1	120.4	6.23	3000
75	1.533E-06	85.5	120.3	7.16	3445
90	1.670E-06	93.1	120.0	8.26	3962
95	1.695E-06	94.5	120.0	8.54	4096
100	1.760E-06	98.1	120.0	9.04	4340

5.1.2 Headloss Measurements

Headloss measurements were derived from the hydraulic profile data shown in Table 5-3, and the data are presented graphically in Figure 5-2. The first two locations (0.3 m, 0.85 m) were highly variable and reflected the turbulence and hydraulic jumps of the influent box-channel junction. The 6.04 m position (at 5678 L/min) was anomalous because of a wave in the channel present at this high flow rate. Based on these observations, headloss calculations were determined from the drop in height from the 3.44 m to the 6.49 m location. An additional headloss was determined at 7700 L/min without the additional hydraulic profile data.

Table 5-3. Hydraulic Profile Data.

Flow (L/min)	Height at 0.30 m (cm)	Height at 0.85 m (cm)	Height at 1.40 m (cm)	Height at 2.44 m (cm)	Height at 3.44 m (cm)	Height at 6.04 m (cm)	Height at 6.49 m (cm)
757	40.6	40.6	42.2	41.9	41.9	41.0	40.6
1893	41.9	42.5	43.2	42.5	42.2	41.3	41.0
3028	43.8	40.6	43.8	43.2	42.9	41.3	41.0
4164	46.4	47.6	43.8	43.2	42.9	41.6	41.3
5678	48.3	50.8	45.7	45.1	44.5	39.4	40.6
7700	--	--	--	--	45.7	--	40.6

Headloss though the lamp modules exists at any non-negligible flow rate because of the hydraulic resistance from obstacles such as lamps and mounting hardware that are present. In ideal, turbulent systems, the headloss increases as a function of the square of flow velocity. For the LPX200 system used in this verification test, the headloss (measured in cm) as a function of flow velocity (measured in cm/s) is shown in Figure 5-3 and is approximated by the relation:

$$headloss = 3.91 \times 10^{-4} (velocity)^2 + 0.0242 (velocity) + 0.475 \qquad (5\text{-}1)$$

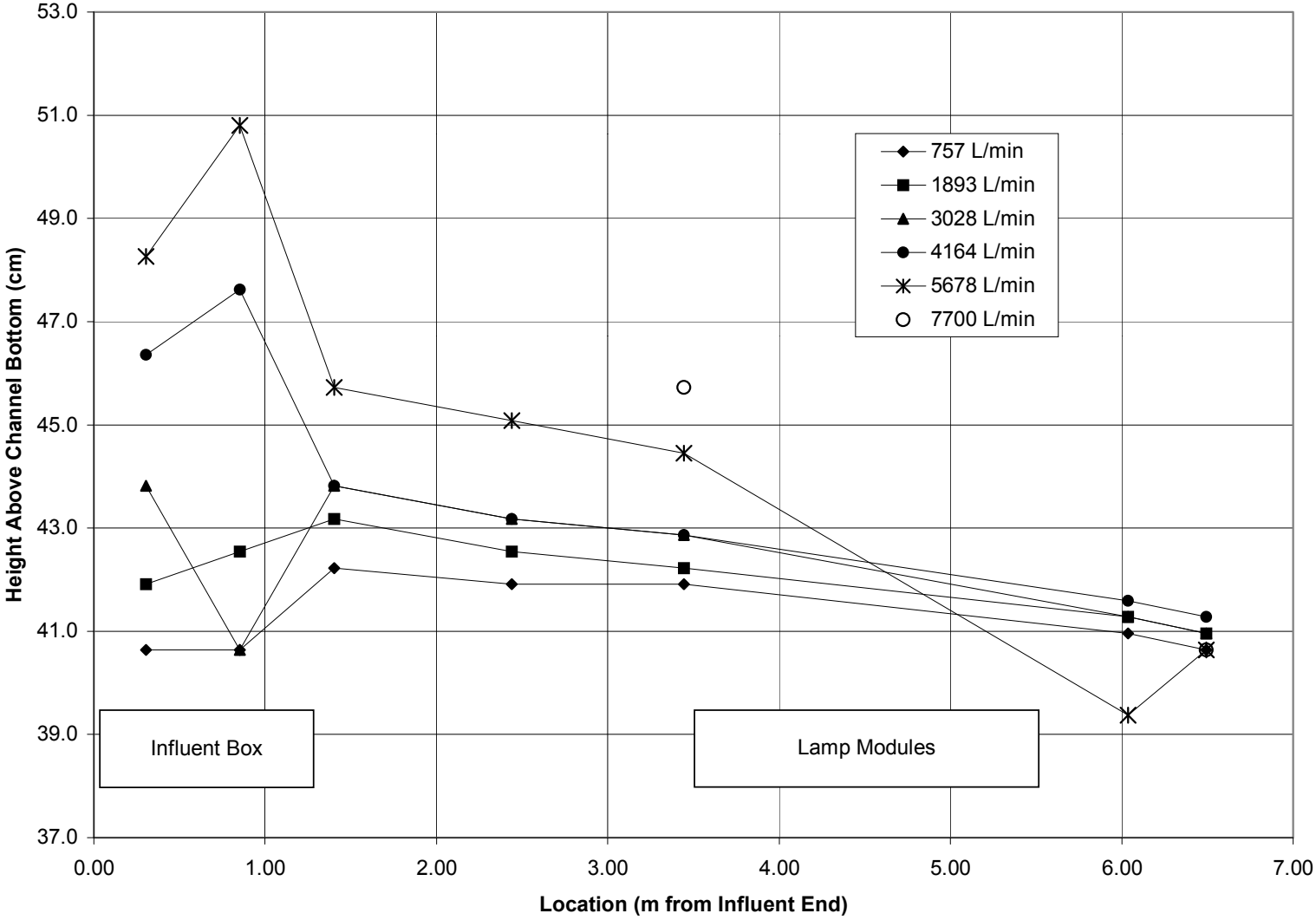


Figure 5-2. Hydraulic Profile Data.

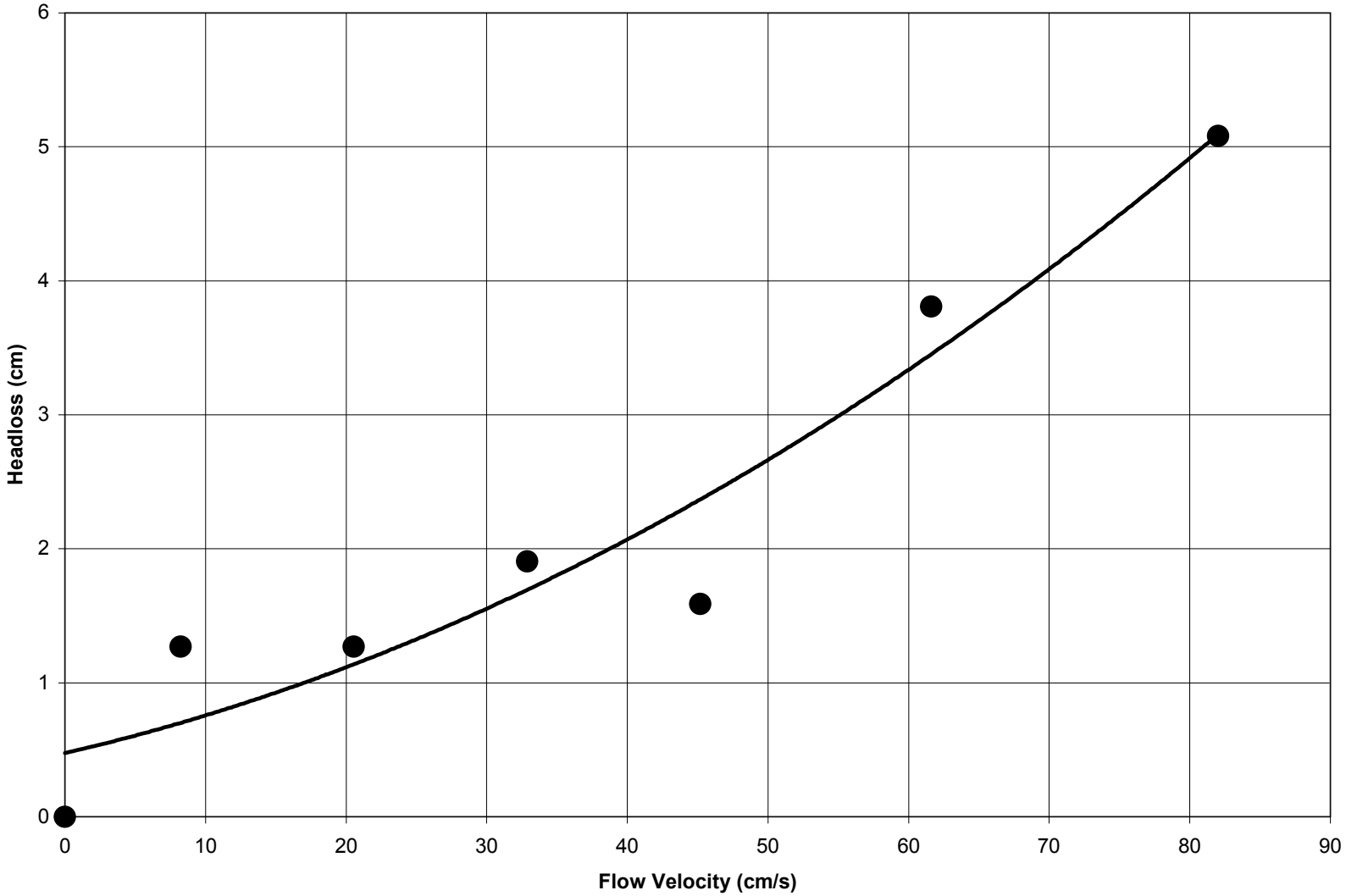


Figure 5-3. Headloss as a Function of Flow Velocity.

It is important to realize that the headlosses were measured in the range of velocities used for the bioassay validations in this ETV: they cannot be extrapolated to different flow rates. Further, the assumption is made that larger full-scale systems will be operated in the same range of flow velocities and will generate similar headlosses. Thus, the flow velocity through a full-scale system must be determined before this headloss data can be applied.

5.1.3 Hydraulic Detention Time Analysis

Data from the step-feed, detention-time analysis are presented in Table 5-4. For each flow rate, the data represents the average of three replicate data acquisition events. The calculated parameters in Table 5-4 are described below with typically acceptable limits.

In general, these parameters are based on quantitative values measured from the step-response curve and are defined in Section 4.2.4.2. These derived parameters provide quantitative indications of the "shape" of the step-response curves. These can then be used to identify significant problems such as short-circuiting or dead spaces and can give an indication of the amount of mixing that occurs in the disinfection unit.

θ/T The ratio of the mean residence time to the theoretical residence time. This should fall between 0.8 and 1.2. The θ/T values for the four lowest flow rates range between 0.90 and 1.16 and are generally acceptable. The values for the two highest flow rates are 1.31 and 1.54 and reflect a systematically increasing trend for θ/T as flow rates increase. This likely reflects a slight offset that occurs because of the manual synchronization between pump shut off and notation on the chart and the 0.5 sec integration time of the IL-1700 radiometer. The high flow rates have residence times that are at the low end of the step-response procedure used. This offset does not affect the other calculated parameters to a significant degree.

t_p/θ The ratio of the peak change in tracer concentration to the mean residence time. This is a measure of the skewness of the concentration curve and should be between 0.9 and 1.1. Numbers deviating significantly from 1.0 would result from short-circuiting or hydraulic "dead" spots. Values range from 0.94 to 1.04 and are acceptable.

t_{90}/t_{10} The ratio of time for 90% of the concentration to 10% of the concentration. This is known as the Morrill Dispersion Index, which is one measure of the residence time spread. A value of 1.0 would indicate perfect plug flow; a value of 21.9 would indicate perfect mixing. Ideally, a reactor should have a value below 2.0. Values range from 1.08 to 1.25, which are acceptable.

t_{50}/θ The ratio of time for 50% tracer concentration to mean residence time. This is another measure for the skewness and should be between 0.9 and 1.1. Values range from 0.97 to 1.02, which are acceptable.

E The dispersion coefficient. A value of less than 100 cm^2/sec is acceptable for UV disinfection systems. These values range from 23.3 to 88.1 cm^2/sec, which are acceptable.

d This is the unitless dispersion number. A value of zero indicates perfect plug flow and a value of infinity indicates only mixing. Values range from 0.0039 at 5678 L/min to 0.023 at the 379 L/min flow rate and are below the accepted value of 0.05.

The hydraulic parameters derived from the step-response behavior of the SUNTEC test unit are within acceptable limits. The exception exists for the θ/T for the higher flow rates. However, additional parameters representing the mean detention time (t_p/θ, t_{50}/θ) are well within acceptable limits. Thus, the detention times are generally within acceptable limits.

While these data show no evidence for short-circuiting or significant dead spots, it is important to realize that the tracer test was conducted in the central part of the lamp array. Non-idealities in the water flow near the channel walls would not have been identified in these tests. In addition, while the distribution of residence times in the lamp module may not have been highly variable, these tests did not quantify the distribution of doses. Thus, while these tests may identify large deviations from ideal hydraulic behavior, the following bioassay results are the ultimate criterion for reactor performance.

Table 5-4. Hydraulic Detention Time Data.

Q (L/min)	Q (gpm)	t_i (sec)	t_P (sec)	t_{10} (sec)	t_{50} (sec)	t_{90} (sec)	T (sec)	θ (sec)	θ/T	t_P/θ	t_{90}/t_{10}	t_{50}/θ	E (cm^2/s)	d
379	100	13.7	42.9	41.2	44.5	51.6	50.4	45.6	0.90	0.94	1.25	0.97	24.2	0.0230
757	200	11.7	23.7	22.9	23.8	26.5	25.2	24.4	0.97	0.98	1.16	0.98	23.3	0.0118
1893	500	5.5	11.8	10.3	11.5	11.8	10.1	11.3	1.12	1.04	1.14	1.02	36.3	0.0085
3028	800	3.8	7.3	6.8	7.3	7.7	6.3	7.3	1.16	1.00	1.14	1.00	59.3	0.0087
4164	1100	2.8	6.0	5.6	6.0	6.6	4.6	6.0	1.31	0.99	1.19	0.99	88.1	0.0113
5678	1500	3.6	5.0	5.0	5.2	5.3	3.4	5.2	1.54	0.97	1.08	1.00	38.9	0.0039
								Average:	1.17	0.99	1.16	0.99	45.0	0.0112

Note: the data for each flow rate is the average of three replicate runs.

5.2 MS2 Dose-Response Calibration Curve

5.2.1 Dose-Response Results

A total of fifteen dose-responses were conducted during this verification test. Thirteen were considered valid; the other two were excluded for the reasons discussed in Section 6.2.2. All raw data are included in Appendix C.

Data from the 13 valid dose-responses conducted on the MS2 bacteriophage batch used during this verification test are shown in Table 5-5. The delivered doses are corrected for 2.5% reflectance at the surface of the sample. This valid data includes nine dose-responses in 99% transmittance saline, two in 55% transmittance challenge water, and two in 65% transmittance challenge water.

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. See Section 6 for the QA/QC discussion of this issue.

5.2.2 Dose-Response Calibration Curve

The dose-response calibration curve is presented in Figure 5-4, 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.

$$Dose = 1.6191(Survival)^2 - 12.782(Survival) + 1.6009$$

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

N_0 = MS2 Concentration in Undosed Sample

N = MS2 Concentration in Dosed Sample

(5-2)

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

	Nominal Dose[1]:		10	20	30	40	50	60	80	100	120
	%T (%/cm)	Matrix	Dose, Survival	Dose, Survival	Dose, Survival	Dose, Survival	Dose, Survival	Dose, Survival	Dose, Survival	Dose, Survival	Dose, Survival
DR1	99	Saline	--	19.4, -1.27	--	38.9, -2.24	--	58.3, -3.27	--	96.9, -4.66	116.4, -5.29
DR2	99	Saline	--	19.5, -1.15	--	39.0, -2.07	--	58.4, -3.06	--	97.2, -4.53	116.7, -5.14
DR3	99	Saline	--	19.4, -1.47	--	38.8, -2.45	--	58.1, -3.46	--	96.7, -4.87	116.1, -5.21
DR4	99	Saline	--	19.6, -1.12	--	39.1, -2.41	--	58.7, -3.41	--	97.8, -4.83	117.4, -5.33
DR5	99	Saline	--	19.5, -1.29	--	39.0, -2.44	--	58.4, -3.32	77.7, -4.21	97.2, -4.81	--
DR6	99	Saline	--	19.5, -1.49	--	39.0, -2.33	--	58.4,-3.24	77.7, -4.21	97.2, -4.73	--
DR7	99	Saline	9.7, -0.51	19.5, -1.49	29.2, -1.77	38.9, -2.18	48.6, -2.58	--	--	--	--
DR8	99	Saline	9.7, -0.66	19.4, -1.33	29.1, -1.79	38.8, -2.37	48.5, -2.67	--	--	--	--
DR9	99	Saline	9.8, -0.65	19.3, -1.15	--	38.9, -2.23	--	58.2, -2.99	77.7, -3.84	--	--
DRS1	54.0	INF	9.7, -0.60	19.6, -1.19	--	39.0, -2.17	--	--	--	--	--
DRS3	65.2	INF	9.8, -0.72	19.5, -1.21	--	39.1, -1.99	--	58.6, -2.93	--	--	--
DRS4	65.2	INF	9.8, -0.46	19.6, -1.17	--	39.2, -1.99	--	58.7, -2.88	--	--	--
DRS6	56.0	INF	9.9, -0.67	19.6, -1.28	--	39.2, -2.02	--	58.9, -3.02	--	--	--

(1) Dose in mJ/cm^2.

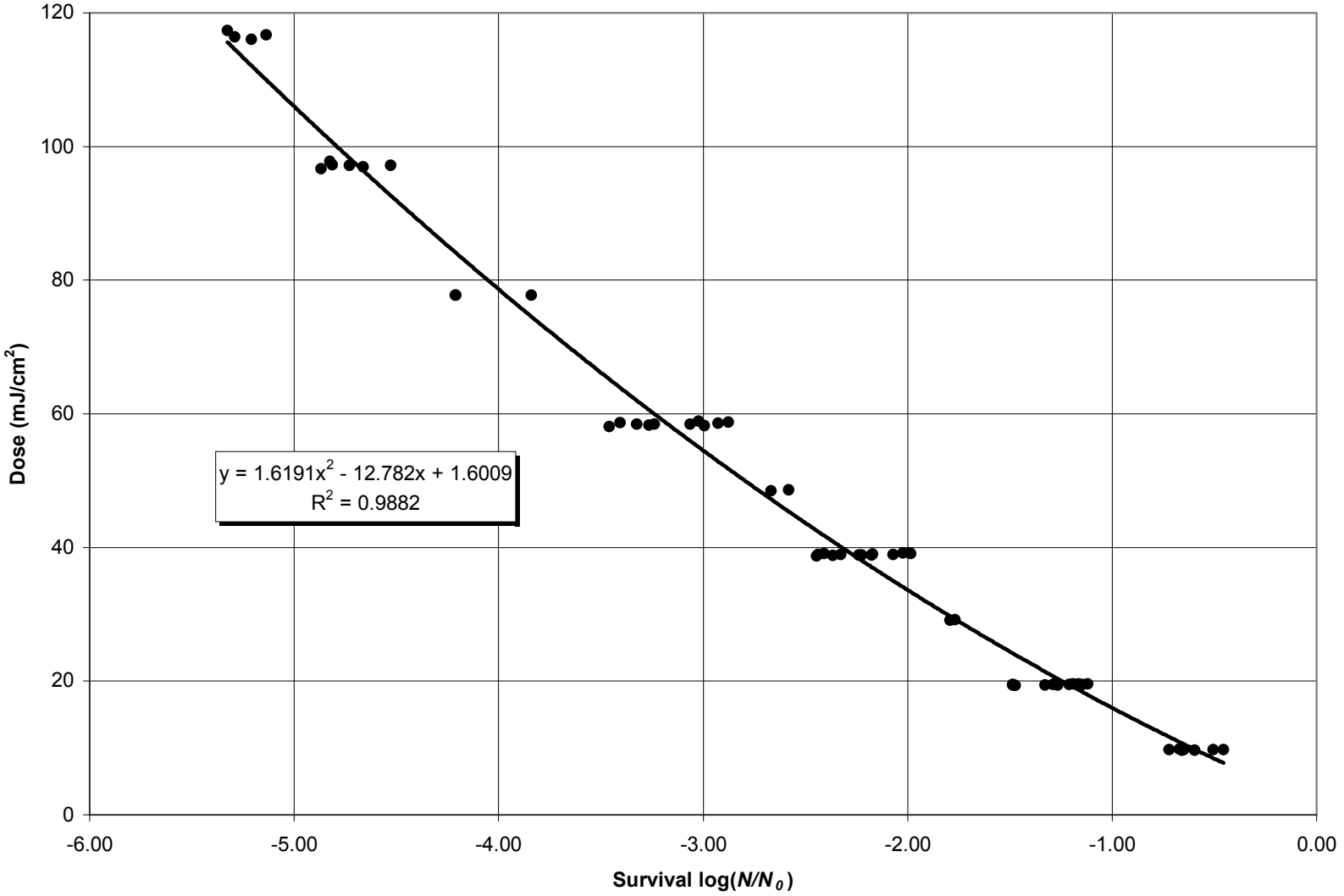


Figure 5-4. Dose-Response Curve for the MS2 Batch Used for This ETV.

5.3 Dose-Flow Assays

5.3.1 Flow Test Summary

A total of 57 flow tests were conducted during this verification test. A total of 47 valid flow tests were obtained over a period of 11 days and are summarized in Table 5-6. Nine flows were excluded for QA/QC reasons, discussed in Section 6.3.3, and a no-dose flow was also conducted (see Section 6.3.2). All raw data and notes are included in Appendix C.

Table 5-6. Summary of Bioassay Flow Test Events.

Test Day	Nominal % T (%T/cm)	Actual %T (%T/cm)	N_0 (pfu/ml)	Flows (L/min)
1	65	65.5	$1.4x10^6$	757, 1893, 3028, 4164
2	65	65.8	$9.3x10^5$	1893, 3028, 4164, 5678, 5678
3	65	65.4	$5.4x10^5$	757, 1893, 3028, 4164, 5678
4	65	64.8	$9.5x10^5$	757, 757, 1893, 3028, 4164, 5678
5	55	53.8	$1.1 x10^6$	1893, 3028, 4164, 5678
6	55	53.2	$9.4x10^5$	757, 1893, 3028, 4164, 5678
7	55	53.2	$6.8 x10^5$	379, 757, 757, 1893, 3028, 4164
8	55	55.8	$9.8 x10^5$	379, 757, 1893, 3028, 4164
9	65	65.5	$7.7 x10^5$	4164
10	55	54.5	$5.4x10^5$	379, 1893, 3028
11	55	56.0	$5.7x10^5$	379, 379, 1893

5.3.2 Data Reduction and Results

Table 5-7 shows the flow test results for each set of flow and transmittance conditions. For the 55% transmittance flow tests, two flows were conducted at 5678 L/min (1500 gpm). After review of these data, the 379 L/min (100 gpm) flow tests were conducted to provide data at higher dose deliveries. The 5678 L/min data are valid and are included for reference, although they do not strictly contribute to the data completion goals specified in the Verification Protocol.

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 survival ratio, log (N/N_0). Thus, each individual flow event resulted in the generation of three survival ratios. These survival ratios were then converted to a delivered dose, with the dose-response curve generated in Section 5.2.2.

Each flow condition resulted in approximately 12 delivered dose estimates (see Table 5-7). The Verification Protocol requires that these data be analyzed statistically at the 75% confidence interval (C.I.) based on the two-tailed t-test for small samples. The C.I. High and the C.I. Low are 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

(5-3)

The individual doses are plotted, along with the 75% confidence intervals, in Figure 5-5.

At the low flow rate (379 L/min at 55% T), the greater variability of the data likely represents true variability present in high-dose survival ratios. It also may represent a lower degree of mixing in the channel at low flow rates. This flow rate is the lower design limit of the test unit.

Table 5-7. Bioassay Flow Test Delivered Dose Data and Statistics.

Conditions	Day	Survival ($\log N/N_0$)	Dose (mJ/cm^2)	Dose Statistics (mJ/cm^2)	
757 L/min, 65 %Transmittance					
(200 gpm)	Day 1	-3.29	61.2	STDEV:	4.80
		-3.38	63.3	MEAN:	60.31
		-3.40	63.8	75%C.I.:	1.68
	Day 3	-2.94	53.2	C.I. Hi:	61.99
		-3.55	67.4	C.I. Low:	58.62
		-2.86	51.4		
	Day 4	-3.42	64.3		
		-3.15	57.9		
		-3.15	57.9		
	Day 4	-3.14	57.7		
		-3.29	61.2		
		-3.43	64.5		

Table 5-7. Bioassay Flow Test Delivered Dose Data and Statistics. (continued)

Conditions	Day	Survival ($\log N/N_0$)	Dose (mJ/cm^2)	Dose Statistics (mJ/cm^2)	
1893 L/min, 65% Transmittance					
(500 gpm)	Day 1	-1.93	32.3	STDEV:	2.31
		-1.89	31.5	MEAN:	29.46
		-1.86	31.0	75%C.I.:	0.81
	Day 2	-1.57	25.7	C.I. Hi:	30.27
		-1.97	33.1	C.I. Low:	28.65
		-1.62	26.6		
	Day 3	-1.76	29.1		
		-1.64	26.9		
		-1.80	29.9		
	Day 4	-1.75	28.9		
		-1.73	28.6		
		-1.81	30.0		
3028 L/min, 65% Transmittance					
(800 gpm)	Day 1	-1.14	18.3	STDEV:	2.43
		-1.23	19.8	MEAN:	19.87
		-1.44	23.4	75%C.I.:	0.85
	Day 2	-1.23	19.8	C.I. Hi:	20.72
		-1.12	17.9	C.I. Low:	19.02
		-1.01	16.2		
	Day 3	-1.33	21.5		
		-1.36	22.0		
		-1.49	24.2		
	Day 4	-1.11	17.8		
		-1.16	18.6		
		-1.19	19.1		

Table 5-7. Bioassay Flow Test Delivered Dose Data and Statistics. (continued)

Conditions	Day	Survival ($\log N/N_0$)	Dose (mJ/cm^2)	Dose Statistics (mJ/cm^2)	
4164 L/min, 65% Transmittance					
(1100 gpm)	Day 1	-1.17	18.8	STDEV:	1.50
		-1.08	17.3	MEAN:	15.70
		-1.03	16.5	75%C.I.:	0.47
	Day 2	-0.97	15.5	C.I. Hi:	16.16
		-0.93	14.9	C.I. Low:	15.23
		-0.91	14.6		
	Day 3	-0.96	15.4		
		-0.84	13.5		
		-0.97	15.5		
	Day 4	-1.07	17.1		
		-1.08	17.3		
		-0.97	15.5		
	Day 9	-0.85	13.6		
		-0.87	13.9		
		-1.00	16.0		
5678 L/min, 65% Transmittance					
(1500 gpm)	Day 2	-0.81	13.0	STDEV:	2.40
		-1.02	16.3	MEAN:	12.52
		-0.88	14.1	75%C.I.:	0.84
	Day 2	-0.94	15.0	C.I. Hi:	13.36
		-0.86	13.8	C.I. Low:	11.68
		-0.89	14.3		
	Day 3	-0.56	9.3		
		-0.56	9.3		
		-0.55	9.1		
	Day 4	-0.76	12.3		
		-0.79	12.7		
		-0.68	11.0		

Table 5-7. Bioassay Flow Test Delivered Dose Data and Statistics. (continued)

Conditions	Day	Survival ($\log N/N_0$)	Dose (mJ/cm^2)	Dose Statistics (mJ/cm^2)	
379 L/min, 55% Transmittance					
(100 gpm)	Day 7	-2.72	48.3	STDEV:	10.71
		-2.83	50.7	MEAN:	60.31
		-2.99	54.3	75%C.I.:	3.59
	Day 8	-2.64	46.6	C.I. Hi:	63.90
		-2.84	51.0	C.I. Low:	56.72
		-2.75	49.0		
	Day 10	-3.23	59.8		
	Day 11	-3.59	68.4		
		-3.77	72.8		
		-3.91	76.3		
	Day 11	-3.67	70.3		
		-3.56	67.6		
		-3.61	68.8		
757 L/min, 55% Transmittance					
(200 gpm)	Day 6	-1.11	17.8	STDEV:	4.44
		-1.10	17.6	MEAN:	20.46
		-0.96	15.4	75%C.I.:	1.55
	Day 7	-1.52	24.8	C.I. Hi:	22.02
		-1.63	26.7	C.I. Low:	18.91
		-1.02	16.3		
	Day 7	-1.11	17.8		
		-1.11	17.8		
		-1.14	18.3		
	Day 8	-1.31	21.1		
		-1.41	22.8		
		-1.76	29.1		

Table 5-7. Bioassay Flow Test Delivered Dose Data and Statistics. (continued)

Conditions	Day	Survival ($\log N/N_0$)	Dose (mJ/cm^2)	Dose Statistics (mJ/cm^2)	
1893 L/min, 55% Transmittance					
(500 gpm)	Day 5	-0.78	12.6	STDEV :	3.09
		-0.93	14.9	MEAN :	16.28
		-0.94	15.0	75%C.I. :	0.87
	Day 6	-0.78	12.6	C.I. Hi :	17.15
		-0.78	12.6	C.I. Low :	15.41
		-0.68	11.0		
	Day 7	-0.86	13.8		
		-1.19	19.1		
		-0.91	14.6		
	Day 8	-1.17	18.8		
		-1.03	16.5		
		-1.22	19.6		
	Day 10	-1.17	18.8		
		-1.35	21.8		
		-1.25	20.1		
	Day 11	-1.13	18.1		
		-1.01	16.2		
		-1.07	17.1		
3028 L/min, 55% Transmittance					
(800 gpm)	Day 5	-0.53	8.8	STDEV :	2.09
		-0.38	6.7	MEAN :	11.21
		-0.47	8.0	75%C.I. :	0.65
	Day 6	-0.87	13.9	C.I. Hi :	11.86
		-0.75	12.1	C.I. Low :	10.56
		-0.90	14.4		
	Day 7	-0.71	11.5		
		-0.75	12.1		
		-0.70	11.3		
	Day 8	-0.67	10.9		
		-0.61	10.0		
		-0.71	11.5		
	Day 10	-0.75	12.1		
		-0.78	12.6		
		-0.76	12.3		

Table 5-7. Bioassay Flow Test Delivered Dose Data and Statistics. (continued)

Conditions	Day	Survival ($\log N/N_0$)	Dose (mJ/cm^2)	Dose Statistics (mJ/cm^2)	
4164 L/min, 55% Transmittance					
(1100 gpm)	Day 5	-0.49	8.3	STDEV:	1.99
		-0.37	6.6	MEAN:	9.59
		-0.36	6.4	75%C.I.:	0.70
	Day 6	-0.53	8.8	C.I. Hi:	10.29
		-0.51	8.5	C.I. Low:	8.89
		-0.53	8.8		
	Day 7	-0.62	10.1		
		-0.68	11.0		
		-0.66	10.7		
	Day 8	-0.71	11.5		
		-0.78	12.6		
		-0.72	11.6		
5678 L/min, 55% Transmittance					
(1500 gpm)	Day 5	-0.33	6.0	STDEV:	1.10
		-0.23	4.6	MEAN:	5.77
		-0.46	7.8	75%C.I.:	0.59
	Day 6	-0.27	5.2	C.I. Hi:	6.36
		-0.30	5.6	C.I. Low:	5.19
		-0.29	5.4		

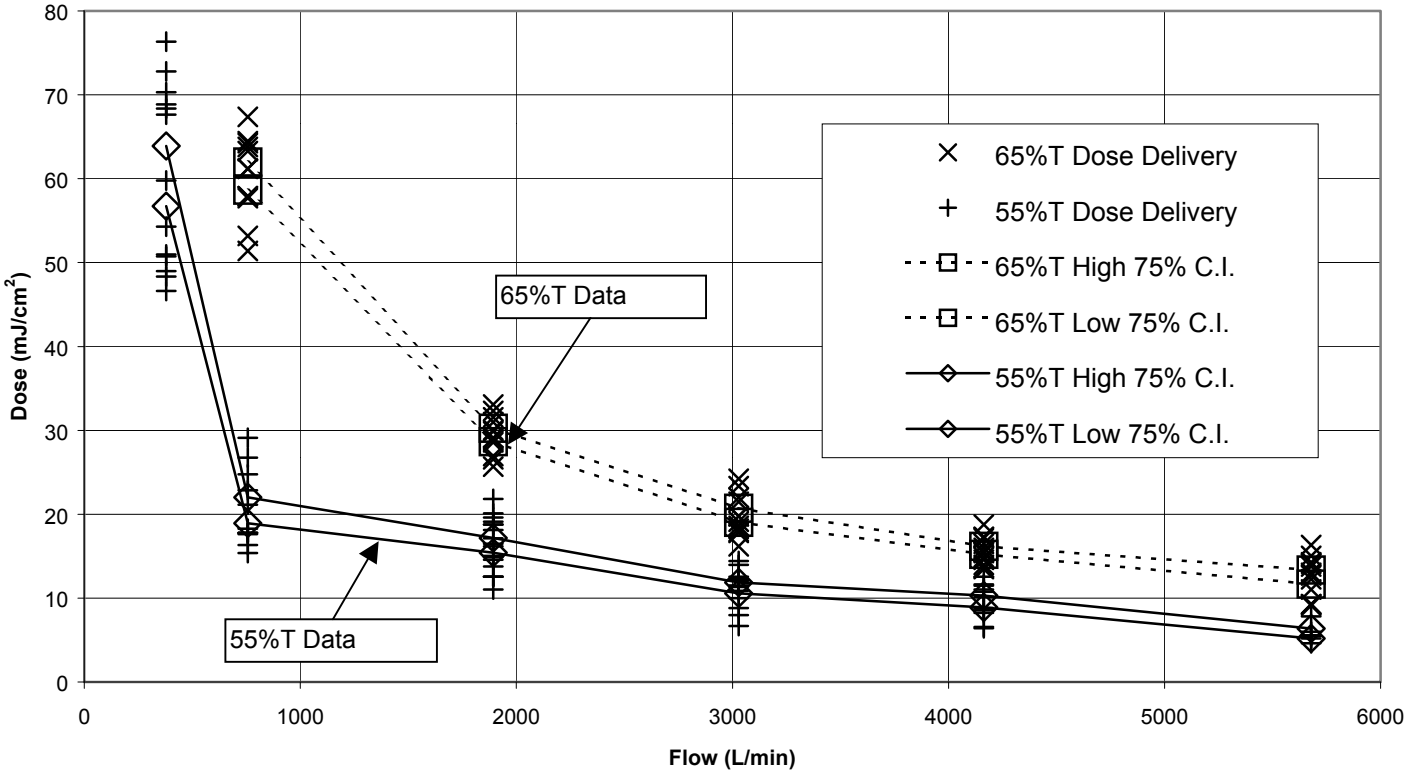


Figure 5-5. Dose Delivery as a Function of Flow Rate for the 20-Lamp Test Unit.

5.3.3 Flow Test Data Analysis

As described in the Verification Protocol, the final analysis of the flow test data is based upon the lower 75% confidence interval result for each flow condition (e.g., flow rate, %T). The results for the 20-lamp test system are shown in Figure 5-6, where they are fitted with a power function. For comparison, the average dose delivery curve is also shown with a dotted line.

A UV disinfection unit with ideal hydraulics should deliver a dose that is a function of 1/flow rate (*Dose = k/(Flow Rate)*). Thus, the power function should have an exponent of -1. An actual UV disinfection system follows the above relation with an exponent that usually differs from -1 because of the complex fluid-dynamic behavior inside the reactor. The exponents for the power functions in Figure 5-6 are less than one and are consistent with the non-ideal behavior of the actual test system. Again, this non-ideal behavior is a strong justification for conducting a bioassay flow test on an actual system.

5.3.4 Dose Delivery and Lamp Power

The delivered dose in Section 5.3.3 is presented as a function of the flow rate through the 20-lamp UV system. A second approach to understanding the dose delivery in the SUNTEC system is to relate the dose delivery to lamp power. The power used in these calculations was for lamps at full power at the end of lamp life (0.7). During this test program, the power was turned down to simulate the end of lamp life. To achieve this, the data are rescaled with L/min-kilowatt on the y-axis in Figure 5-7, where the lower 75% C.I. data are shown with the lower 75% C.I. curve and the average dose delivery curve is shown as a dashed line. This normalization of dose to the power consumed presents information for evaluating power usage efficiency.

The relationships derived from Figure 5-7 are as follows for the end of lamp life:

$$\text{For 65\% Transmittance: } \textit{Power Usage}\ (\textit{L/min-kW}) = 28721(\textit{Dose})^{-1.2485}$$

$$\text{For 55\% Transmittance: } \textit{Power Usage}\ (\textit{L/min-kW}) = 11163(\textit{Dose})^{-1.2341} \qquad (5\text{-}4)$$

For example, at 65% transmittance, a dose of 40 mJ/cm^2 will be delivered to 287 L/min per kilowatt of power used at the end of lamp life. For 55% transmittance, the same dose will be delivered to 117 L/min per kilowatt of power used at the end of lamp life. Note that this lower efficiency for lower transmittance is an example of the "UV demand" of lower transmittance waters.

An application requiring the delivery of 40 mJ/cm^2 to 20,000 L/min of 65% transmittance waters at the end of lamp life would consume 69.7 kW of power, as shown here:

$$\frac{20000\,L/\min}{287\,L/\min - kW} = 69.7\,kW \qquad (5\text{-}5)$$

5.3.5 Dose Delivery and Number of Lamps

An alternative way to view the results from these dose delivery verification tests is to normalize the dose delivery to L/min-Lamp. This allows a potential UV disinfection system user to determine the number of lamps that would be needed for a certain application. The data are plotted in the same fashion as Figure 5-7, except the vertical axis is rescaled to reflect the hydraulic loading per lamp shown in Figure 5-8.

The relationships derived from Figure 5-8 are as follows for the end of lamp life:

$$\text{For 65\% Transmittance: } Hydraulic\,Loading\,(L/\min - Lamp) = 6134.8(Dose)^{-1.2485}$$

$$\text{For 55\% Transmittance: } Hydraulic\,Loading\,(L/\min - Lamp) = 2422.3(Dose)^{-1.2341} \qquad (5\text{-}6)$$

For example, at 65% transmittance, a dose of 40 mJ/cm^2 will be delivered to 61 L/min per lamp at the end of lamp life; for 55% transmittance, the same dose will be delivered to 25 L/min per lamp at the end of lamp life. Thus, an application requiring the delivery of 40 mJ/cm^2 to 20,000 L/min of 65% transmittance water would require a minimum of 328 lamps, as shown below, at the end of lamp life:

$$\frac{20000\,Lpm}{61\,L\,\min - Lamp} = 328\,Lamps \qquad (5\text{-}7)$$

It is important to note that this value is appropriate only in a limited number of conditions. If the transmittance of the water were to decrease to 55%, modules containing 800 lamps would be required to maintain the dosing level.

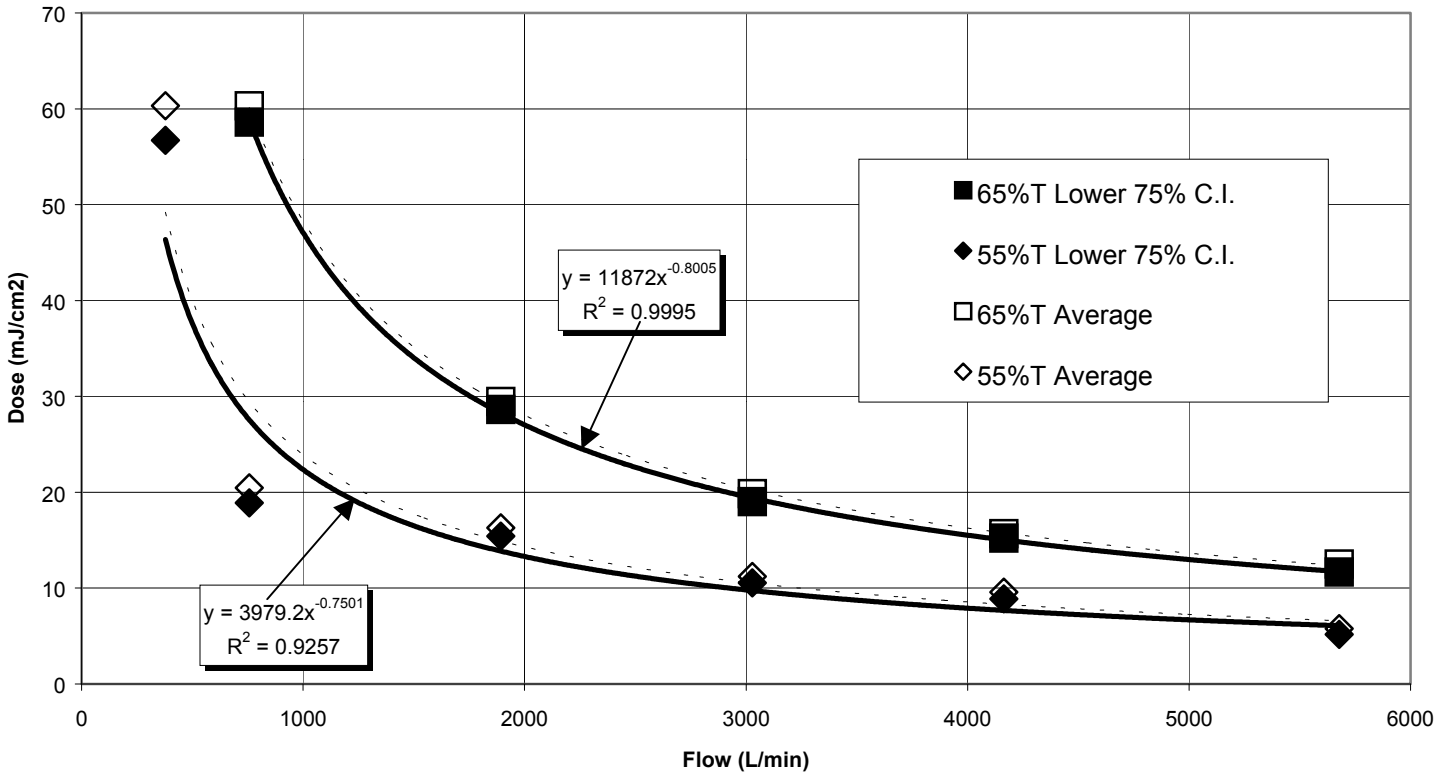


Figure 5-6. Dose Delivery Curves Based on Lower 75 Percent Confidence Intervals.

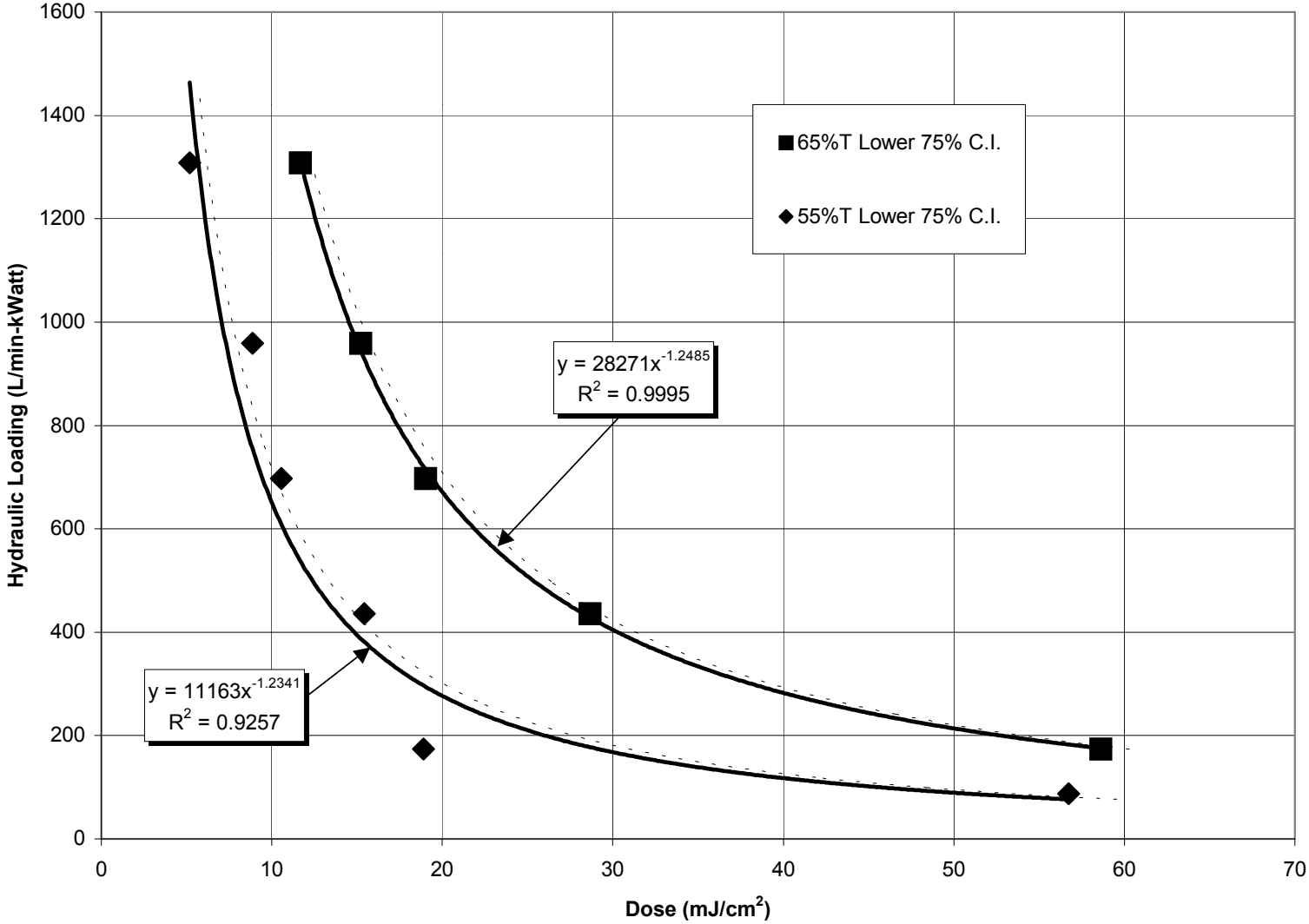


Figure 5-7. Relationship Between Dose Delivery and Power Usage.

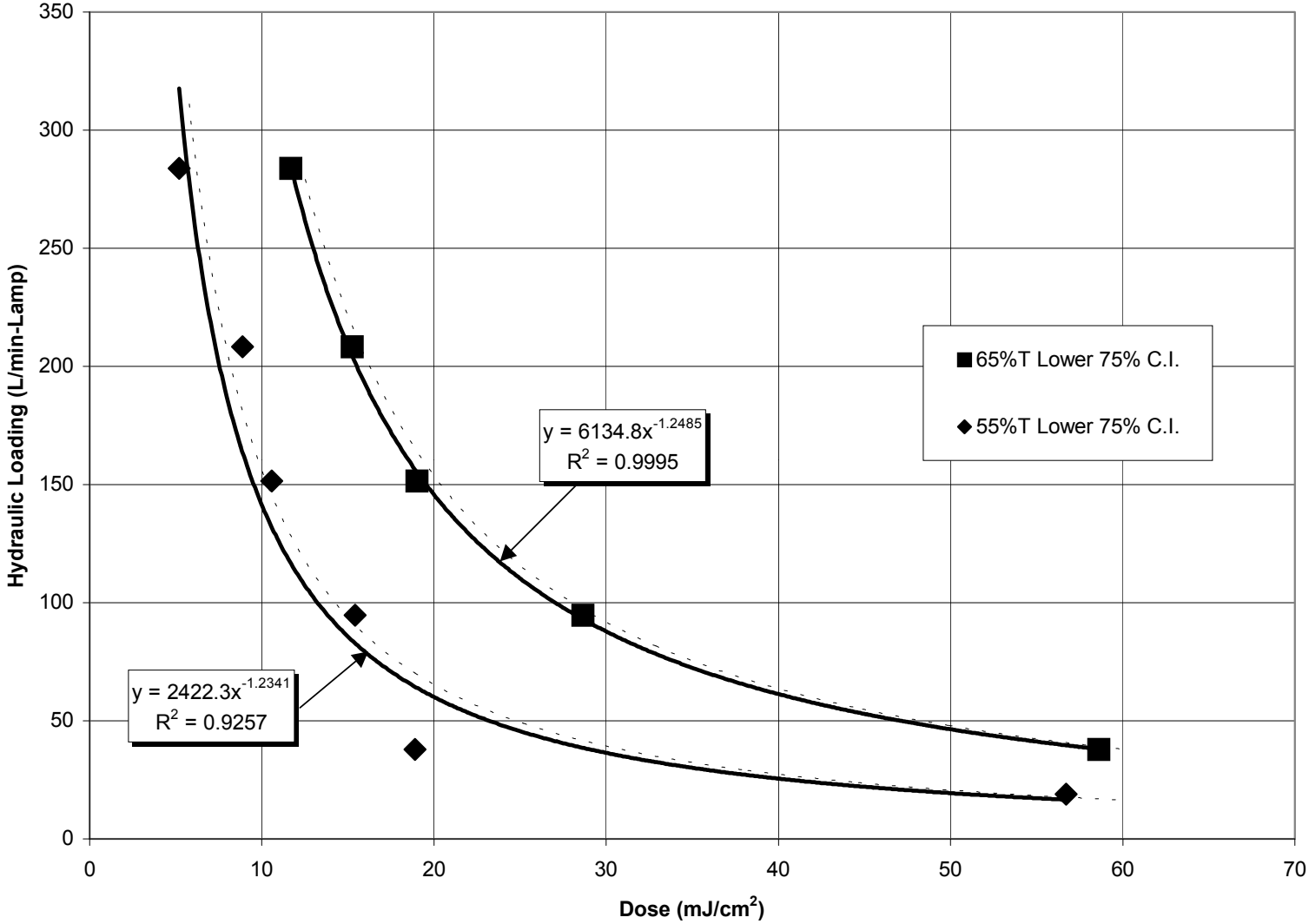


Figure 5-8. Relationship Between Dose Delivery and Number of Lamps.

5.3.6 Scalability

The results in the above sections can be used to estimate the dose delivery for different sized lamp arrays. In order for these results to be scaled up using, for example, the dose delivery per lamp, several assumptions must be verified to assure conformance of the full-scale reactor with the test reactor provided for this verification test.

(1) The lamps, sleeves, LRCM, and lamp current (100%) are identical.
(2) The lamp outputs are equal to or greater than the 70% EOL simulation used in this ETV.
(3) The lamp spacing, the distance from channel walls, and the submersion of the upper lamp row are identical.
(4) The flow velocities are in the range of those tested in this ETV.

The Verification Protocol (NSF, 2002) allows the scale-up of the ETV results to systems up to 10 times the size of the test system. The results cannot be scaled down. This is predicated on the assumption that the efficiency of a larger array is higher due to the smaller fraction of the water flowing along the walls, the "edge effect". Water traveling along the walls of the channel only receives a UV dose from one direction.

For the SUNTEC LPX200 system, the average intensity as a function of transmittance is shown in Figure 5-9 for the 20-lamp system in this verification test and for a hypothetical full-scale 64-lamp system. The I_{AVE} was calculated with the UVDIS program for several transmittances between 30% and 70%. This was based on calculations using lamps with arc-lengths of 162.6 cm, sleeves with 23 mm outside diameters, and lamp outputs of 68 W of UVC. This data is not intended to represent the actual I_{AVE} present, but is intended to compare the relative geometries of the two systems. As shown in Figure 5-9, a larger lamp array results in an I_{AVE} that is equal to or greater than that present in the 20-lamp test system. This justifies the assumption that scaling up the dose delivery results from this verification test is an inherently conservative approach.

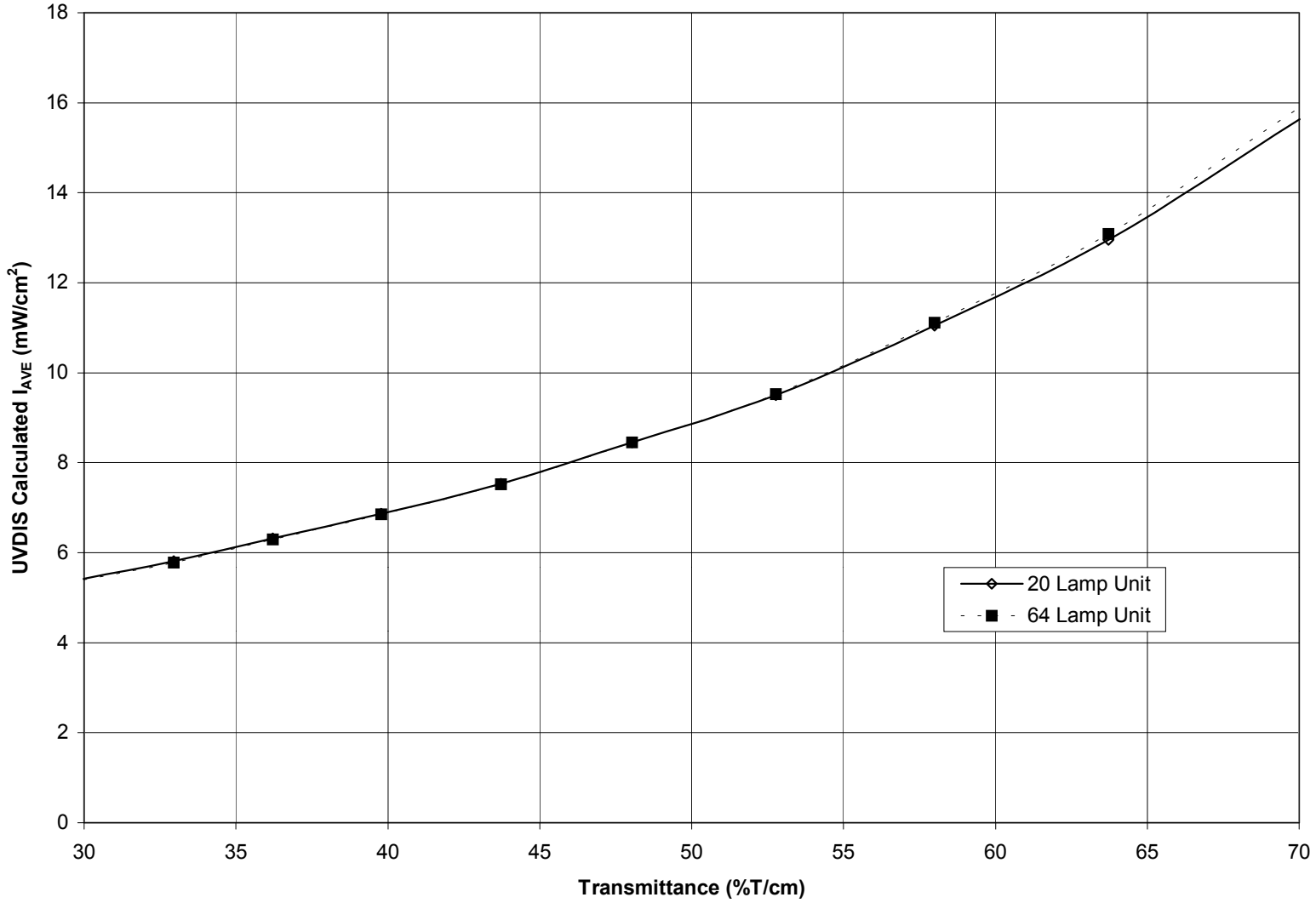


Figure 5-9. A Comparison of UVDIS Results for 20- and 64-Lamp LPX200 Systems.

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 controlling the UV dose delivery. 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.

This calibration procedure was repeated for flow rates between 757 L/min to 5678 L/min (200 gpm and 1500 gpm). For the two highest flow rates (4164 and 5675 L/min), it was necessary to take the measurements every 30 seconds because of the rapid tank drawdown rate.

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 98%, 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** (%)
211	200	757	95
463	500	1892	108
850	800	3027	94
1159	1100	4162	95
1538	1500	5675	98
		Average:	98

6.1.2 Radiometer Calibration

UV irradiances were measured during dose-response test procedures using an International Light IL-1700 Radiometer with an SED detector that included a quartz wide-eye diffuser and an NS254 filter. The detector was calibrated on July 10, 2001, and in February 25, 2002. The change in responsivity during this period was -4.25%.

6.2 Dose-Response Data

All raw data for dose-response analyses 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 21 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 0.96 and 1.04.

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 these two samples' titers 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:

$$Similarity = \log\left(\frac{Inital\,Control(pfu/mL)}{Final\,Control(pfu/mL)}\right) \qquad (5\text{-}8)$$

For the 15 dose-response series completed during this verification test, the similarities are shown in Figure 6-1. The similarities between the control titers are generally less than 0.15, but range up to 0.26, which is still less than the 0.32 acceptable value.

6.2.2 Excluded Data

Two dose-response series' are excluded from the analysis of the verification test. DRS2 had too few (<30) plaque counts on the undosed control, and DRS5 had too many (>300) plaque counts on the dosed samples.

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 ETV. Of the 60 data points from the 13 valid dose-responses, 51 points (85%) lie within the specified QC boundary lines. Thus, the valid dose-response data generated for this verification test is accepted as valid.

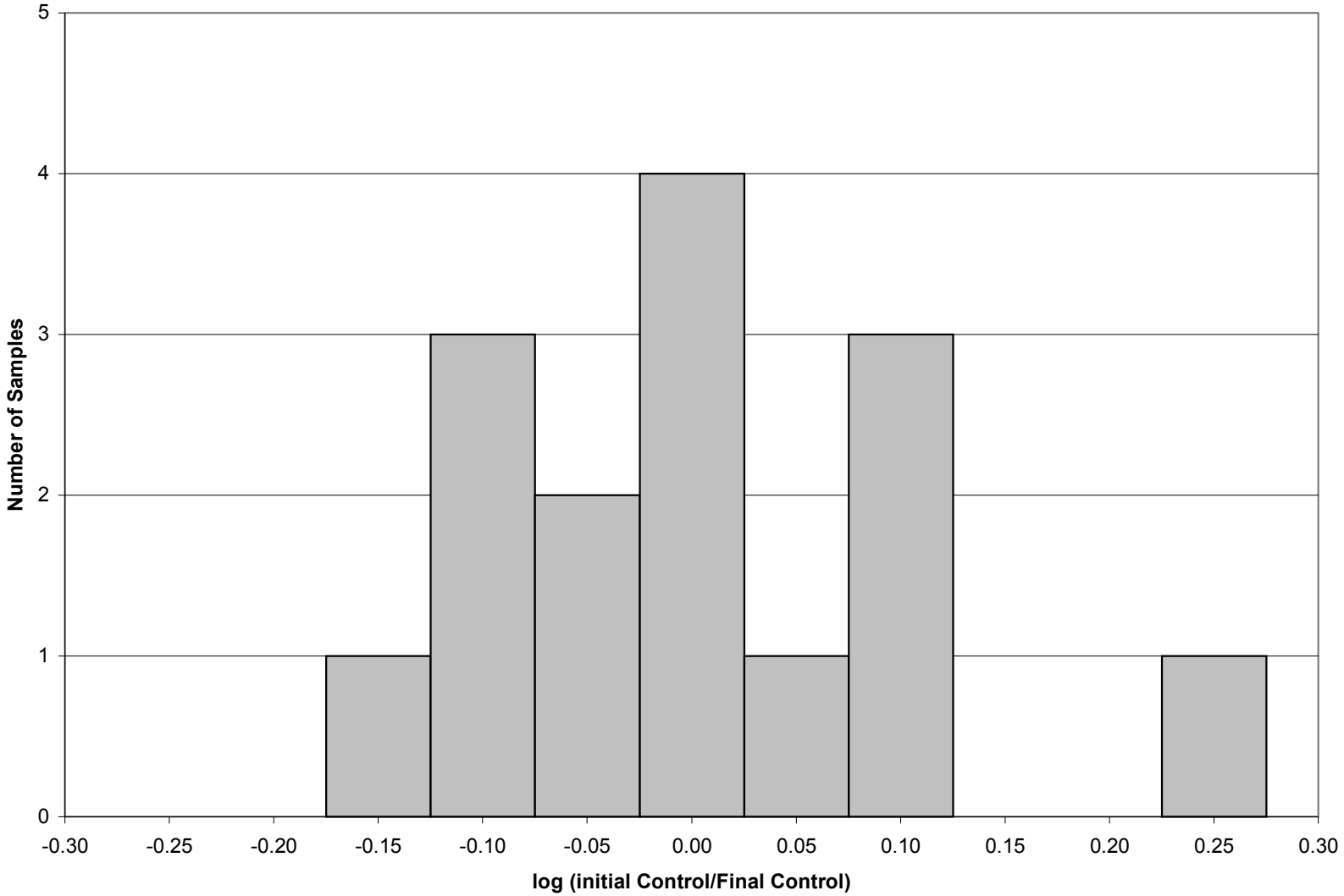


Figure 6-1. Similarity Between Initial and Final Dose-Response Controls.

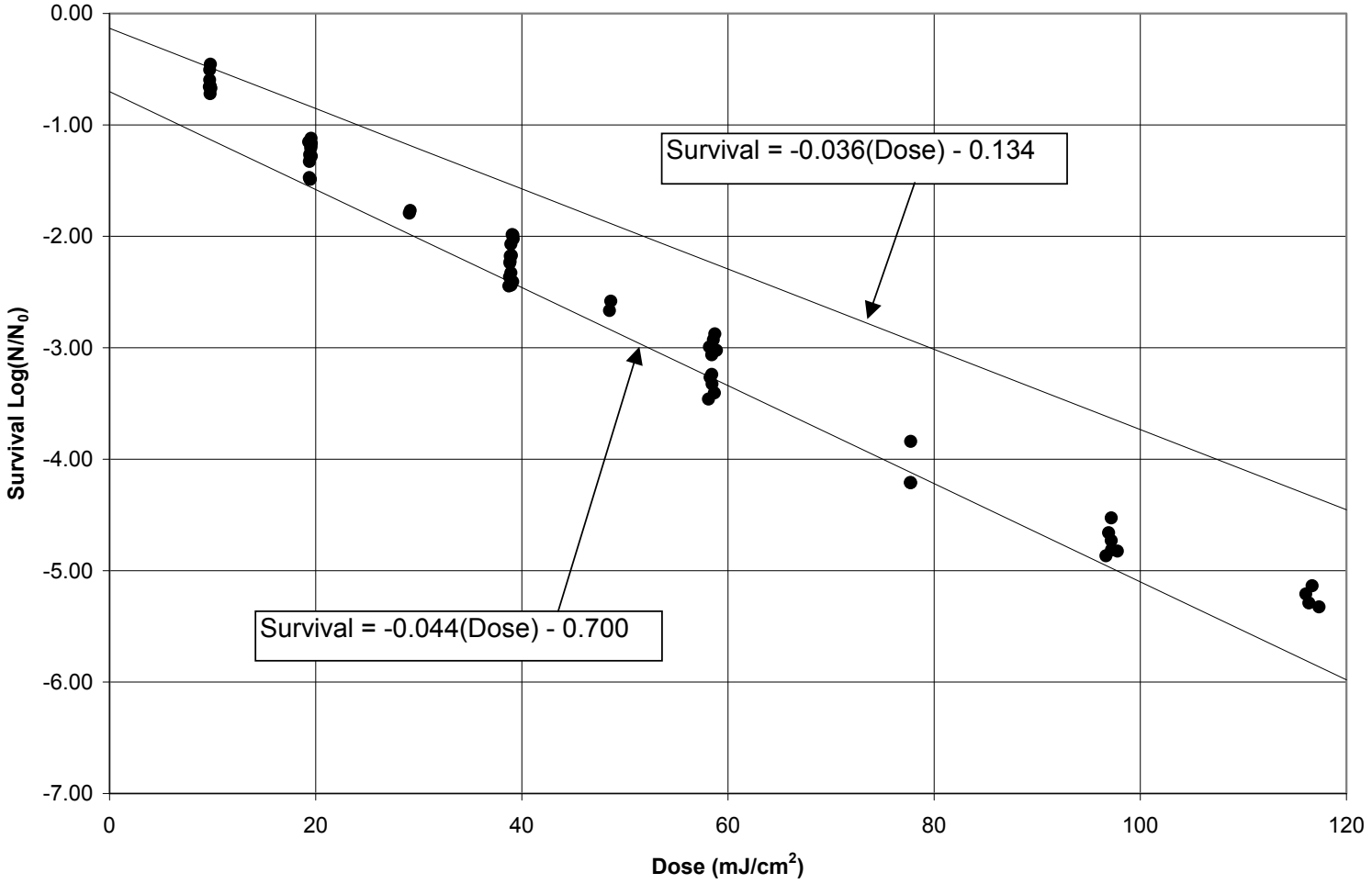


Figure 6-2. Dose-Response Data and QA/QC Boundary Lines.

6.3 Flow Test Data

All flow test data are included in Appendix C.

6.3.1 Quantitative QC Criteria

6.3.1.1 Flow Test Sample Replicates

The VTP 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 22 replicate platings. The similarity of these titers allows a quantitative evaluation of the plating procedure.

The titers are compared by calculating the similarity:

$$Similarity = \log\left(\frac{Sample\,Titer\,1\left(pfu/mL\right)}{Sample\,Titer\,2\left(pfu/mL\right)}\right) \tag{5-9}$$

Figure 6-3 shows a distribution of the replicate similarity data. For the 22 samples plated in replicate during this ETV, all were within the acceptable limit of 0.46 log units (a factor of three). With the exception of one sample, the replicate titer similarities are within 0.3 log units. Since the exceptional sample had only one countable plate for the replicate, it is probably skewed.

6.3.1.2 Duplicate Flows

During each of four flow series', a flow test was duplicated (i.e., flow tests were performed at the same flow rate) to determine the repeatability of the flow settings during the test. The average survival data, and similarity for each of these duplicate flows, is shown in Table 6-2.

Table 6-2. Results From Flow Test Duplicates.

Day	Flow	Survival Flow A	Survival Flow B	Similarity
Day 2	5678	-0.90	-0.89	-0.01
Day 4	757	-3.24	-3.28	0.04
Day 7	757	-1.39	-1.12	-0.27
Day 11	379	-3.76	-3.61	-0.14

The maximum similarity is 0.27 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 the ETV, each influent sample was analyzed for percent transmittance at 254 nm at the laboratory. In 17 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*):

$$RPD = \frac{Analysis\,1 - Analysis\,2}{Average(Analysis)} \times 100\% \qquad (5\text{-}10)$$

Figure 6-4 shows the *RPD* of the 17 transmittance measurements that were replicated. In all cases, the replicate measurements are in agreement within the 0.5% allowed by the test plan.

6.3.2 No-Dose Flow

On day 8, a flow was conducted at 757 L/min (200 gpm) at the end of the 55% T five-flow series, with the lamps turned off. This no-dose flow was conducted to determine if there was any "memory" effect from dosed coliphage collecting on the reactor.

A comparison of the effluent samples with the average of the three influent replicates resulted in survival ratios of 0.07, -0.06, and -0.15 for an average of -0.05. These titer differences are well within the range of similarity for identical samples, reflecting that there are no extraneous effects on the survival ratios observed during flow tests.

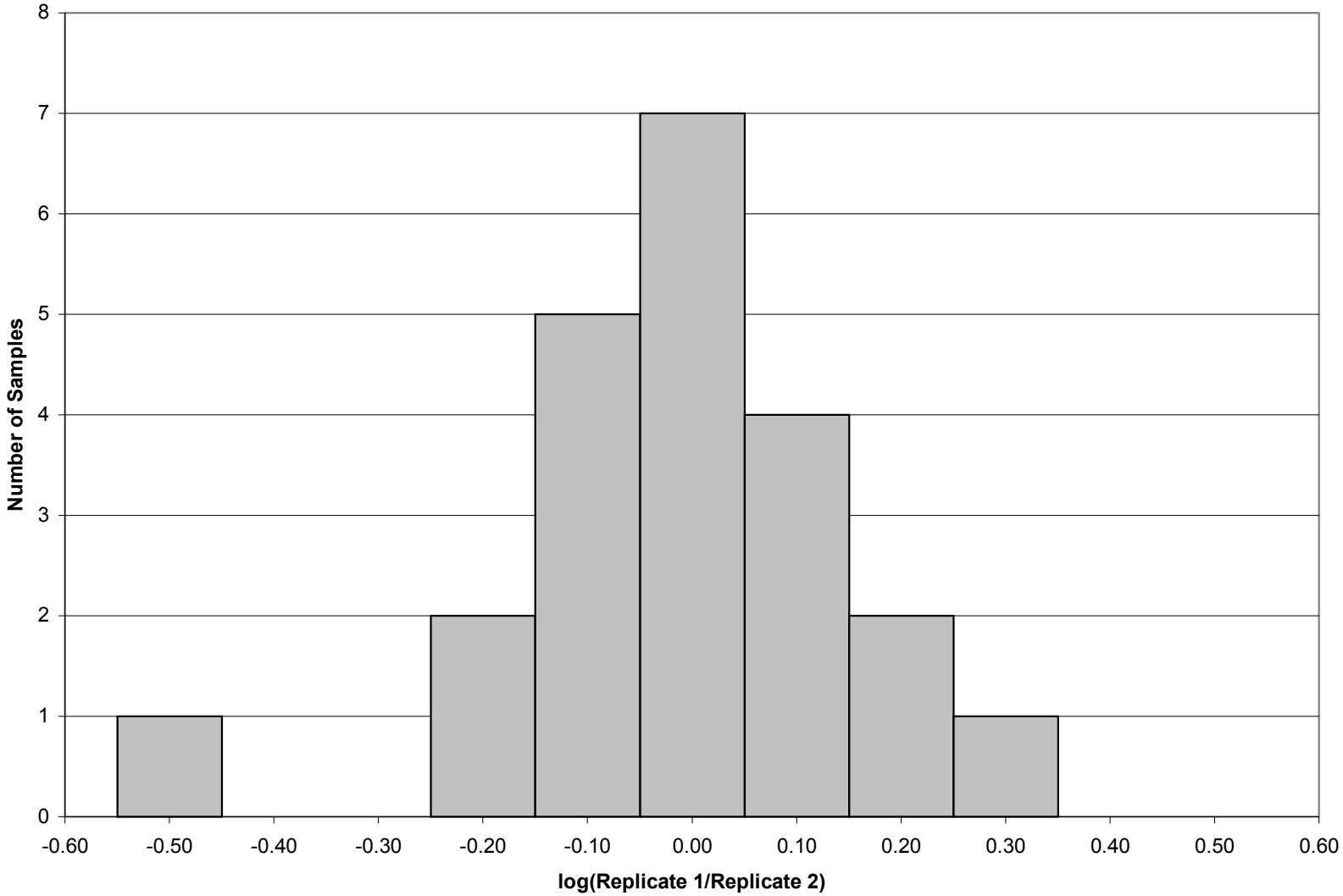


Figure 6-3. Similarity Among Replicate Flow Test Samples.

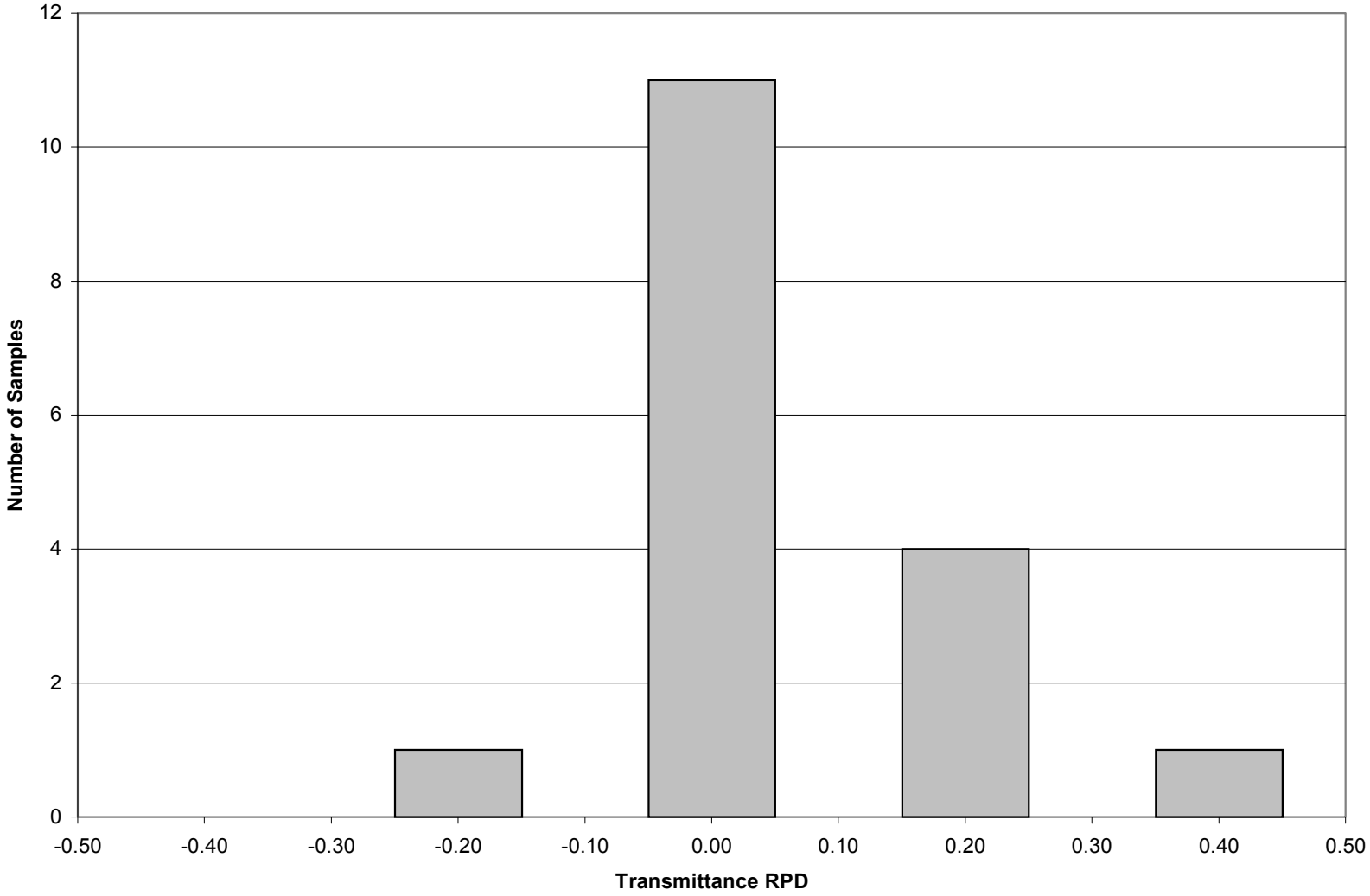


Figure 6-4. Relative Percent Difference for Percent Transmittance Replicates.

6.3.3 Excluded Data

Of the 57 flow tests conducted during this ETV, 9 were excluded because they were shakedown flows or did not meet some QA/QC criterion. The individual flow tests are shown in Table 6-3 with the justification for exclusion. The data for these flows are included in Appendix C.

Table 6-3. Excluded Flow Test Data.

Day	Flow	Justification
S/Down	5678	Bad Transmittance.
S/Down	3028	Bad Transmittance.
S/Down	757	Bad Transmittance.
Day 2	757	Channel probably not flushed completely.
Day 5	757	Wrong dilutions, out of 30-300 range.
Day 9	757	Wrong dilutions, out of 30-300 range.
Day 9	3028	Wrong dilutions, out of 30-300 range.
Day 10	379	Wrong dilutions, out of 30-300 range.
Day 11	757	Anomalous result.

6.3.4 Power Monitoring

Power stability was not monitored for all flow tests because of the cumbersome nature of the power measurement for the LRCM's. To address this difficulty, a flow series was conducted with detailed power measurements, and the flow results were compared to flow tests where power monitoring was not conducted. Table 6-4 shows the power measurements taken during a three-flow series with 55% T water. This table includes the conditions (including lamp intensity) both before and after the power turndown adjustment.

Table 6-4. Power Measurements During One Flow Series.

Event	Panel Setting	Bal 1 (V)	Bal 2 (V)	Bal 3 (V)	Bal 4 (V)	Bal 1 (A)	Bal 2 (A)	Bal 3 (A)	Bal 4 (A)	Intensity (mW/cm^2)
Potable	100%	119.3	119.1	119.2	119.1	9.35	9.22	9.38	9.28	$1.70x10^{-8}$
Potable	55%	119.7	119.8	119.7	119.8	5.97	5.86	6.10	5.88	$1.19x10^{-8}$
757 L/min	55%	119.7	119.8	119.7	119.8	5.96	5.88	6.11	5.88	Ratio: 0.70
1892 L/min	55%	119.6	119.7	119.9	119.8	5.98	5.87	6.12	5.89	
3027 L/min	55%	119.6	119.8	119.8	119.8	5.98	5.86	6.10	5.89	
Average	55%	119.7	119.8	119.8	119.8	5.97	5.87	6.11	5.89	

The intensity was monitored with an SUD detector attached near the lamps during the lamp turndown. It is only possible to monitor the intensity turndown at the beginning of the flow test because a constant flow rate must be used and potable water (with a high percent T) must be flowing through the test unit for accurate, relative, intensity readings. The 55% panel current setting resulted in an intensity reduction to 70% (see Table 6-4), which is similar to the settings used for other flow tests. In addition, the electrical monitoring during the flow tests shows that both the voltage and the current did not vary significantly throughout the flow test series.

To demonstrate that the conditions during the limited number of monitored flows were typical for the other, unmonitored, flows in this verification test, flow test dose delivery data from monitored and unmonitored flows are compared. Table 6-5 shows a statistical comparison of the delivered doses at three flow rates, both with and without power monitoring. The four or five flows conducted without power monitoring are analyzed for the 95% confidence interval and compared with the doses achieved during monitoring.

The data are comparable, with the possible exception of the doses at 1893 L/min, where the dose achieved during the power monitoring test is slightly above the 95% confidence interval. This monitored dose of 20.3 is less than 10% higher than the highest unmonitored dose of 18.3. It reflects variation that is not unusual in the bioassay procedure. With this minor caveat, the monitored and unmonitored flow tests were comparable, indicating that the power monitoring during this limited flow series was representative for the remainder of the flow tests.

Table 6-5. Dose Delivery Data Comparison for Power Monitoring.

Flow Event	(L/min)	379	1893	3028
Dose 1 Unmonitored	(mJ/cm^2)	51.2	14.1	7.8
Dose 2 Unmonitored	(mJ/cm^2)	49.0	12.1	13.5
Dose 3 Unmonitored	(mJ/cm^2)	72.6	15.7	11.6
Dose 4 Unmonitored	(mJ/cm^2)	66.2	18.3	10.9
Dose 5 Unmonitored	(mJ/cm^2)	--	17.1	--
Mean[1]	(mJ/cm^2)	59.8	15.5	11.0
95% High[1]	(mJ/cm^2)	78.0	18.5	14.7
95% Low[1]	(mJ/cm^2)	41.5	12.4	7.2
Dose with Monitoring[2]	(mJ/cm^2)	59.8	20.3	12.3

1 Statistics determined only for flows with no electrical monitoring. High and Low are boundaries of the 95% confidence interval, based on the t-test for a small sample.

2 Dose determined for flows where electrical monitoring was performed.

Appendices

A Verification Test Plan for the SUNTEC *environmental* UV Disinfection System for Secondary Effluent Applications, V 3.0

B Operation and Maintenance Manual for the SUNTEC LPX 200 Disinfection System

C Master Data Volumes 1 and 2: SUNTEC LPX 200 UV System ETV 2nd EFF Testing Program

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 deposited into a solution to be disinfected. Units are usually mJ/cm^2 (millijoules per square centimeter).

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

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

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

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

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

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

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

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

Survival Ratio - The $\log_{10}$ of the ratio of bacteriophage concentration in a UV-dosed solution to 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.

Testing Organization (TO) - An organization qualified to conduct studies and testing of UV disinfection equipment in accordance with the Verification Protocol.

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 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 Report – A written document that details the procedures and methods used during a verification test and the results of the test, including appendices with all raw and analyzed data, all QA/QC data sheets, descriptions of all collected data, and all QA/QC results. The verification test plan (VTP) shall be included as part of this document.

Verification Statement - A document that summarizes the final verification report and is reviewed and approved by 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.

References

1) International Standards Organization (1987). "Water for analytical laboratory use – Specification and test method." Switzerland: International Standards Organization, ISO 3696.

2) International Standards Organization (1995). "Water Quality-Detection and Enumeration of Bacteriophage. Part I: Enumeration of F-Specific RNA Bacteriophage." Switzerland: International Standards Organization, ISO 10705-1.

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

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

5) United States Environmental Protection Agency (1986). "Design Manual, Municipal Wastewater Disinfection." EPA/625/1-86/021.