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Environmental Technology Verification Report

Reduction of Microbial Contaminants in Drinking Water by Ultraviolet Technology

ETS UV Technology
ETS UV Model ECP-113-5

Prepared by

NSF International

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

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ETS UV Technology
(A joint venture of Engineered Treatment Systems and atg UV Technology)

ETS UV MODEL ECP-113-5

Prepared by:

NSF International
Ann Arbor, Michigan 48105

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

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Notice

The U.S. Environmental Protection Agency, through its Office of Research and Development, funded and managed, or partially funded and collaborated in, the research described herein. It has been subjected to the Agency's peer and administrative review and has been approved for publication. Any opinions expressed in this report are those of the author(s) and do not necessarily reflect the views of the Agency, therefore, no official endorsement should be inferred. Any mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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Abbreviations and Acronyms

A_{254}	Absorbance at wavelength 254 nm
ASTM	American Society of Testing Materials
ATCC	American Type Culture Collection
atg	atg UV Technology
°C	degrees Celsius
CFU	Colony Forming Units
cm	Centimeter
DWS	Drinking Water Systems
DVGW	Deutscher Verein des Gas- und Wasserfaches e.V. - Technisch - wissenschaftlicher Verein -German Technical and Scientific Association for Gas and Water
EPA	U. S. Environmental Protection Agency
ETS	Engineered Treatment Systems
ETS UV	ETS UV Technology - joint venture of ETS and atg
ETV	Environmental Technology Verification
°F	Degrees Fahrenheit
gpm	gallons per minute
in	inch(es)
h	hours
HPC	Heterotrophic Plate Count
L	Liter
lbs	pounds
LIMS	Laboratory Information Management System
log I	log base 10 Inactivation
LSA	Sodium Lignin Sulfonic Acid
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
m	meter
min	minute
mJ	milli-joules
mg	Milligram
mL	Milliliter
MS2	MS2 coliphage ATCC 15597 B1
NaOH	Sodium Hydroxide
ND	Non-Detect
NIST	National Institute of Standards and Technology
nm	Nanometer
NRMRL	National Risk Management Research Laboratory
NSF	NSF International (formerly known as National Sanitation Foundation)
NTU	Nephelometric Turbidity Unit
ONORM	Österreichisches Normungsinstitut Austria Standard
ORD	Office of Research and Development
pfu	Plaque Forming Units
Protocol	Generic Protocol

psig	Pounds per Square Inch, gauge
QA	Quality Assurance
QC	Quality Control
QA/QC	Quality Assurance/Quality Control
QAPP	Quality Assurance Project Plan
QMP	Quality Management Plan
RED	Reduction Equivalent Dose
RED_{meas}	Measured Reduction Equivalent Dose - from test runs
RED_{Val}	Validated Reduction Equivalent Dose - based on selected pathogen and uncertainty
RPD	Relative Percent Deviation
SM	Standard Methods for the Examination of Water and Wastewater
SOP	Standard Operating Procedure
SPt	Set Point Condition
TQAP	Test / Quality Assurance Plan
TDS	Total Dissolved Solids
TSA	Tryptic Soy Agar
TSB	Tryptic Soy Broth
UVT	ultraviolet transmittance
µg	microgram
µm	microns
UVDGM	Ultraviolet Disinfection Guidance Manual - 2006
USEPA	U. S. Environmental Protection Agency
U_{DR}	uncertainty of collimated beam data
U_{SP}	uncertainty of set point
U_S	uncertainty of sensor
U_{VAL}	uncertainty of validation

Chapter 1
Introduction

1.1 ETV Program Purpose and Operation

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

ETV works in partnership with recognized standards and testing organizations; with stakeholder groups consisting of buyers, vendor organizations, and permitters; and with 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 testing, collecting and analyzing data; and by preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

The USEPA has partnered with NSF International (NSF) under the ETV Drinking Water Systems Center (DWS) to verify performance of drinking water treatment systems that benefit the public and small communities. It is important to note that verification of the equipment does not mean the equipment is "certified" by NSF or "accepted" by USEPA. Rather, it recognizes that the performance of the equipment has been determined and verified by these organizations under conditions specified in ETV protocols and test plans.

1.2 Purpose of Verification

The purpose of the ETV testing was to validate, using the set line approach, the UV dose delivered by the ETS UV Technology (ETS UV) *Model ECP-113-5* Water Purification System (*Model ECP-113-5*) as defined by these regulatory authorities and their guidelines and regulations:

- Water Supply Committee of the Great Lakes--Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers otherwise known as The Ten States Standards 2012 ;
- The Norwegian Institute of Public Health (NIPH) and its guidelines; and
- The New York Department of Health (NYDOH) and its code.

Another purpose was to use the same data set to calculate the log inactivation of a target pathogen such as *Cryptosporidium* using the *Generic Protocol for Development of Test / Quality*

Assurance Plans for Validation of Ultraviolet (UV) Reactors, August 2011 10/01/EPADWCTR (GP-2011) which is based on *Ultraviolet Design Guidance Manual For the Long Term 2 Enhanced Surface Water Treatment Rule*, Office of Water, US Environmental Protection Agency, November 2006, EPA 815-R-06-007 (UVDGM-2006).

The setline approach was based on validation testing at three set points (a set point is defined a single flow rate and irradiance output that delivers the targeted UV dose). The results of the three set point tests were used to develop a setline that defines the maximum flow rate - minimum irradiance output required to ensure the UV dose is achieved. The microorganism used for this validation test was MS2 coliphage virus (MS2). The target UV dose was a measured Reduction Equivalent Dose (RED_{meas}) of $\geq$40 mJ/cm^2. This dose was calculated based on the understanding of dose calculations used internationally and by the Ten States Standards. The RED_{meas} was then adjusted based on the uncertainty of the measurements to calculate a MS2 based validated dose (RED_{val}) where the RED bias is set equal to one (1.0) in accordance with the unique approach of the State of New York. The REDmeas data were also adjusted for uncertainty and the *Cryptosporidium* RED bias factors from the UVDGM-2006 Appendix G. The data were used to estimate the log inactivation of *Cryptosporidium* so that a regulatory agency could grant log credits under the USEPA's Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR).

ETS UV Technology (ETS UV) selected flow rates of 50, 75, and 100 gpm as the target flow rates based on their system design for *Model ECP-113-5*.

Based on the result of the three set points, a setline was developed for this unit. During full-scale commercial operation, Federal regulations require that the UV intensity as measured by the UV sensor(s) must meet or exceed the validated intensity (irradiance) to ensure delivery of the required dose. Reactors must be operated within the validated operating conditions for maximum flow rate - minimum irradiance combinations, UVT, and lamp status [40 CFR 141.720(d)(2)]. Under the UV setline approach, UV Transmittance (UVT) does not have to be measured separately. The intensity readings by the sensor take into account changes in the UVT and the setline establishes the operating conditions over a range of flow rates used during the validation test.

ETS UV also requested an additional set point be tested, at a higher flow rate of 175 gpm. The purpose of this additional set point was to demonstrate a minimum 3-log inactivation of *Cryptosporidium* at the higher flow rate. The goal was to use the additional set point and, combined with the set points at 50, 75 and 100 gpm, to develop a set line for flow rate and irradiance conditions that could achieve a minimum 3-log inactivation of *Cryptosporidium*.

This verification test did not evaluate cleaning of the lamps or quartz sleeves, nor any other maintenance and operational issues. The automated wiper system was operated before and during the test in accordance with the operating manual.

1.3 Verification Test Site

UV dose validation testing was performed at the NSF Testing Laboratory in Ann Arbor, Michigan. The NSF laboratory performs all of the testing activities for NSF certification of drinking water treatment systems, and NSF certification of pool and spa treatment systems.

1.4 Testing Participants and Responsibilities

The following is a brief description of each of the ETV participants and their roles and responsibilities.

1.4.1 NSF International

NSF is an independent, not-for-profit organization dedicated to public health and safety, and to protection of the environment. Founded in 1944 and located in Ann Arbor, Michigan, NSF has been instrumental in the development of consensus standards for the protection of public health and the environment. The USEPA partnered with NSF to verify the performance of drinking water treatment systems through the USEPA's ETV Program.

NSF performed all verification testing activities at its Ann Arbor, MI location. NSF prepared the test/QA plan (TQAP), performed all testing, managed, evaluated, interpreted, and reported on the data generated by the testing, and reported on the performance of the technology.

Contact: NSF International
789 N. Dixboro Road
Ann Arbor, MI 48105
Phone: 734-769-8010
Contact: Mr. Bruce Bartley, Project Manager
Email: bartley@nsf.org

1.4.2 U.S. Environmental Protection Agency

USEPA, through its Office of Research and Development (ORD), has financially supported and collaborated with NSF under Cooperative Agreement No. R-82833301. This verification effort was supported by the DWS Center operating under the ETV Program. This document has been peer-reviewed, reviewed by USEPA, and recommended for public release.

1.4.3 ETS UV Technology

ETS UV Technology supplied the UV test unit for testing, required reference sensors, detailed specifications on the equipment, UV lamps, lamp sleeves, and duty sensors, and written and verbal instructions for equipment operation. ETS also provided logistical and technical support, as needed.

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W9652 Beaverland Parkway
Beaver Dam, Wisconsin
Phone: 1-877-885-4628
Email: info@ets-uv.com

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Pemberton
Wigan, WN5 8AA
United Kingdom
Phone: +44(0) 1942216161
Website: www.atguv.com

Chapter 2
Equipment Description

2.1 General Information ETS UV Technology

ETS UV was founded in January 2005 in a joint venture between atg UV Technology (atg) and Engineered Treatment Systems (ETS) to accommodate the growing demand for ultraviolet disinfection and photolysis across the US pools and recreational water markets. Systems are manufactured at the Beaver Dam production facility located in, Beaver Dam, Wisconsin. Production of ultraviolet disinfection systems for the US market began in January 2008. In 2009, the second phase of ETS UV became operational. Based in Ohio, ETS UV Industrial & Municipal offers low and medium pressure UV systems for municipal drinking water, waste water and industrial UV treatment applications.

The atg UV is based in the North West of England, serving an international customer base. Since being founded in 1981 as Willand UV System, atg indicates that they have served a number of markets including municipal drinking water and wastewater disinfection, industrial processes and manufacturing, offshore and marine industries and swimming pool applications.

ETS is based in Beaver Dam Wisconsin. ETS states that it has over three decades of experience and over 1500 successful case studies in the custom design and production of UV disinfection systems for a range of applications.

2.2 ETS *Model ECP-113-5* UV System Description

The ETS UV Water Purification System validated in this test is *Model ECP-113-5*. This unit is rated by ETS UV to handle 260 gpm for 3 log reduction of *Cryptosporidium* and 180 gpm to deliver 40 mJ/cm^2 RED_{meas} based on MS2. The system uses one (1) medium pressure mercury amalgam lamp and one intensity sensor mounted in a stainless steel flow chamber. Figure 2-1 presents a photograph of the system and a system configuration drawing is shown in Figure 2-2. Additional specifications for the unit are presented in Section 2.3. The operating manual and technical information is provided in Attachment 1. The operating manual includes schematics and tables with parts and dimensions for the reactor, the sensors, the lamps and the quartz sleeves. All specifications and equipment information was provided by ETS UV in advance of the actual shipment of the unit to NSF. ETS UV provided additional information for the UV sensor (spectral data, measuring angle, measuring range, and output range) and for UV lamps (lamp life, irradiance output, power requirements, aging data, etc.) as required for the validation test. This information is presented in Attachment 2.

NSF performed a normal technical review of the sensor specifications, UV lamp and quartz sleeve specification, and general review of the reactor chamber and overall system as required by the GP-2011.

The operating manual, technical book and other supplemental specifications for the sensor, lamp, quartz sleeve, and control system provided by ETS UV are included in Attachments 1 and 2 ~~to this report~~ for reference.

Figure 2-1. ETS UV *Model ECP-113-5.*

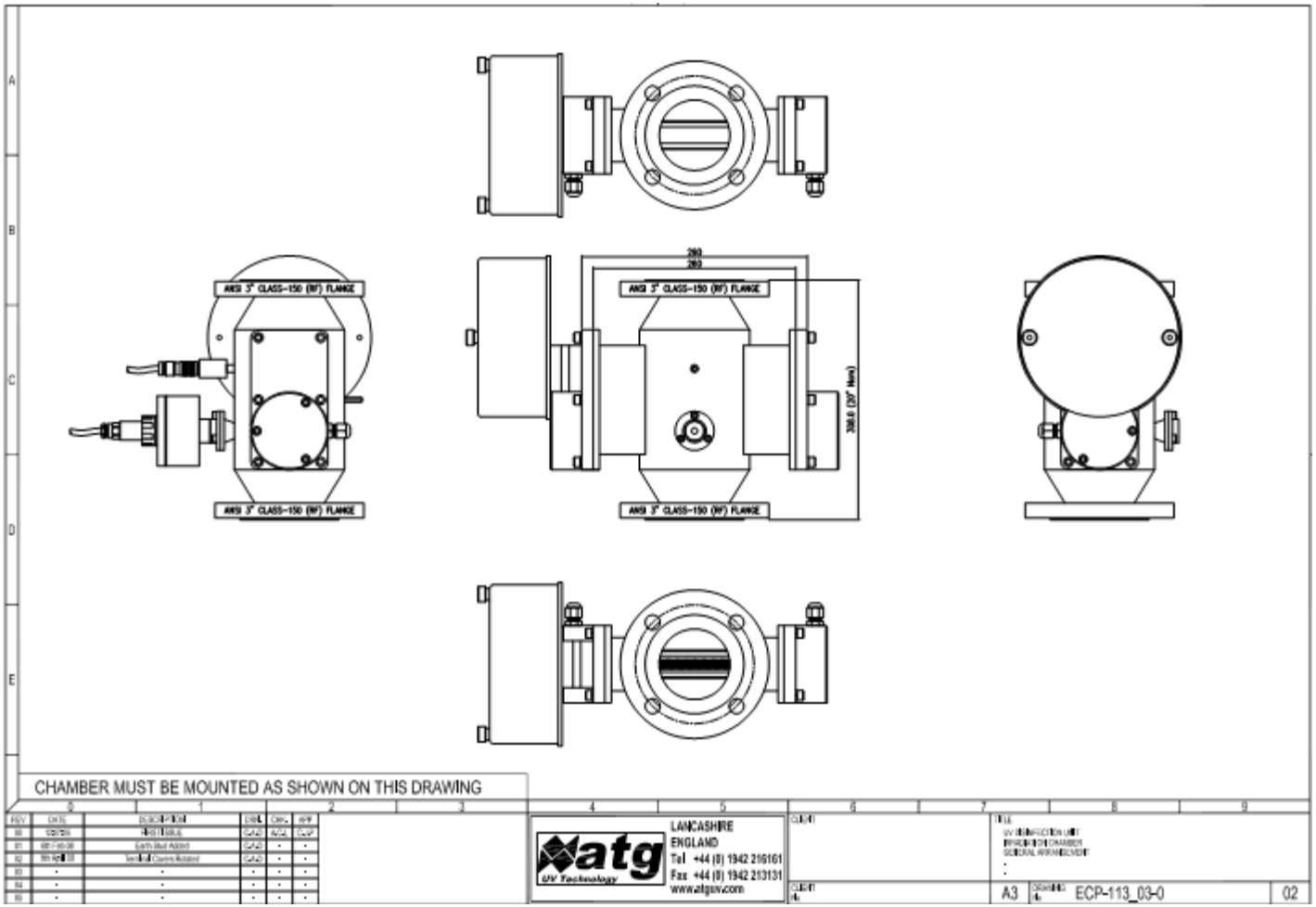

Figure 2-2. ETS UV *Model ECP-113-5* configuration drawing.

2.3 ETS UV *Model ECP-113-5* Specifications and Information

ETS UV has provided the following information about their UV reactor:

Table 2.1. Basic UV Chamber Information.

Manufacturer/Supplier	ETS UV Technology
Type or model	ECP-113-5
Description	Cross Flow Medium Pressure UV Disinfection System
Year of manufacture	2008 and onwards
Maximum flow rate	260 gpm
Net dry weight	42 lbs
Volume	236 cubic inches
Electrical power	2 phase 220 VAC, 60Hz; 20 amp single pole, earth ground.
Operating power consumption	1300 W
Maximum pressure	60 psi
Ambient water temperature	40 to 114 degrees °F
Maximum cleaning temperature	180 degrees °F (unit turned off)
Inlet pipe size	3 in

Table 2.2. Medium Pressure Lamp Information.

Type	Medium-pressure
Model	W1501200
Number of lamps per reactor	1
UV emission at wavelengths ranging from 240-290 nm	See Lamp spectral graph in Attachment 1..
Lamp life	4000 hrs
Power supply unit's name, make and serial numbers	SPECTRA R4.02 SP-A-220 #A18587-X
Ballast	Magnetic Choke with Igniter
Irradiance @1m	90 W/cm
UV output	35 W
Operating lamp power	1300 W
Lamp current and voltage	9.0 A; 160 V
Arc length	140 mm

Table 2.3. UV Lamp Sleeve Information.

Type or model	GE 214 Clear Fused Quartz
Quartz material	Clear Fused Quartz
Pressure resistance	7000 psi

Table 2.4. UV Sensor Information.

Manufacturer / model	UV-Technik SUV20.1 A2Y2C
Measuring field angle	160 degree
Number of sensors per reactor and placement	1
Signal output range	4 - 20 mA
Measuring range Output signal	0 - 100 W/m^2

Additional UV sensor spectral information provided by ETS UV prior to the start of testing demonstrated the sensor met the requirements of the *Generic Protocol for Development of Test/Quality Assurance Plans for Validation of Ultraviolet (UV) Reactors, NSF International, 7/2010* (GP-2010) and the GP-2011. The GP-2010 and the updated GP-2011 are based on the USEPA's UVDGM-2006 requirements. The sensor meets the GP-2010 and GP-2011 requirement that >90% of the response is between 200-300 nm. The sensor information is included in Attachment 2.

Chapter 3
Methods and Procedures

3.1 Introduction

The tests followed the procedures described in the *Test/Quality Assurance Plan for The ETS UV Ultraviolet (UV) Reactor, Medium Pressure Lamps, June 2010* (TQAP). The TQAP was adapted from the GP-2010 and was updated in 2011. The ETV Generic Protocol was derived from the USEPA's UVDGM-2006. The TQAP is available from NSF upon request.

The approach used to validate UV reactors is based on biodosimetry which determines the log inactivation of a challenge microorganism during full-scale reactor testing for specific operating conditions of flow rate, UV transmittance (UVT), and UV intensity (measured by the duty sensor). A dose-response equation for the challenge microorganism (MS2 coliphage for this test) is determined using a collimated beam bench-scale test. The observed log-inactivation values from full-scale testing are input into the collimated beam derived-UV dose-response equations to estimate a "Reduction Equivalent Dose (RED)". The RED value is adjusted for uncertainties and biases to produce the validated dose of the reactor for the specific operating conditions tested.

The methods and procedures were designed to accomplish the primary objective of the validation test of the *Model UVL-200-4*, which was to develop a set line based on three set points (each set point is a specific flow rate- UV intensity combination) that would ensure a measured RED (RED_{meas}) of at least 40mJ/cm^2 based on MS2 as defined by the Ten States Standards 2012. Test procedures were also designed so that the RED_{meas} could be adjusted based on the uncertainty of the measurements to calculate a MS2 based validated dose (RED_{Val}) in accordance with the unique approach of the State of New York. The RED_{meas} data were also adjusted for uncertainty and the *Cryptosporidium* RED bias factors from the UVDGM-2006 Appendix G.

During testing of the unit, an additional single set point test at a higher flow rate and intensity was performed which defined an operating condition that could achieve a minimum of 3-log inactivation of *Cryptosporidium*. This higher flow rate point was then used with the other set points to develop of a set line that demonstrated a 3-log inactivation of *Cryptosporidium*.

UV reactor validation included:

1. Obtain the technical specifications for the system as provided by ETS UV.
2. Assessment of the UV sensors.
3. Collimated beam laboratory bench scale testing.
4. Full scale reactor testing.
5. Calculations to determine the RED_{meas}.
6. Adjust the RED_{meas} for uncertainty in UV dose and calculate a validated dose for *Cryptosporidium*.

The target UV dosage validated was a RED_{meas} of 40 mJ/cm^2, based on MS2. ETS UV selected flow rates of 50, 75, and 100 gpm as the target flow rates based on their system design for *Model*

ECP 113-5. The additional flow rate selected for testing based on ETS UV's request was 175 gpm.

3.2 UV Sensors Assessment

The *Model ECP-113-5* duty sensor was evaluated according to the UV sensor requirements in the GP-2011 prior to the verification testing. All UV intensity sensors (the duty and two reference sensors) were new sensors and specifications provided with the sensors showed they were designed in accordance with the DVGW guideline W 294 (June, 2006) and the ÖNORM M5873-2 standard (June 2002), respectively. Evidence of calibration of the sensors within the last 12 months, traceable to a standard of the Physikalisch Technische Bundesanstalt (PTB) in Braunschweig, was provided by ETS UV as provided to them by the sensor manufacturer (*uv-technik)*.

The validation testing requires confirmation of the duty sensor spectral response to assess whether the sensors are germicidal (see UVDGM-2006 Glossary for definition of germicidal) with a defined spectral response of at least 90% between 200 and 300 nm. The technical specifications of the ETS UV sensor and representation of sensitivity to the germicidal wavelength was provided by ETS UV and found to meet the requirements. The technical specifications of the ETS UV sensor and representation of sensitivity to the germicidal wavelength is included in Attachment 2.

During validation testing, the duty UV sensor measurement was compared to two reference sensor measurements to assure the duty sensor was within 10% of the average of the two reference sensor measurements.

The following steps were used to check the uncertainty of the duty and reference UV sensors. The sensors were checked before and after the validation testing.

1. Step 1: Water was passed through the reactor at the maximum UV transmittance (UVT) and the maximum lamp power setting to be used during validation testing.

2. Step 2: Using two recently calibrated (at a minimum annually) reference UV sensors, each reference sensor was installed on the UV reactor at the sensor port. The UV intensity was measured and recorded.

   Step 2 was repeated using the duty UV sensor.

3. Step 3: Steps 1 and 2 were repeated at maximum UVT and lamp power decreased to the minimum level expected to occur during validation testing.

4. Step 4: For a given lamp output and UVT value, the difference between the reference and duty UV sensor measurements were calculated as follows:

   $$\text{The absolute value of } [(S_{duty} / S_{Avg\ Ref}) - 1]$$

Where:

S_{duty} = Intensity measured by a duty UV sensor,

$S_{Avg\ Ref}$ = Average UV intensity measured by all the reference UV sensors in the same UV sensor port with the same UV lamp at the same UV lamp power.

3.3 Headloss Determination

Headloss through the unit was determined over the range of expected flow rates, in this case from 50 gpm to 200 gpm. The inlet pressure near the inlet flange and the outlet pressure near the outlet flange were measured at several flow rates. Measurements were recorded for flow rates of 50, 100, 150 and 200 gpm. These data are reported in Section 4.11.

3.4 Power Consumption Evaluation

The amperage and voltage used by the unit were measured during all reactor test runs.

Power data are presented in Section 4.10.

3.5 Feed Water Source and Test Rig Setup

The water source for this test was City of Ann Arbor Michigan municipal drinking water. The water was de-chlorinated using activated carbon, as confirmed by testing in the laboratory. For the lowered UVT conditions, the chemical Sodium Lignin Sulfonic Acid (LSA) was used to lower the UV transmittance to the UVTs of <79%, <90% and <94%. LSA was added to the supply tank before each set of the lowered UVT runs and was well mixed using a recirculating pump system. UVT was measured continuously using an in-line UVT meter (calibrated daily) to confirm that proper UVT was attained. UVT measurements were also confirmed by the collection of samples during each test run and analysis by a bench top spectrophotometer.

NSF used a UV test rig and system setup that is designed to conform to the specifications as described in the GP-2011 and UVDGM-2006. Figure 3-1 shows a basic schematic of the NSF test rig and equipment setup. The schematic is reproduced for informational purposes and is copyright protected. A photograph of the actual setup is shown in Figure 3-2.

The feed water pump to the test unit was a variable speed pump. Flow rate was controlled by adjusting the power supplied to the pump and by a control valve. A magnetic water flow meter was used to monitor flow rate. The meter was calibrated and easily achieved the required accuracy of $\pm$ 5%. A chemical feed pump (injector pump) was used to inject MS2 coliphage upstream of an inline static mixer. The inline mixer ensured sufficient mixing of the microorganism prior to the influent sampling port, which was located upstream of the 90^{o} elbow installed directly on the inlet to the unit. The effluent sampling port was located downstream of a 90^{o} elbow that was installed directly on the outlet port of the unit and downstream of a second in-line mixer. This use of an in-line mixer met the UVDGM-2006 requirement to ensure good mixing of the treated water prior to the effluent sampling port.

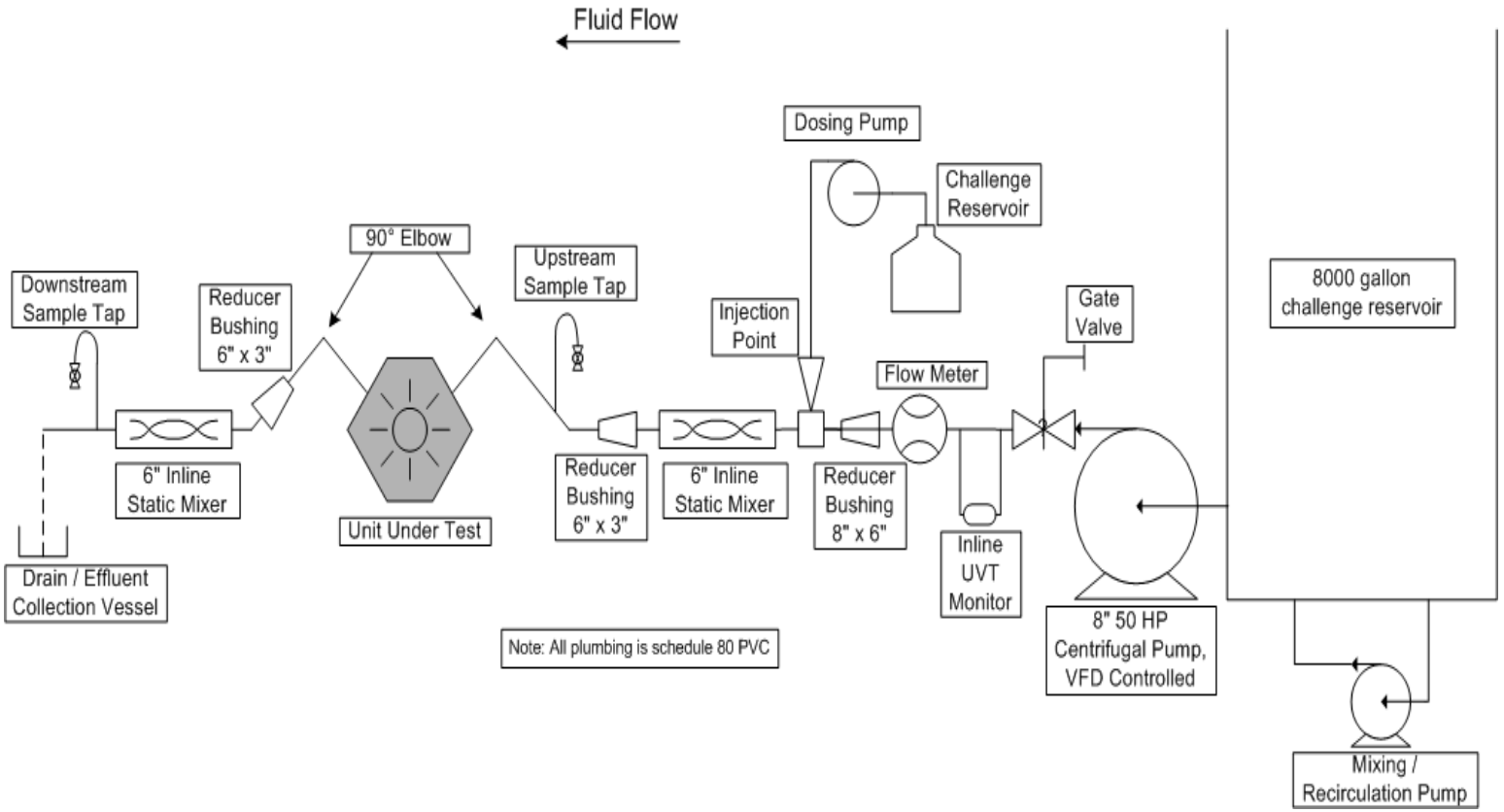

Figure 3-1 Schematic of NSF test rig©

Figure 3-2 Photograph of the *Model ECP-113-5* Test Setup

3.6 Installation of Reactor and Lamp Burn-in

The UV reactor and the reactor inlet and outlet connections were installed at the NSF laboratory in accordance with the ETS UV installation and assembly instructions. Two 90 degree elbows, one upstream and one downstream of the unit, were used in the test rig setup to eliminate stray UV light. Figure 3-2 shows a photograph of the test rig setup, which conforms to the GP-2011.

The UV lamp was new and therefore the system was operated for 100 hours with the lamps turned on at full power prior to the start of the test.

There is one duty sensor and one lamp in the *Model ECP-113-5*. Therefore, the lamp positioning check requirements (checking each lamp and placing the lowest output lamp closest to the sensor) were not required for this validation.

3.7 Collimated Beam Bench Scale Testing

The collimated beam procedure involves placing a sample collected from the test rig and containing MS2 in a petri dish and then exposing the sample to collimated UV light for a predetermined amount of time. The UV dose is calculated using the measured intensity of the UV light, UV absorbance of the water, and exposure time. The measured concentration of microorganisms before and after exposure provides the "response," or log inactivation of the microorganisms from exposure to UV light. Regression analysis of measured log inactivation for a range of UV doses produces the dose-response curve.

Appendix C of the UVDGM-2006 provides guidance on how to conduct the collimated beam bench-scale testing and to produce a UV dose-response curve. Based on the UVDGM-2006 guidance, the following sections describe the details of the collimated beam testing.

3.7.1 Test Microorganism (Challenge)

MS2 coliphage ATCC 15597-B1 was used in collimated beam bench scale testing and for the full-scale reactor dose validation tests. MS2 coliphage ATCC 15597-B1 is a recommended microorganism for UV lamp validation tests. Further reasons for selecting this microorganism for UV validation are based on its inter-laboratory reproducibility (UVDGM-2006), ease of use and culturing, and demonstrated performance of MS2 in validation testing.

3.7.2 Test Conditions

The collimated beam tests were performed in duplicate at the minimum and maximum UVT test conditions. This validation test included three days of testing. The lowered UVT test runs were performed on the first day (July 18, 2012). The intensity readings at each UVT (79%. 89%, 93%) were recorded during test runs with full lamp power. Collimated beam tests were run on the minimum UVT water (79%) with duplicate runs being performed. On the second day (July 19, 2012) using high UVT water (95%), the power was reduced to achieve the same intensity as measured for each of the lowered UVT waters on day one. Collimated beam tests were run on day two on the high UVT water (95%) with duplicate runs being performed. Additional testing was performed on September 11, 2012 (test day three) for the lowest flow rate (50 gpm) for both the lowered UVT water (79%) and for the lowered power tests. In addition, one medium flow rate test (75 gpm) at the lowered power setting required a retest as part of the September test runs. This third day of testing included both lowered UVT water (79%) and the use of high UVT water (97%) for the lowered power runs. Collimated beam tests were performed in duplicate on both the 79% and 97% UVT water on the third day of testing. Therefore, for this validation test, there are four sets of duplicate collimated beam test data, two for the lowest UVT water (79%) and two for the high UVT water (water not adjusted with LSA).

UV doses covered the range of the targeted RED dose, which in this case is 40mJ/cm^2. UV doses were set at 0, 20, 30, 40, and 60 and 80 mJ/cm^2. The samples are clustered close to the 40mJ/cm^2 target dose with two doses above and below the target of 40 mJ/cm^2.

The collimated beam radiometers were calibrated to ensure that the measured UV intensity met the criteria of an uncertainty of 8 percent or less at a 95-percent confidence level.

3.7.3 Test Apparatus

NSF uses a collimated beam apparatus that conforms to NSF/ANSI Standard 55 section 7.2.1.2 and the UVDGM-2006. A description of the apparatus is presented in NSF/ANSI Standard 55© Annex A, which is presented in Attachment 3.

3.7.4 Collimated Beam Procedure

NSF collected two (2) one liter samples from the influent sampling port of the test rig for collimated beam testing. Each bottle was used for one of the replicates for the collimated beam test. The MS2 spiked water was collected directly from the test rig each day during the test runs. Therefore, the collimated beam test water and microorganism culture was the same as used in the full scale reactor tests.

NSF microbiological laboratory personnel followed the "Method for Challenge Microorganism Preparation, Culturing the Challenge Organism and Measuring its Concentration" in Annex A of NSF/ANSI Standard 55, which is attached to the TQAP for reference. Please note that all reproduced portions of NSF/ANSI Standards are copyright protected.

For collimated beam testing of a water sample containing challenge microorganisms, NSF's laboratory followed this procedure:

1. Measure the A_{254} of the sample.
2. Place a known volume from the water sample into a petri dish and add a stir bar. Measure the water depth in the petri dish.
3. Measure the UV intensity delivered by the collimated beam with no sample present using a calibrated radiometer using a calibrated UV sensor. The UV sensor is placed at the same distance from the radiometer as the sample surface.
4. Calculate the required exposure time to deliver the target UV dose described in the next section.
5. Block the light from the collimating tube using a shutter or equivalent.
6. Center the petri dish with the water sample under the collimating tube.
7. Remove the light block from the collimating tube and start the timer.
8. When the target exposure time has elapsed, block the light from the collimating tube.
9. Remove the petri dish and collect the sample for measurement of the challenge microorganism concentration. Analyze immediately or store in the dark at 4 ºC (for up to 6 hours). Multiple dilutions are used to bracket the expected concentration range (e.g. sample dilutions of 10X, 100X, 1000X). Plate each dilution in triplicate and calculate the average microbial value for the dilution from the three plate replicates that provide the best colony count.

10. Re-measure the UV intensity and calculate the average of this measurement and the measurement taken in Step 3. The value should be within 5 percent of the value measured in Step 3. If not, recalibrate radiometer and re-start at Step 1.
11. Using the equation described in the next section, calculate the UV dose applied to the sample based on experimental conditions. The calculated experimental dose should be similar to the planned target dose.
12. Repeat Steps 1 through 11 for each replicate and target UV dose value. Repeat all steps for each water test condition replicate.

The UV dose delivered to the sample is calculated using the following equation:

$$D_{CB} = E_s * P_f * (1-R) * [L * (1-10^{-A_{254} * d})/(d + L) * A_{254} * d * \ln(10)] * t$$

Where:

D_{CB} = UV dose (mJ/cm^2)
E_s = Average UV intensity (measured before and after irradiating the sample) (mW/cm^2)
P_f = Petri Factor (unitless)
R = Reflectance at the air-water interface at 254 nm (unitless)
L = Distance from lamp centerline to suspension surface (cm)
d = Depth of the suspension (cm)
A_{254} = UV absorbance at 254 nm (unitless)
t = Exposure time (s)

To control for error in the UV dose measurement, the uncertainties of the terms in the UV dose calculation met the following criteria:

- Depth of suspension (d) ≤ 10%
- Average incident irradiance (E_s) ≤ 8%
- Petri Factor (P_f) ≤ 5%
- L/(d + L) ≤ 1%
- Time (t) ≤ 5 %
- $(1 - 10^{-ad})/ad \leq 5\%$

Further details and definitions of these factors are available in the collimated procedure and technical papers as referenced in the GP-2011 and UVDGM-2006. The QC data for these factors are presented in Section 5.5.3.

3.7.5 Developing the UV Dose-response Curve

The collimated beam tests produced:

- UV Dose in units of mJ/cm^2,
- Concentration of microorganisms in the petri dish prior to UV exposure (N_o) in units of plaque forming units (pfu)/mL, and
- Concentration of microorganisms in the petri dish after UV exposure (N) in units of pfu/mL.

The procedure for developing the UV dose response curves was as follows:

1. For each UV test condition (high or low UVT water) and its replicate and for each day of testing, log N (pfu/mL) was plotted vs. UV dose (mJ/cm^2). A best fit regression line was determined and a common N_o was identified as the intercept of the curve at UV dose = 0. A separate equation was developed for each UVT condition (lowest and highest) for each day of testing at that condition. In this test there were three days of testing and there were four sets of data (low UVT - test day 1; high UVT test day 2; low UVT test day 3; high UVT test day 3).

2. The log inactivation (log I) was calculated for each measured value of N (including zero-dose) and the common N_o identified in Step 1 using the following equation:

$$\log I = \log(N_o/N)$$

Where:

N_o = The common N_o identified in Step 1 (pfu/mL);
N = Concentration of challenge microorganisms in the petri dish after exposure to UV light (pfu/mL).

3. The UV dose as a function of log I was plotted for each day of testing and included water from both high and low UVT test conditions.

4. Using regression analysis, an equation was derived that best fit the data, forcing the fit through the origin. The force fit through the origin is used rather than the measured value of N_o, because any experimental or analytical error in the measured value is carried to all the data points, adding an unrelated bias to each measurement. Using the y-intercept of the curve eliminates error carry through. The regression equation was then used to calculate the RED for each full scale test sample.

The full set of collimated beam data and all calculations and regression analyses are presented in Chapter 4.

The regression analysis was used to derive an equation that best fits the data with a force fit through the origin. Both linear and a polynomial equations were evaluated to determine the best fit of the data. The regression coefficient, R^2, was determined for each trend line and was considered acceptable if it was 0.9 or greater.. The equation coefficients for each day were also evaluated statistically to determine which terms were statistically significant based on the P factor. All coefficients were found to be significant (i.e. $P < 0.05$).

For this validation for the first two days of testing, a single curve corresponding to one day's worth of full scale reactor testing was used to calculate RED values for that day. The higher UVT dose response curve was used for the high UVT water (day two) with reduced power and the lower UVT dose response curve was used for day one when the UVT of the test water was lowered with LSA. On the third day of testing the low UVT collimated beam results were used

for the low UVT test runs and the high UVT collimated beam data were used for the high UVT test runs.

3.7.6 Collimated Beam Data Uncertainty

The collimated beam data was fit to a polynomial regression and the uncertainty of the dose response equation based on a 95% confidence interval (U_{DR}) was calculated as follows: :

$$U_{DR} = t * [SD/ \text{ UV Dose}_{CB}] * 100\%$$

Where:

U_{DR} = Uncertainty of the UV dose-response fit at a 95% confidence level

UV Dose_{CB} = UV dose calculated from the UV dose-response curve for the challenge microorganism

SD = Standard deviation of the difference between the calculated UV dose response and the measured value

t = t-statistic at a 95% confidence level for a sample size equal to the number of test condition replicates used to define the dose-response.

The U_{DR} calculations are included in Sections 4.4.

3.8 Full Scale Testing to Validate UV dose

3.8.1 Evaluation, Documentation and Installation of Reactor

ETS UV provided technical information on *Model ECP-113-5* and basic information on the UV lamps, sensor, and related equipment. An operating manual and a technical specification book were provided prior to the start of testing. All documentation and equipment data were reviewed prior to the start of testing. Basic descriptions of the equipment were presented previously in Section 2. Attachments 1 and 2 include the manuals, specifications, and sensor data provided by ETS UV.

3.8.2 Test Conditions for UV Intensity Set-Point Approach

The purpose of this testing was to determine a RED_{meas} dose of $\geq$40 mJ/cm^2 at three set points that were then used to establish a set line based on the three UV intensity and flow rate pairs. ETS UV specified the target flow rates (50, 75, 100 gpm) and UV target intensity levels (80, 90, 105 W/m^2) based on the results of screening test performed at NSF prior to the validation tests. The intensity targets were based on the expected intensity at UVT's of 79%, 89%, and 94%. Data were also developed during an additional set point (175 gpm, intensity of 105 W/m2) for validating a dose that would achieve a minimum of 3-log inactivation of *Cryptosporidium*.

Each set point represents a given flow rate with testing under two conditions, (1) lowered UVT-max power and (2) high UVT-reduced power. The first test condition involved reducing the UVT until the UV intensity measured by the unit UV sensor equaled the target UV intensity set point. The second test condition was run with high UVT and with the power reduced until the unit UV intensity measured by the sensor was equal to the target UV intensity set point. Three target flow rates - intensity points (50 gpm - 80 W/m^2; 75 gpm - 90 W/m^2; 100 gpm - 105

W/m^2) were tested for the set line. All conditions were performed in duplicate. The intensity targets were based on expected intensity at UVT's of 79%, 89%, and 94%.

The LT2ESWTR requires validation of UV reactors to determine a log inactivation of *Cryptosporidium* or other target pathogen so that States may use the data to grant log credits. Therefore, in addition to determining the setline to achieve a minimum RED_{meas} of 40 mJ/cm^2, additional calculations (adjusting RED_{meas} for uncertainty and RED bias) were performed to demonstrate the log inactivation of *Cryptosporidium*.

An additional fourth set point test at a higher flow rate of 175 gpm, UVT target of 94% and intensity target of 105 W/m^2 was performed to provide additional data for demonstrating *Cryptosporidium* log inactivation. These tests were performed with both lowered UVT (with full power) and reduced power (with high UVT) and were performed in duplicate.

A reactor control test (MS2 injection with the lamp off) was run at the low flow rate (50 gpm) and with high UVT water, which demonstrated that there was no reduction of MS2 with the lamps off. A reactor blank was also run on each day of testing. The reactor blank was run with no phage injection at the low flow rate with high UVT water to demonstrate the testing system was low in MS2 concentration and other microorganisms. Reactor blank and control samples were collected in triplicate at the influent and effluent sampling locations and submitted for MS2 analyses.

Trip blanks were prepared and analyzed for each day of testing. The microbiology laboratory took two samples from the challenge solution prepared for one of the test runs. The first sample remained in the microbiology laboratory and the second sample traveled with challenge solution to the engineering laboratory and then was returned with the samples collected from the test run. Both samples were analyzed for MS2 and the results were compared to determine any change that might have occurred during transport of the samples. As with stability testing, trip blanks are important when samples must be shipped or carried long distance with the inherent holding time before delivery to the lab. At NSF the test rig and laboratory are in the same building and the trip is "down the hall". Therefore travel related impacts are of less concern, but trip blanks were run as part of the QC plan for these tests.

Table 3-1 shows a summary of the test conditions that were run for the validation test. A Sample and Analysis Management Program was also prepared and was provided to the NSF engineering and microbiology laboratories for use during the testing and for setting up the sample and analysis in the NSF sample management system.

Five sets of samples were collected at the influent and effluent sample ports for MS2 analysis during each test condition and it's duplicate. The delivered dose was calculated for each of the five samples and then the average of the five results was calculated to determine an average delivered dose (RED).

Flow rate, intensity, and UVT data (from the NSF in-line UVT monitor) were collected at each of the five sample collection times for all test runs. These data were averaged to determine the average flow rate, UVT, and intensity for each test condition and its duplicate.

In addition, samples for pH, turbidity, temperature, total and residual chlorine, *e coli,* and HPC were collected at the influent and effluent sample ports once during each test run. Samples for iron (Fe) and manganese (Mn) analyses were collected once during each test run at the influent sample port to provide additional basic water quality data. Samples were also collected at the influent and effluent for UVT analysis by the chemistry laboratory bench scale spectrophotometer to confirm the in-line UVT measurements.

Samples of the low and high UVT waters were collected at the influent and effluent locations for UVT scans. The samples were scanned for UVT measurements in the range of 200 to 400 nm.

Table 3-1. Test Conditions for Validation with MS2 Phage.

Validation Test	Target Flow Rate	UV Transmittance Target UVT (%)	Lamp Power	Intensity Sensor Reading
Condition 1	50 gpm	79%	Maximum	Record actual reading
	75 gpm	90%		
	100 gpm	94%		
	175 gpm	94%		
Condition 2	50 gpm	>95%	Lowered to achieved intensity from Condition 1	Set to equal Condition 1 by lowering lamp power
	75 gpm	>95%		
	100 gpm	>95%		
	175 gpm	>95%		
Condition 3 (reactor control)	50 gpm	>95%	Turned off	Not applicable
Condition 4 (reactor blank)	50 gpm	Daily Source water - ether high or low UVT	Full Power	Record

Condition 1 and 2 performed in duplicate
Reactor blanks run for each day of testing
UVT scan of feed water with and without UVT adjustment
Trip blanks and method blanks run for each day of testing

3.8.3 Preparation of the Challenge Microorganisms

The challenge microorganism (MS2) used to validate UV reactors was cultured and analyzed by NSF's microbiology laboratory as specified in *Standard Methods for the Examination of Water and Wastewater*. NSF personnel followed the method for "Culture of challenge microorganism" in Annex A of NSF/ANSI Standard 55 as presented in Attachment 3.

Propagation resulted in a highly concentrated stock solution of essentially monodispersed phage whose UV dose-response follows second-order kinetics with minimal tailing. Over the range of RED values demonstrated during validation testing, the mean UV dose-response of the MS2 phage stock solution was within the 95-percent prediction interval of the mean response in Figure A.1 in Appendix A of the UVDGM-2006. Over a UV dose range of 0 to 120 millijoules

per centimeter squared (mJ/cm2), the prediction intervals of the data shown in Appendix A of the UVDGM-2006 are represented by the following equations"

$$\textit{Upper Bound: } \log I = -1.4 \times 10^{-4} \times \textit{UV Dose}^2 + 7.6 \times 10^{-2} \times \textit{UV Dose}$$
$$\textit{Lower Bound: } \log I = -9.6 \times 10^{-5} \times \textit{UV Dose}^2 + 4.5 \times 10^{-2} \times \textit{UV Dose}$$

City of Ann Arbor tap water was filtered using activated carbon to remove any residual chlorine (confirmed by chemical analysis for total chlorine of the test water), organic surfactants and dissolved organic chemicals that may be UV absorbers. The filtered challenge water was then tested for the following parameters and found acceptable if the result is non-detectable or as otherwise indicated below:

- Total chlorine,
- Free chlorine,
- UV_{254} ,
- UVT > 95%
- Total iron,
- Total Manganese,
- Turbidity ≤ 0.3 Nephelometric Turbidity Units (NTU);
- Total coliform (<1 cfu/100mL),
- Heterotrophic plate count (<100 cfu/mL).

3.8.4 Conduct Testing – Measuring UV Dose

During full-scale reactor testing, the reactor was operated at each of the test conditions for flow rate, UVT, and lamp power as described in section 3.8.2. The following steps were taken to assure meeting data quality objectives:

1. Steady-state conditions were confirmed before injecting the challenge microorganism. Confirmation of steady state involved monitoring UV sensor measurements and the UVT to assure the test water and reactor met the test conditions such as UVT reading of 90%. After typically 3-5 minutes of operation and confirmation that UVT, sensor readings, and flow rate were steady, the injection pump was started and steady state conditions were achieved by waiting until the injection pump was at a steady flow rate based on measurements of weight loss of solution over 15 second time intervals. In all cases, sampling did not start until at least 2 minutes after the injection pump was started.
2. MS2 was injected into the feed water upstream of the reactor to achieve a greater than $1x10^5$ pfu/mL so that a minimum of a 4 log reduction could be measured during the runs.
3. Sample taps remained open over the duration of the test.
4. Samples were collected in accordance with standards of good practice as defined by *Standard Methods* Section 9060.
5. Five (5) sample pairs were collected during approximately ten minutes of continuous flow at steady conditions. Each set of influent and effluent grab samples were

collected as close in time as possible. The five sets of samples were spread out over the 10 to 12 minute continuous flow run.

6. Sample volumes for assessing the challenge microorganism concentrations in the influent and effluent were collected in 125 mL bottles.
7. Samples were collected in bottles that had been cleaned and sterilized by the NSF microbiology laboratory~~; and~~,.
8. Collected samples were delivered directly to the microbiological lab located in the same building after each sampling period. Sample analyses were generally started immediately, but if samples could be stored in the refrigerator, in the dark, they were analyzed a couple of hours later. All MS2 analyses were started within 4-6 hours of the time the sample was collected.

The following measurements and recordings were taken during each test run:

1. The flow rate through the reactor, UV sensor reading and on-line UVT measurements were recorded when each sample was collected during each run, yielding a minimum of five measurements for each test run;
2. Water chemistry and other microbiological grab samples were collected once per test condition after one of the challenge organism samples were collected. Samples for temperature, pH, *E. coli*, and Heterotrophic Plate Count were collected at the influent and effluent locations, and samples for iron, manganese, turbidity and residual chlorine were collected at the influent location;
3. A sample for UVT was collected and measured by a UV spectrophotometer for each influent sample and at least one effluent sample;
4. A sample of the influent and effluent water was collected at the beginning of each test day and a UVT scan performed over the range of 200 to 400 nm, and
5. The electrical power consumed by system was recorded.

Chapter 4 describes the calculations and presents the data for determining the RED_{meas} and the validated dose (RED_{Val}) at a each set point.

3.9 Analytical Methods

All laboratory analytical methods for water quality parameters are listed in Table 3-2.

Table 3-2. Analytical Methods for Laboratory Analyses.

Parameter	Method	NSF Reporting Limit	Lab Accuracy (% Recovery)	Lab Precision (%RPD [1])	Hold Time (days)	Sample Container	Sample Preservation
Temperature	SM[2] 2550	-	-	-	-	-	-
pH	SM[2] 4500-H^+		± 0.1 SU of buffer	± 0.1 SU	(3)	NA	None
E. coli / Total Coliform	SM 9223	1 CFU /100mL	-	-	24 h	500 mL plastic	1% Tween 80
Iron	EPA 200.7	20 µg/L	70-130	10%	180 days	125 mL polyethylene	Nitric acid
Manganese	EPA 200.8	1 µg/L	70-130	10%	180 days	125 mL polyethylene	Nitric acid
Turbidity	SM[2] 2130	0.1 NTU	95-105	-	(3)	NA	None
MS2	Top Agar Overlay	1 pfu/mL	-	-	24 h[4]	125 mL plastic	1% Tween 80
Absorbance UV 254	SM 5910B	NA	60-140	≤ 20	2	1 L plastic	None
Residual chlorine	SM 4500-Cl D	0.05 mg/L	90-110	≤10%	(3)	NA	None
HPC	SM 9215	1 CFU/mL	-	-	24 h	125 mL plastic	1% Tween 80

(1) RPD = Relative Percent Deviation
(2) SM = Standard Methods
(3) Immediate analysis required
(4) h = hours

3.9.1 Sample Processing, and Enumeration of MS2:

MS2 sample processing and enumeration followed the procedures used in NSF / ANSI Standard 55.

3.9.2 Percent UVT Measurements:

The percent UVT for laboratory measurements was calculated from A_{254}. The equation for UVT using A_{254} is:

$$UVT\ (\%) = 100 * 10^{-A_{254}}$$

The on-line UVT analyzer provided immediate data throughout all test runs. The on-line analyzer was calibrated every day of operation. A primary standard was used before the first day of testing began. Daily calibration was performed on all test days using a certified secondary standard. Before the start of each day's testing, a sample was taken to the laboratory and analyzed for direct comparison with the on-line analyzer to ensure the data were comparable.

All UVT measurements used a 1-cm path length and are reported on a 1-cm path length basis. Spectrophotometer measurements of A_{254} were verified using NIST-traceable potassium dichromate UV absorbance standards and holmium oxide UV wavelength standards. The UV

spectrophotometer internal Quality Assurance/Quality Control (QA/QC) procedures outlined in the UVDGM-2006 were used to verify calibration. UV absorbance of solutions used to zero the spectrophotometer were verified using reagent grade organic-free water certified by the supplier to have zero UV absorbance.

The measurement uncertainty of the spectrophotometer must be 10 percent or less. To achieve this goal, the following procedures were used:

1. Verify that the spectrophotometer reads the wavelength to within the accuracy of a holmium oxide standard (typically ± 0.2 nm at a 95-percent confidence level),
2. Verify that the spectrophotometer reads A_{254} within the accuracy of a dichromate standard (e.g., 0.281 ± 0.005 at 257 nm with a 20 mg/L standard), and
3. Verify that the water used to zero the instrument has an A_{254} value that is within 0.002 cm^{-1} of a certified zero absorbance solution.

3.9.3 Analytical QA/QC Procedures

Accuracy and precision of sample analyses were ensured through the following measures:

- pH – Three-point calibration (4, 7, and 10) of the pH meter was conducted daily using traceable buffers. The accuracy of the calibration was checked daily with a pH 8.00 buffer. The pH readings for the buffer were within 10% of its true value. The precision of the meter was checked daily using duplicate synthetic drinking water samples. The difference of the duplicate samples was within $\pm$ 0.1 SU.

- Temperature – The thermometer used to give the reportable data had a scale marked for every 0.1ºC. The thermometer is calibrated yearly using a Hart Scientific Dry Well Calibrator Model 9105.

- Total chlorine – The calibration of the chlorine meter was checked daily using a DI water sample (blank), and three QC standards. The measured QC standard values were within 10% of their true values. The precision of the meter was checked daily by duplicate analysis of synthetic drinking water samples. The RPD of the duplicate samples was less than 10%.

- Turbidity – The turbidimeter was calibrated as needed according to the manufacturer's instructions with formazin standards. Accuracy was checked daily with a secondary Gelex standard. The calibration check provided readings within 5% of the true value. The precision of the meter was checked daily by duplicate analysis of synthetic drinking water samples. The RPD of the duplicate samples was less than 10% or had a difference of less than or equal to 0.1 NTU at low turbidity levels.

3.9.4 Sample Handling

All samples were labeled with unique identification numbers. These identification numbers were entered into the NSF Laboratory Information Management System (LIMS), and were used on the NSF lab reports for the tests. All challenge organism samples were stored in the dark at 4 ± 2 °C and processed for analysis within 4-6 hours.

3.10 Full Scale Test Controls

The following quality-control samples and tests for full-scale reactor testing were performed:

- *Reactor controls* – Influent and effluent water samples were collected with the UV lamps turned off. The change in log concentration from influent to effluent should correspond to no more than 0.2 $\log_{10}$.
- *Reactor blanks* – Influent and effluent water samples were collected with no addition of challenge MS2 to the flow passing through the reactor. Blanks were collected once on each day of testing. The reactor blank is acceptable when the MS2 concentration is less than 0.2 $\log_{10}$.
- *Trip controls* – Trip controls were collected to monitor any change in challenge MS2 during transport to the laboratory (in the same building).
- *Method blanks* – A sample bottle of sterilized reagent grade water was analyzed using the challenge microorganism assay procedure. The concentration of challenge MS2 in the method blank was non-detectable.
- *Stability samples* – Influent and effluent samples at low and high UVT prior to the introduction of MS2. These samples were used to assess the stability of the challenge microorganism concentration and its UV dose-response over the time period from sample collection to completion of challenge microorganism assay. The challenge MS2 were added to achieve a concentration of 1,000 plaque forming units (pfu)/L in the samples containing test water at the lowest and highest UVT. A sample was analyzed immediately (called time 0) and then 4 hours, 8 hours and 24 hours after time 0. All analyses were performed in triplicate. While stability samples were performed during the test, they are not directly applicable in this case as all sample analyses for MS2 ~~was~~ were started within a couple of hours of collection.

3.11 Power Measurements

The voltmeter and ammeter meter used to measure UV equipment had traceable evidence of calibration. The meters had a tag showing that it was calibrated. Calibrations are performed at least yearly and all power equipment was calibrated within the past year.

3.12 Flow Rate

During validation testing, the QC goal was that the accuracy of flow rate measurements should be within $\pm$5 percent of the true value. Flow meter accuracy was verified by monitoring the draw down volume in the supply tanks over time. The supply tanks have been calibrated using the catch and weigh technique. The flow meter accuracy was within 0.6 to 2.7% of the true value. Flow meter calibration data are presented in Section 5.6.

3.13 Evaluation, Documentation and Installation of Reactor

ETS UV provided technical information on the *Model ECP-113-5* and basic information on the UV lamps, sensor, and related equipment. An operating manual was provided prior to the start of testing. Additional information on the lamp output (confirmation of spectral output) was provided prior to the start of the validation test. All documentation and equipment data was

reviewed prior to the start of testing. The following documentation was reviewed and found to conform to the GP-2011 and UVDGM-2006 requirements:

Reactor Specifications

- Technical description of the reactor's UV dose-monitoring strategy, including the use of sensors, signal processing, and calculations (if applicable)
- Dimensions and placement of all critical components (e.g., lamps, sleeves, UV sensors, baffles, and cleaning mechanisms) within the UV reactor
- A technical description of lamp placement within the sleeve
- Specifications for the UV sensor port indicating all dimensions and tolerances that impact the positioning of the sensor relative to the lamps

Lamp specifications

- Technical description
- Lamp manufacturer and product number
- Electrical power rating
- Electrode-to-electrode length
- Spectral output of the lamps (specified for 5 nm intervals or less over a wavelength range that includes the germicidal range of 250 – 280 nm and the response range of the UV sensors)

Lamp sleeve specifications

- Technical description including sleeve dimensions
- Material of construction
- UV transmittance at 254 nm

Specifications for the reference and the duty UV sensors

- Manufacturer and product number
- Technical description including external dimensions

Sensor measurement properties

- Working range
- Spectral and angular response
- Linearity
- Calibration factor
- Temperature stability
- Long-term stability

Installation and operation documentation

- Flow rate and pressure rating of the reactor
- Assembly and installation instructions
- Electrical requirements, including required line frequency, voltage, amperage, and power
- Operation and maintenance manual including cleaning procedures, required spare parts, and safety requirements

Chapter 4
Results and Discussion

4.1 Introduction

ETS UV specified target flow rates of 50, 75, and 100 gpm. The intensity initial targets were 80, 90, and 105 W/m^2 based on the expected intensities at UVTs of 79%, 90%, and 94%. These points were projected to deliver a RED of >40 mJ/cm^2. An additional set point at 175 gpm with intensity of 105 W/m^2 was tested to demonstrate of 3 log *Cryptosporidium* inactivation.

The main validation tests were run on two days, July 18 and July 19, 2012. A retest of the lower flow rate (50 gpm) and one medium flow rate (75 gpm) was performed on September 11, 2012. The first day of testing was dedicated to the test conditions and duplicate runs where the UVT of the feed water was lowered to the target levels (<79%, <90%, and <94%) and the lamps were operated at full power. The second day of testing was dedicated to the test conditions and duplicates where high UVT feed water (>95% target) was used and the lamp power was reduced to achieve the target intensity level. On the third day of testing, both low UVT water (<79%) with full power at a flow rate of 50 gpm and high UVT water with reduced power for flow rates of 50 and 75 gpm were used. The test conditions and detail on the test rig setup, sampling procedures, and unit operation ~~have been~~ are described in Chapter 3 Methods and Procedures.

All tests were conducted at the NSF laboratory in Ann Arbor, MI, and all analyses were performed by the NSF microbiological and chemistry laboratories at this location.

4.2 Sensor Assessment

The *Model ECP-113-5* duty sensor was evaluated according to the UV sensor requirements in the EPA's UVDGM-2006 prior to and after the verification testing. All UV intensity sensors (the duty and two reference sensors) were new sensors and specifications provided with the sensors showed they were designed in accordance with the DVGW guideline W 294 (June, 2006) and the ÖNORM M5873-1 standard (June , 2002), respectively. Evidence of calibration of the sensors traceable to a standard of the Physikalisch Technische Bundesanstalt (PTB) in Braunschweig, was provided by ETS UV as provided to them by the sensor manufacturer *uv-technik*. Certificates are presented in Attachment 2.

The same duty sensor was used for monitoring intensity (irradiance) for all test runs. This sensor measured the intensity from the single medium pressure lamp in the unit. The control panel provided direct readings of intensity in W/m^2. This direct reading was based on converting the 4-20 mA output signal to intensity based on the calibration certificate provided with the sensor. Attachment 2 includes the certificates for the two reference sensors and one duty sensor, plus the spectral data for the sensor.

The duty sensor was compared against two reference sensors to demonstrate that the duty sensor was within 10% of the average of the two reference sensors. This evaluation was conducted before and after the validation test runs for both the July and September 2012 test runs, using the procedure described in the GP-2011 and the UVDGM-2006. Tables 4-1 and 4-2 present the

results of the sensor assessment. These data demonstrate that the duty sensor was within 10 percent of the average of the two reference sensors. The two reference sensors showed a variance range of 0.0 to 2.1% at 100% power and 0.0 to 3.5% at 64% power.. The percent differences were calculated by taking the difference between a given sensor intensity reading and the average of the two reference sensor readings.

$$\% \text{ difference} = \text{The absolute value of } [(I_{Ref} / I_{Avg\ Ref}) - 1] \text{ X100}$$

where:

I_{Ref} = Intensity measured by a reference UV sensor (Ref 1 or Ref 2),

$I_{Avg\ Ref}$ = Average UV intensity measured by the two reference UV sensors in the same UV sensor port with the same UV lamp at the same UV lamp power.

The power could not be reduced below 64% as the lamp would lose its arc and shut down below at less than 64% power level (4.1 - 4.2 amps) when the input voltage was 207 V. During the retest runs at the lowest power setting, power was reduced to approximately 45-50% and the lamps did not lose its arc when the input voltage was 242 V.

Table 4-1. Sensor Assessment Data First Set of Test Runs (July 2012)

Sensor	Intensity at 100% power Before testing (W/m^2)	Intensity at 100% power After testing (W/m^2)	Intensity at 64% Power Before testing (W/m^2)	Intensity at 64% Power After testing (W/m^2)
Reference #1 V6154	46.51	138.36	22.96	67.71
Reference #2 V6156	46.51	136.01	22.96	65.35
Average of Reference Sensor	46.51	137.03	22.96	66.53
Duty Sensor V6161	44.16	131.38	21.78	64.18
Deviation of Duty Sensor from Reference	5.1%	4.1%	5.1%	3.5%
	UVT = 78%	UVT = 97%	UVT = 78 %	UVT = 97%

Table 4-2. Sensor Assessment Data Second Set of Test Runs (September 2012)

Sensor	Intensity at 100% power Before testing (W/m^2)	Intensity at 100% power After testing (W/m^2)	Intensity at 64% Power Before testing (W/m^2)	Intensity at 64% Power After testing (W/m^2)
Reference #1 V6154	252.59	254.94	137.19	138.36
Reference #2 V6156	241.99	252.59	133.65	137.19
Average of	247.29	253.77	135.42	137.78

Reference Sensor				
Duty Sensor V6161	238.46	237.28	128.94	127.77
Deviation of Duty Sensor from Reference	3.6%	6.5%	4.8%	7.3%
	UVT = 97%	UVT = 97%	UVT = 97 %	UVT = 97%

The test results shown in the later tables and the sensor assessment data collected before and after the test were performed to demonstrate the intensity was stable throughout the testing as a function of ballast power and UVT. The steady sensor readings from the start through the end of the testing at the various UVT-power combinations indicated that lamp output was constant and no fouling occurred to the lamp sleeves and sensor windows.

4.3 Collimated Beam Dose Response Data

Collimated Beam dose response data were generated for both low and high UVT waters in accordance with the procedures described in Section 3.7.4. The collimated beam tests were performed in duplicate at the minimum and maximum UVT test conditions. This validation test included three days of testing. The lowered UVT test runs were performed on the first day. The intensity readings at each UVT (78%, 89%, 93%) were recorded during each test run with full lamp power. Collimated beam tests were run on the minimum UVT water (79%) with duplicate runs being performed. On the second day using high UVT water (95%), the power was reduced to achieve the same intensity as measured for each of the lowered UVT waters on day one. Collimated beam tests were run on day two on the high UVT water (95%) with duplicate runs being performed. Additional testing was required for the lowest flow rate (50 gpm) for both the lowered UVT water (79%) and for the lowered power tests. In addition one medium flow rate test (75 gpm) at the lowered power setting required a retest. This third day of testing included both lowered UVT water (79%) and the use of high UVT water (97%) for lowered power runs. Collimated beam tests were performed in duplicate on both the 79% and 97% UVT water on the third day of testing. Therefore, for this validation test, there are four sets of duplicate collimated beam test data, two for the lowest UVT water (79%) and two for the highest UVT water (water not adjusted with LSA).

UV doses covered the range of the targeted RED dose, which in this case was >40 mJ/cm^2. UV target doses were set at 0, 20, 30, 40, 60 and 80 mJ/cm^2. As discussed in the RED results presented later, the actual RED for two test runs exceeded the maximum collimated beam dose of 80 mJ/cm^2. RED cannot be quantitatively determined if the measured RED exceeds the top range of the collimated beam data. These data are presented as calculated, but any RED values above 80 mJ/cm^2 should be used as estimates only.

The collimated beam samples were collected directly from the test rig during the normal testing runs. A one liter bottle of the seeded influent water (MS2 injection pumping run during the test run) was collected to provide the two samples for duplicate analyses. Using this approach, the dose response data reflect the identical conditions to the biodosimetric flow tests for sample

matrix, UVT, and MS2 concentration. The collimated beam samples were irradiated on the same day as sample collection, and were plated in triplicate along with the flow test samples. Therefore analytical conditions for the dose response data were also identical to those for the flow test samples.

The collimated beam results are presented in Tables 4-3 through 4-6. These data were calculated as the average of the three individual results obtained at each dose level.

4.4 Development of Dose Response

The development of the UV dose response curves for use with flow tests to establish the RED is a three step process.

1. For each collimated beam test and its replicate for each day of testing, the log N (pfu/mL) was plotted vs. UV dose (mJ/cm^2). Figures 4-1 through 4-4 show the curves for the low and higher UVT waters.

2. A separate equation (second order polynomial) was developed for each UVT condition (low and high). Therefore, there are four sets (low and high UVT) of data with each set containing collimated test performed in duplicate. A common N_o was identified for each data set as the intercept of the curve at UV dose = 0.

3. The log inactivation (log I) was then calculated for each day for each measured value of N (including zero-dose) and the common N_o identified in Step 1 using the following equation:

$$\log I = \log (N_o/N)$$

Where:

N_o = the common N_o identified in Step 1 (pfu/mL);

N = Concentration of challenge microorganisms in the petri dish after exposure to UV light (pfu/mL).

Tables 4-3 through 4-6 show the calculated values for log inactivation (LI).

Finally, the UV dose as a function of log I was plotted for each set of data. Figures 4-5 through 4-8 show the curves for dose as a function of log inactivation. Using regression analysis, an equation was derived that best fit the data, forcing the fit through the origin. In each case the equation was a second order polynomial, which is the most common for MS2 collimated beam data. The regression equation was then used to calculate the RED_{meas} for each full scale flow test sample~~s~~. RED_{meas} calculations and full scale data ~~is~~are presented in Section 4.5.

The equation coefficients for each day were also evaluated statistically to determine which terms were statistically significant based on the P factor. All coefficients were found to be significant ($P < 0.05$) for all of the dose response curves. The statistics are shown in Tables 4-3 through 4-6.

A Grubbs' test was also run to determine if any replicates should be omitted from the development of the dose response curve. The Grubbs' test results show that no replicates should be omitted from the data set. The Grubbs' statistics are shown in Tables 4-3 through 4-6.

A summary of the statistics for uncertainty for the collimated beam dose response data is presented at the end of Tables 4-2 through 4-6. The uncertainty (U_{DR}) of the collimated beam results was slightly higher than 30% at 1 log inactivation for the September retest data set for the high UVT water (33.46%). The U_{DR} for the high UVT water for the first set of data (July 2012) was 20.74%. The uncertainty for the sets of low UVT water (July and September) was 27.48%

and 26.99%, respectively. At 2-log inactivation (dose of approximately 40 mJ/cm^2 RED) the U_{DR} was between 9.33% and 14.92%.

Figures 4-5 through 4-8 show the results of the U_{DR} calculations plotted on the dose response curve. Also shown in Figures 4-5 through 4-8 are the QC limits for MS2 taken from the UVDGM-2006. The results show that the MS2 dose response curves are within the boundaries established for MS2.

Table 4-3. UV Dose – Response Data from Collimated Beam Tests at 79% UVT (July 2012)

UVT (%)	Rep	Target UV Dose (mJ/cm^2)	Actual UV Dose	UV Dose^2	Avg pfu/ml	Avg Log(pfu)	Log I	Log I^2	P_{RED} Dose	Residual (mJ/cm^2)	G	Outlier?
78.9	1	0	0.00	0	188,000	5.27	-0.02	0.000	-0.29	0.3	0.1	OK
		20	20.76	431	15,900	4.20	1.05	1.110	18.76	2.0	0.9	OK
		30	31.20	973	4,900	3.69	1.56	2.448	29.89	1.3	0.6	OK
		40	41.49	1721	1,760	3.25	2.01	4.038	40.65	0.8	0.4	OK
		60	62.23	3873	257	2.41	2.84	8.094	63.56	-1.3	0.6	OK
		80	82.80	6856	84	1.93	3.33	11.083	78.46	4.3	2.0	OK
	2	0	0.00	0	153,000	5.18	0.07	0.005	1.08	-1.1	0.5	OK
		20	20.74	430	15,800	4.20	1.06	1.116	18.82	1.9	0.8	OK
		30	31.26	977	3,970	3.60	1.66	2.743	32.02	-0.8	0.4	OK
		40	41.37	1711	1,150	3.06	2.19	4.814	45.41	-4.0	1.9	OK
		60	62.24	3874	258	2.41	2.84	8.084	63.51	-1.3	0.6	OK
		80	82.62	6826	57	1.76	3.50	12.243	83.96	-1.3	0.7	OK

Avg:	0.07
SD:	2.18
	12
p:	0.05
t (95%):	2.228

DRC	
A:	15.147
B:	2.5292

Log N_o
5.25

Grubbs' Test for Outliers	
p:	0.10
t (90%):	3.691
Grubbs' Statistic (G_{CRIT}):	2.412

DRC - dose response coefficients

Table 4-3. (continued)

Uncertainty of Dose-Response (U_{DR})					
Log I	Dose (mJ/cm^2)	t	SD	U_{DR} (%)	D_L (mJ/cm^2/Log I)
0.001	0.0				15.15
0.25	3.9	2.23	2.18	123.12	15.78
0.50	8.2	2.23	2.18	59.19	16.41
1.00	17.7	2.23	2.18	27.48	17.68
1.50	28.4	2.23	2.18	17.09	18.94
2.00	40.4	2.23	2.18	12.02	20.21
2.50	53.7	2.23	2.18	9.05	21.47
3.00	68.2	2.23	2.18	7.12	22.73
3.50	84.0	2.23	2.18	5.78	24.00
4.00	101.1	2.23	2.18	4.81	25.26
3.50	84.0	2.23	2.18	5.78	24.00

t - student t test factor SD - standard deviation

Dose Response Curve Statistics

Regression Statistics	
Multiple R	0.999054
R Square	0.998109
Adjusted R Square	0.89792
Standard Error	2.287586
Observations	12

ANOVA	Df	SS	MS	F	Significance F
Regression	2	27620.61	13810.31	2639.055	3.46E-13
Residual	10	52.33049	5.233049		
Total	12	27672.94			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0							
X Variable 1	15.14714	1.250784	12.11012	2.68E-07	12.36022	17.93406	12.36022	17.93406
X Variable 2	2.529192	0.435994	5.80098	0.000173	1.557737	3.500647	1.557737	3.500647

Table 4-4. UV Dose – Response Data from Collimated Beam Tests at 95% UVT (July 2012)

UVT (%)	Rep	Target UV Dose (mJ/cm^2)	Actual UV Dose	UV Dose^2	Avg pfu/ml	Avg Log(pfu)	Log I	Log I^2	P_{RED} Dose	Residual (mJ/cm^2)	G	Outlier?
95.3	1	0	0.00	0	313000	5.50	-0.02	0.000	-0.27	0.3	0.1	OK
		20	20.67	427	23700	4.37	1.10	1.215	18.70	2.0	1.2	OK
		30	30.94	957	6000	3.78	1.70	2.886	30.73	0.2	0.1	OK
		40	41.45	1718	1990	3.30	2.18	4.745	41.36	0.1	0.0	OK
		60	62.06	3851	277	2.44	3.03	9.209	62.50	-0.4	0.3	OK
		80	82.46	6800	59	1.77	3.71	13.752	81.07	1.4	0.8	OK
	2	0	0.00	0	251000	5.40	0.08	0.006	1.16	-1.2	0.8	OK
		20	20.75	429	22200	4.35	1.13	1.279	19.24	1.5	0.9	OK
		30	31.11	968	6530	3.81	1.66	2.763	29.95	1.2	0.7	OK
		40	41.49	1721	1500	3.18	2.30	5.294	44.22	-2.7	1.8	OK
		60	62.26	3876	225	2.35	3.12	9.765	64.89	-2.6	1.7	OK
		80	82.57	6818	57.3	1.76	3.72	13.830	81.37	1.2	0.7	OK
									Avg:	0.07		
									SD:	1.56		
										12		
										0.05		
									t (95%):	2.228		

DRC	
A:	14.898
B:	1.8771

Log N_o
5.48

Grubbs' Test for Outliers	
p:	0.10
t (90%):	3.691
Grubbs' Statistic (G_{CRIT}):	2.412

DRC - dose response coefficients

Table 4-4. (continued)

Uncertainty of Dose-Response (U_{DR})					
Log I	Dose (mJ/cm^2)	t	SD	U_{DR} (%)	D_L (mJ/cm^2/Log I)
0.001	0.0				14.90
0.25	3.8	2.23	1.56	90.57	15.37
0.50	7.9	2.23	1.56	43.95	15.84
1.00	16.8	2.23	1.56	20.74	16.78
1.50	26.6	2.23	1.56	13.10	17.71
2.00	37.3	2.23	1.56	9.33	18.65
2.50	49.0	2.23	1.56	7.10	19.59
3.00	61.6	2.23	1.56	5.65	20.53
3.50	75.1	2.23	1.56	4.63	21.47
4.00	89.6	2.23	1.56	3.88	22.41
3.72	81.4	2.23	1.56	4.28	21.88

t - student t test factor SD - standard deviation

Dose Response Curve Statistics

Regression Statistics	
Multiple R	0.999512
R Square	0.999025
Adjusted R Square	0.898927
Standard Error	1.639565
Observations	12

ANOVA	Df	SS	MS	F	Significance F
Regression	2	27540.78	13770.39	5122.581	1.76E-14
Residual	10	26.88174	2.688174		
Total	12	27567.66			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0							
X Variable 1	14.89799	0.822193	18.11982	5.62E-09	13.06603	16.72995	13.06603	16.72995
X Variable 2	1.877055	0.263522	7.122945	3.21E-05	1.289891	2.464219	1.289891	2.464219

Table 4-5. UV Dose – Response Data from Collimated Beam Tests at 79% UVT (September 2012)

UVT (%)	Rep	Target UV Dose (mJ/cm^2)	Actual UV Dose	UV Dose^2	Avg pfu/ml	Avg Log(pfu)	Log I	Log I^2	P_{RED} Dose	Residual (mJ/cm^2)	G	Outlier?
78.8	1	0	0.00	0	1,000,000	6.00	-0.05	0.002	-0.65	0.6	0.3	OK
		20	20.66	427	51,000	4.71	1.25	1.555	22.08	-1.4	0.7	OK
		30	30.74	945	20,500	4.31	1.64	2.699	30.81	-0.1	0.1	OK
		40	40.77	1662	11,600	4.06	1.89	3.573	36.68	4.1	1.9	OK
		60	61.37	3766	1,120	3.05	2.91	8.441	64.18	-2.8	1.4	OK
		80	81.42	6629	350	2.54	3.41	11.632	79.89	1.5	0.7	OK
	2	0	0.00	0	930,000	5.97	-0.01	0.000	-0.20	0.2	0.1	OK
		20	20.74	430	64,000	4.81	1.15	1.319	20.04	0.7	0.3	OK
		30	31.05	964	14,500	4.16	1.79	3.216	34.34	-3.3	1.6	OK
		40	41.34	1709	9,200	3.96	1.99	3.963	39.16	2.2	1.0	OK
		60	61.79	3818	1,230	3.09	2.86	8.206	62.97	-1.2	0.6	OK
		80	81.97	6719	310	2.49	3.46	11.994	81.60	0.4	0.1	OK

Avg:	0.08
SD:	2.07
	12
p:	0.05
t (95%):	2.228

DRC	
A:	14.413
B:	2.6421

Log N_o
5.95

Grubbs' Test for Outliers	
p:	0.10
t (90%):	3.691
Grubbs' Statistic (G_{CRIT}):	2.412

DRC - dose response coefficients

Table 4-5. (continued)

Uncertainty of Dose-Response (U_{DR})					
Log I	Dose (mJ/cm^2)	t	SD	U_{DR} (%)	D_L (mJ/cm^2/Log I)
0.001	0.0				14.42
0.25	3.8	2.23	2.07	122.15	15.07
0.50	7.9	2.23	2.07	58.51	15.73
1.00	17.1	2.23	2.07	26.99	17.06
1.50	27.6	2.23	2.07	16.70	18.38
2.00	39.4	2.23	2.07	11.68	19.70
2.50	52.5	2.23	2.07	8.76	21.02
3.00	67.0	2.23	2.07	6.87	22.34
3.50	82.8	2.23	2.07	5.56	23.66
4.00	99.9	2.23	2.07	4.61	24.98
3.46	81.6	2.23	2.07	5.64	23.56

t - student t test factor SD - standard deviation

Dose Response Curve Statistics

Regression Statistics	
Multiple R	0.999131
R Square	0.998263
Adjusted R Square	0.898089
Standard Error	2.168467
Observations	12

ANOVA	Df	SS	MS	F	Significance F
Regression	2	27022.78	13511.39	2873.389	2.36E-13
Residual	10	47.02248	4.702248		
Total	12	27069.8			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0							
X Variable 1	14.41301	1.147736	12.55778	1.9E-07	11.8557	16.97033	11.8557	16.97033
X Variable 2	2.642101	0.399141	6.619463	5.93E-05	1.752759	3.531443	1.752759	3.531443

Table 4-6. UV Dose – Response Data from Collimated Beam Tests at 97% UVT (September 2012)

UVT (%)	Rep	Target UV Dose (mJ/cm^2)	Actual UV Dose	UV Dose^2	Avg pfu/ml	Avg Log(pfu)	Log I	Log I^2	P_{RED} Dose	Residual (mJ/cm^2)	G	Outlier?
97.6	1	0	0.00	0	850,000	5.93	-0.04	0.002	-0.70	0.7	0.2	OK
		20	20.77	431	31,300	4.50	1.39	1.930	26.20	-5.4	2.1	OK
		30	31.05	964	17,800	4.25	1.63	2.671	31.70	-0.6	0.3	OK
		40	41.04	1684	8,570	3.93	1.95	3.809	39.21	1.8	0.6	OK
		60	61.43	3774	1,150	3.06	2.82	7.975	62.10	-0.7	0.3	OK
		80	81.79	6690	244	2.39	3.50	12.231	82.04	-0.3	0.1	OK
	2	0	0.00	0	817,000	5.91	-0.03	0.001	-0.43	0.4	0.1	OK
		20	20.85	435	58,700	4.77	1.12	1.246	20.39	0.5	0.1	OK
		30	31.27	978	35,700	4.55	1.33	1.774	24.96	6.3	2.3	OK
		40	41.52	1724	6,300	3.80	2.09	4.349	42.50	-1.0	0.4	OK
		60	62.32	3884	990	3.00	2.89	8.346	63.94	-1.6	0.7	OK
		80	83.18	6919	253	2.40	3.48	12.121	81.55	1.6	0.5	OK
									Avg:	0.15		
									SD:	2.71		
										12		
									p:	0.05		
									t (95%):	2.228		

DRC	
A	15.834
B	2.1804

Log N_o
5.88

Grubbs' Test for Outliers	
p:	0.10
t (90%):	3.691
Grubbs' Statistic (G_{CRIT}):	2.412

DRC - dose response coefficients

Table 4-6. (continued)

Uncertainty of Dose-Response (U_{DR})					
Log I	Dose (mJ/cm^2)	t	SD	U_{DR} (%)	D_L (mJ/cm^2/Log I)
0.001	0.0				15.84
0.25	4.1	2.23	2.71	147.21	16.38
0.50	8.5	2.23	2.71	71.24	16.92
1.00	18.0	2.23	2.71	33.46	18.01
1.50	28.7	2.23	2.71	21.04	19.10
2.00	40.4	2.23	2.71	14.92	20.19
2.50	53.2	2.23	2.71	11.33	21.28
3.00	67.1	2.23	2.71	8.98	22.37
3.50	82.1	2.23	2.71	7.34	23.46
4.00	98.2	2.23	2.71	6.14	24.56
3.50	82.0	2.23	2.71	7.35	23.46

t - student t test factor SD - standard deviation

Dose Response Curve Statistics

Regression Statistics	
Multiple R	0.998529
R Square	0.997061
Adjusted R Square	0.896767
Standard Error	2.842009
Observations	12

ANOVA	Df	SS	MS	F	Significance F
Regression	2	27401.4	13700.7	1696.258	2.52E-12
Residual	10	80.77013	8.077013		
Total	12	27482.17			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0							
X Variable 1	15.83368	1.475888	10.72824	8.32E-07	12.5452	19.12217	12.5452	19.12217
X Variable 2	2.180374	0.50681	4.302155	0.001556	1.051131	3.309616	1.051131	3.309616

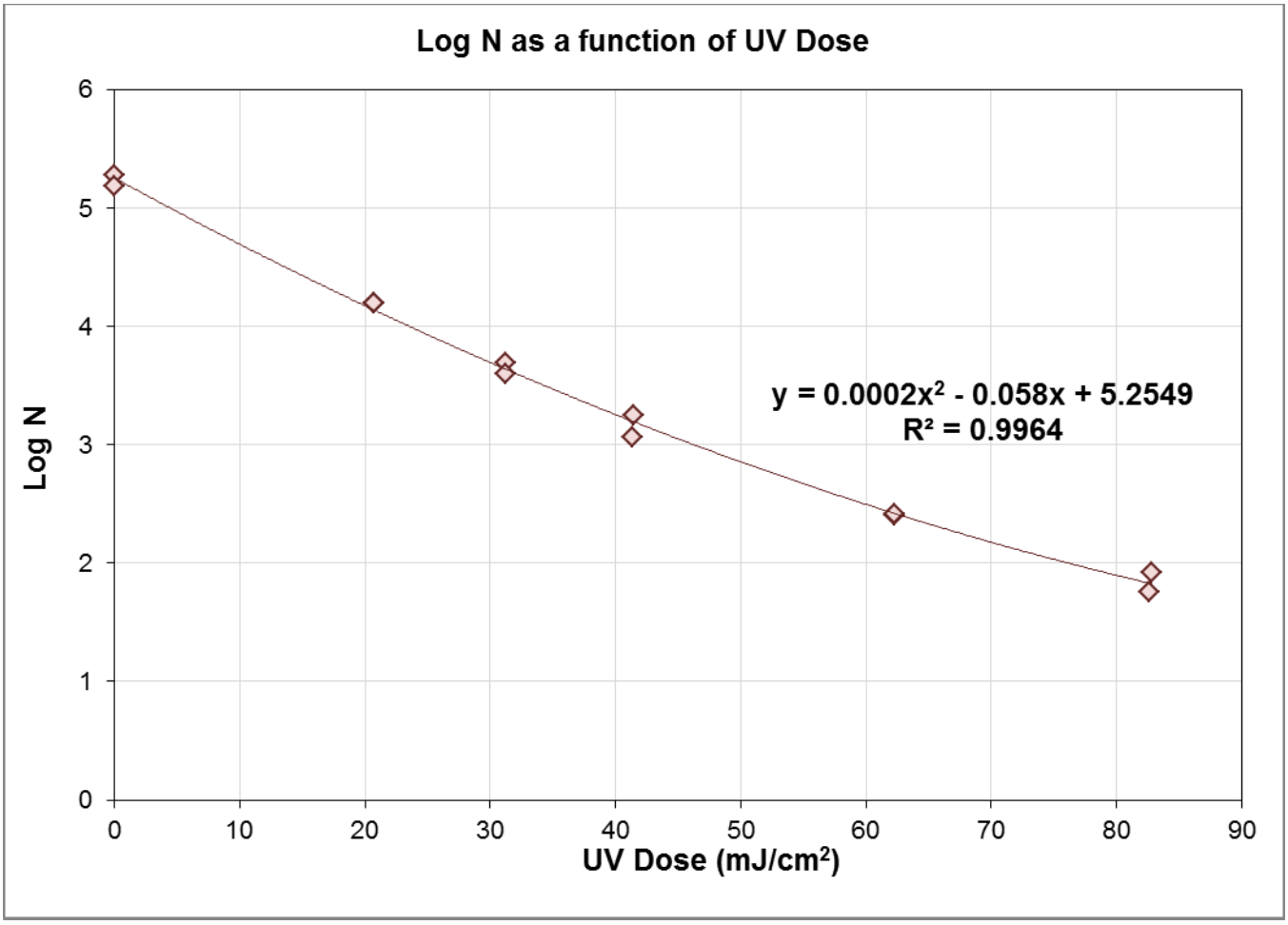

Figure 4-1 Collimated beam dose versus log N UVT 79% (July 2012)

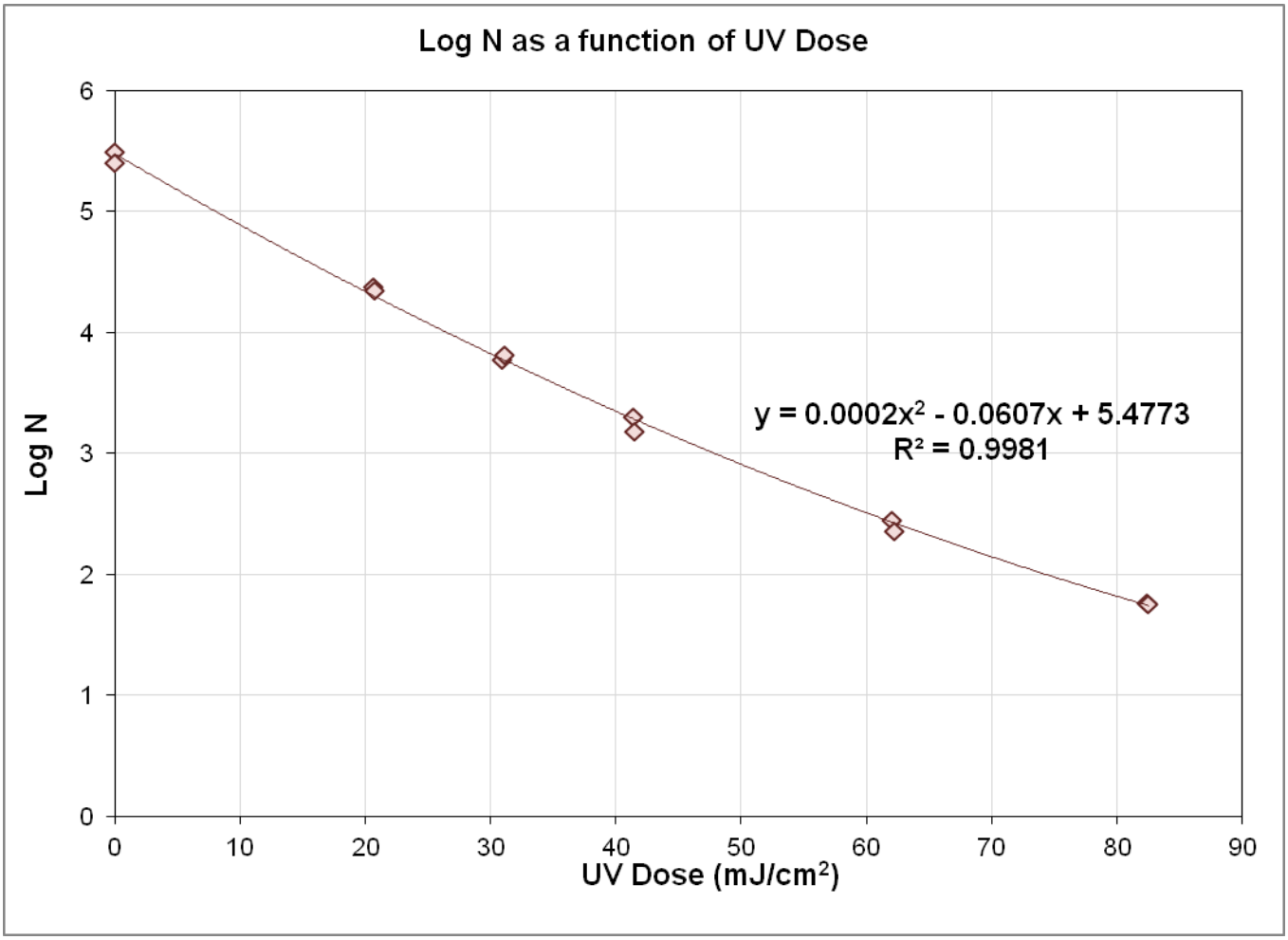

Figure 4-2 Collimated beam dose versus log N UVT 95% (July 2012)

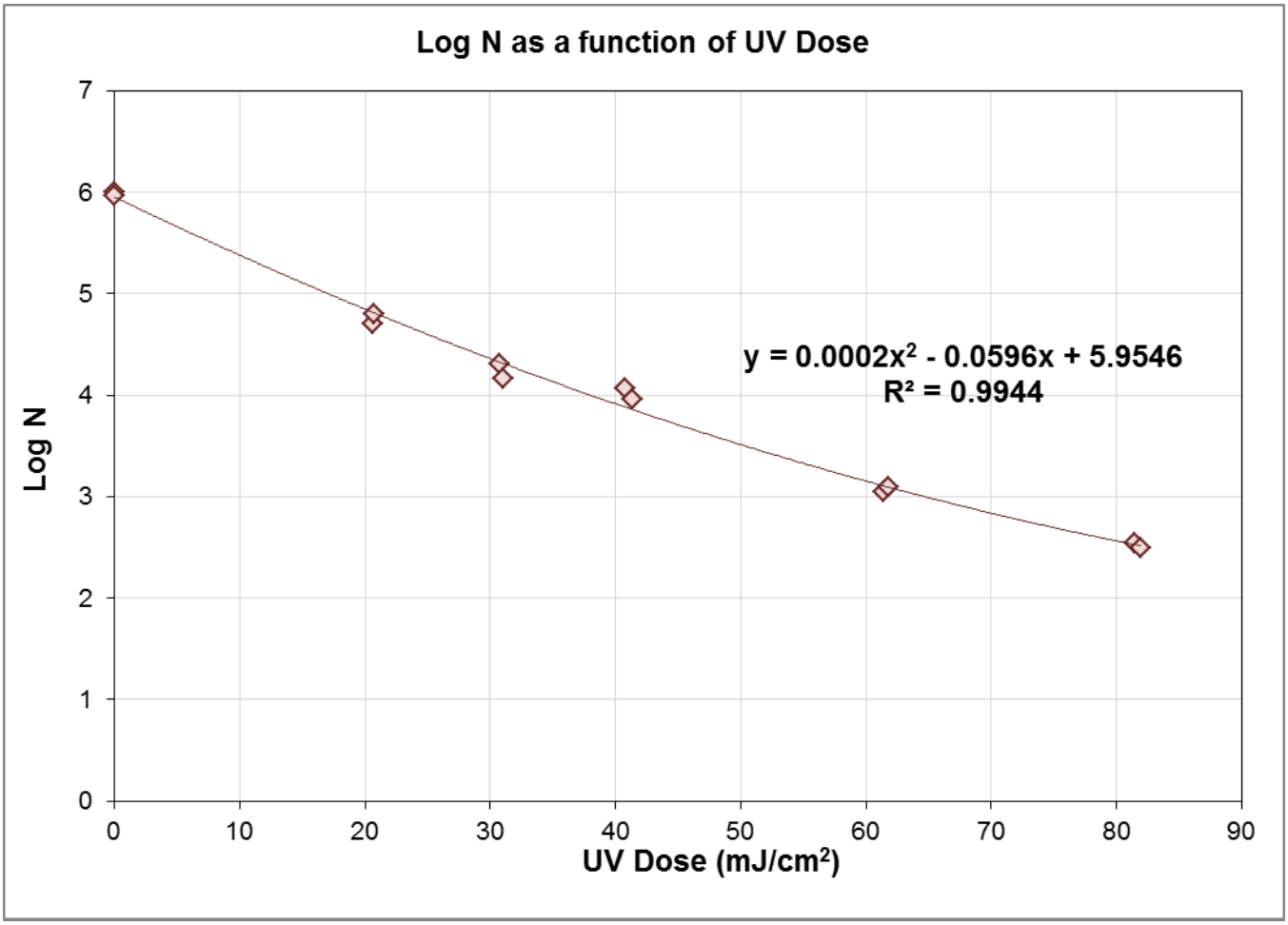

Figure 4-3 Collimated beam dose versus log N UVT 79% (September 2012)

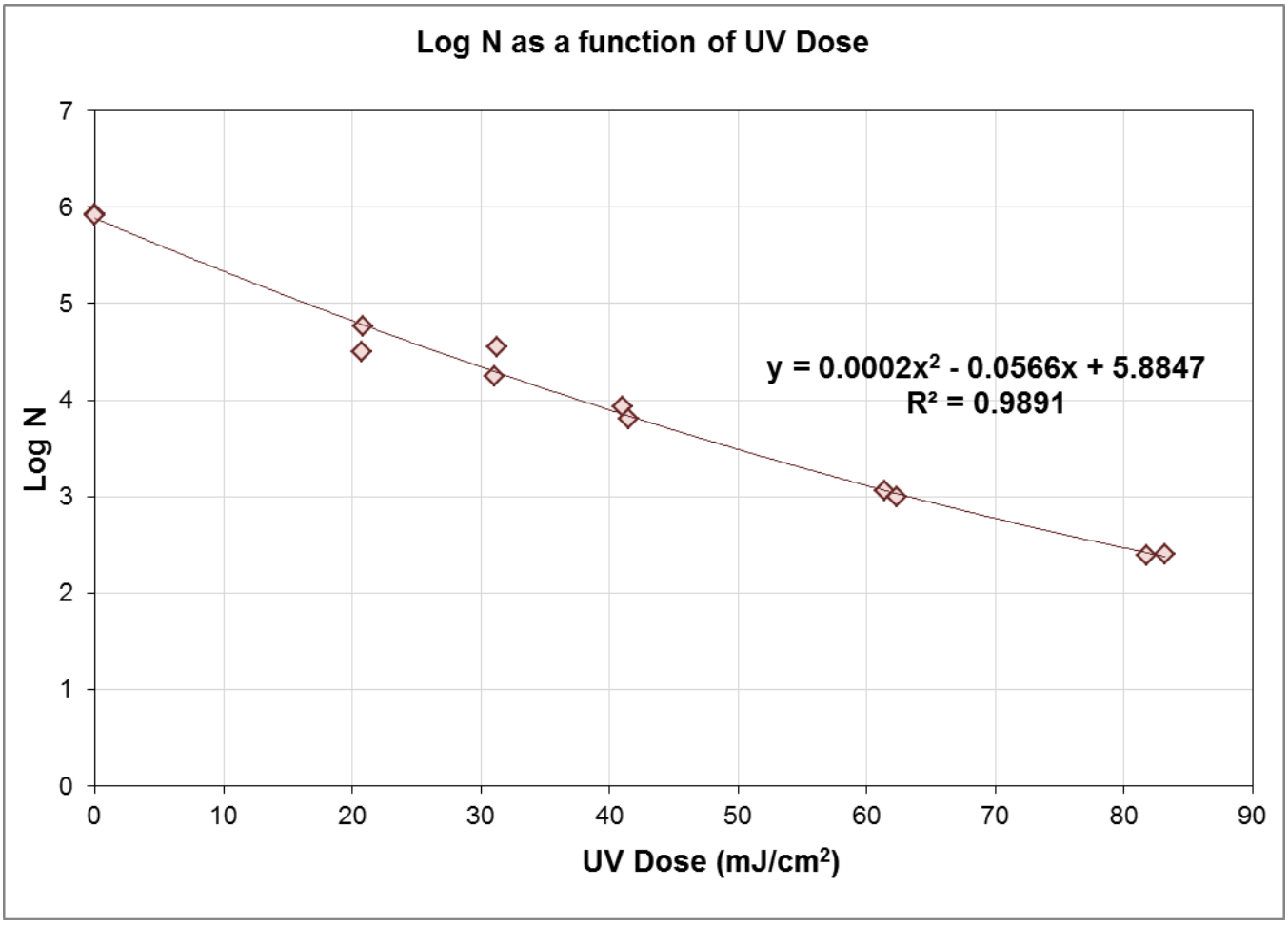

Figure 4-4 Collimated beam dose versus log N UVT 97% (September 2012)

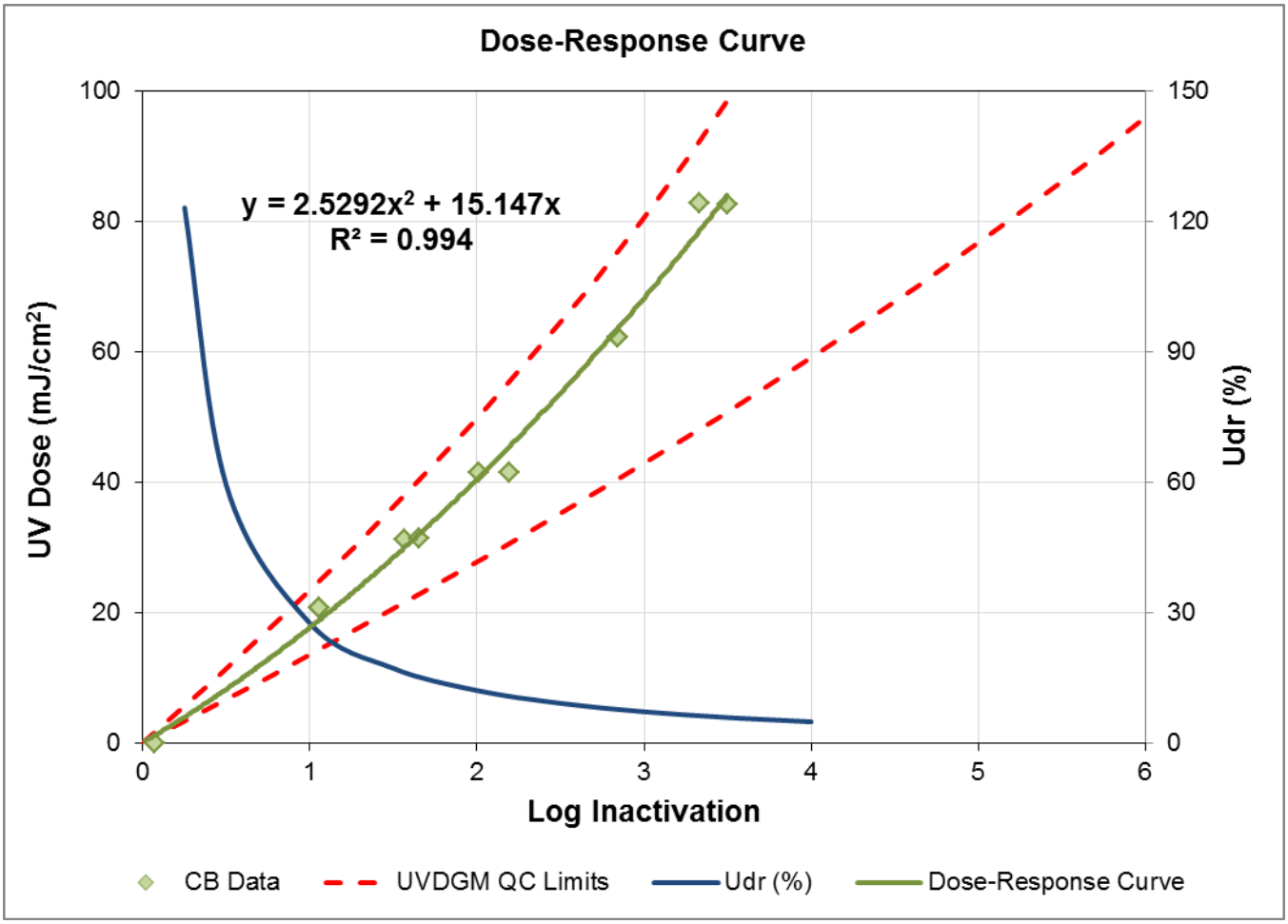

Figure 4-5 Dose response - log I versus dose UVT 79% (July 2012)

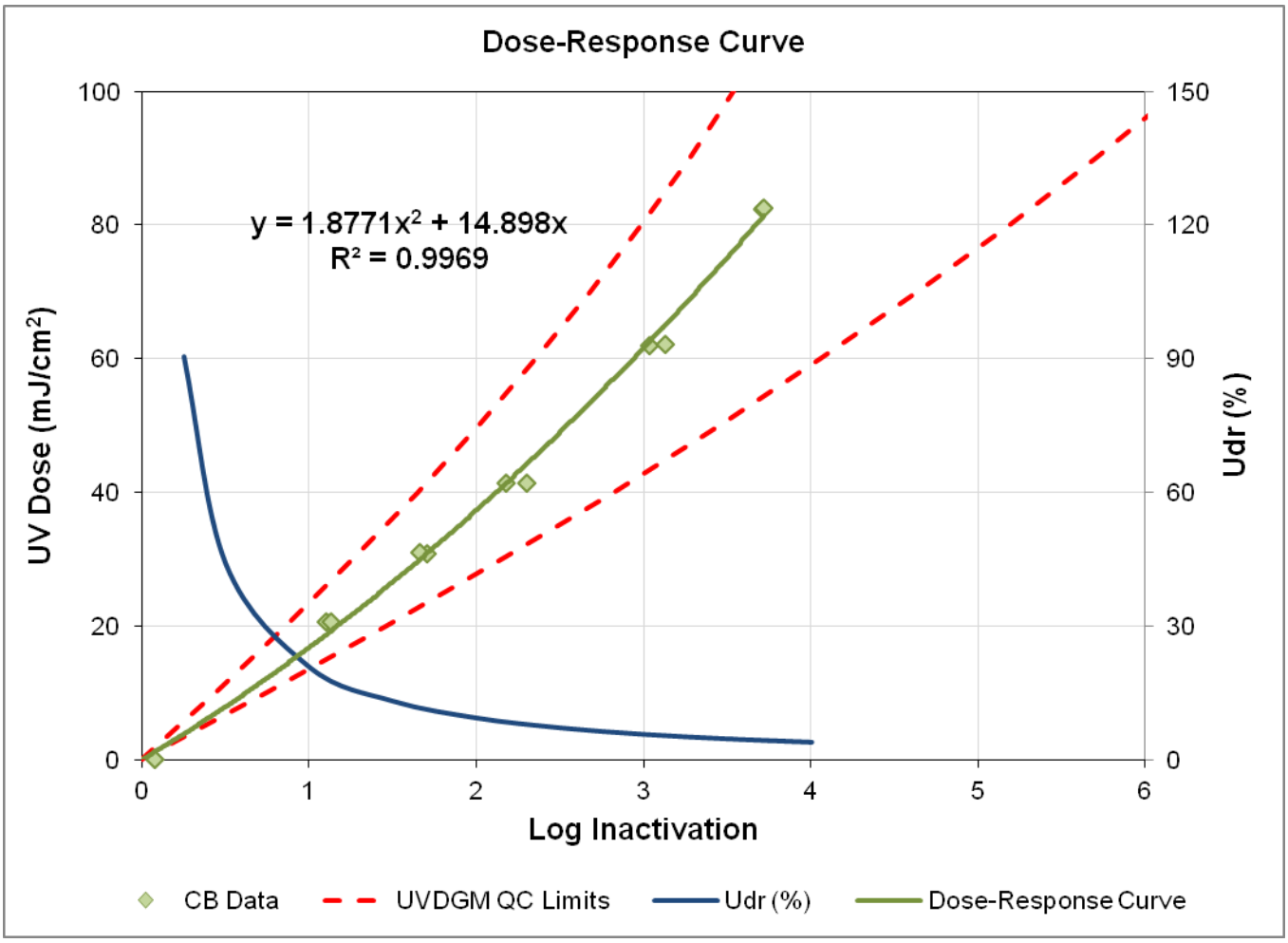

Figure 4-6 Dose response - log I versus Dose UVT 95% (July 2012)

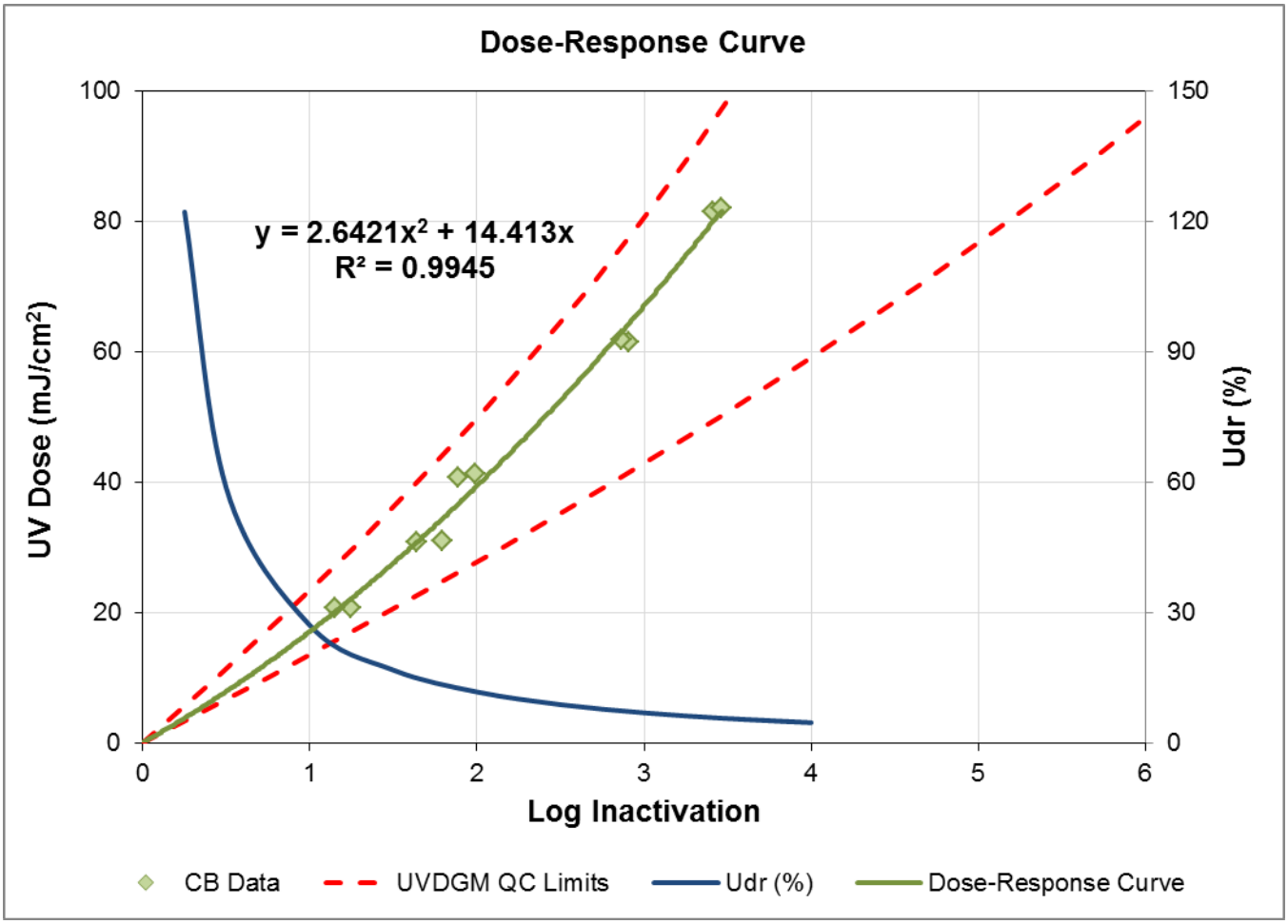

Figure 4-7 Dose response - log I versus dose UVT 79% (September 2012)

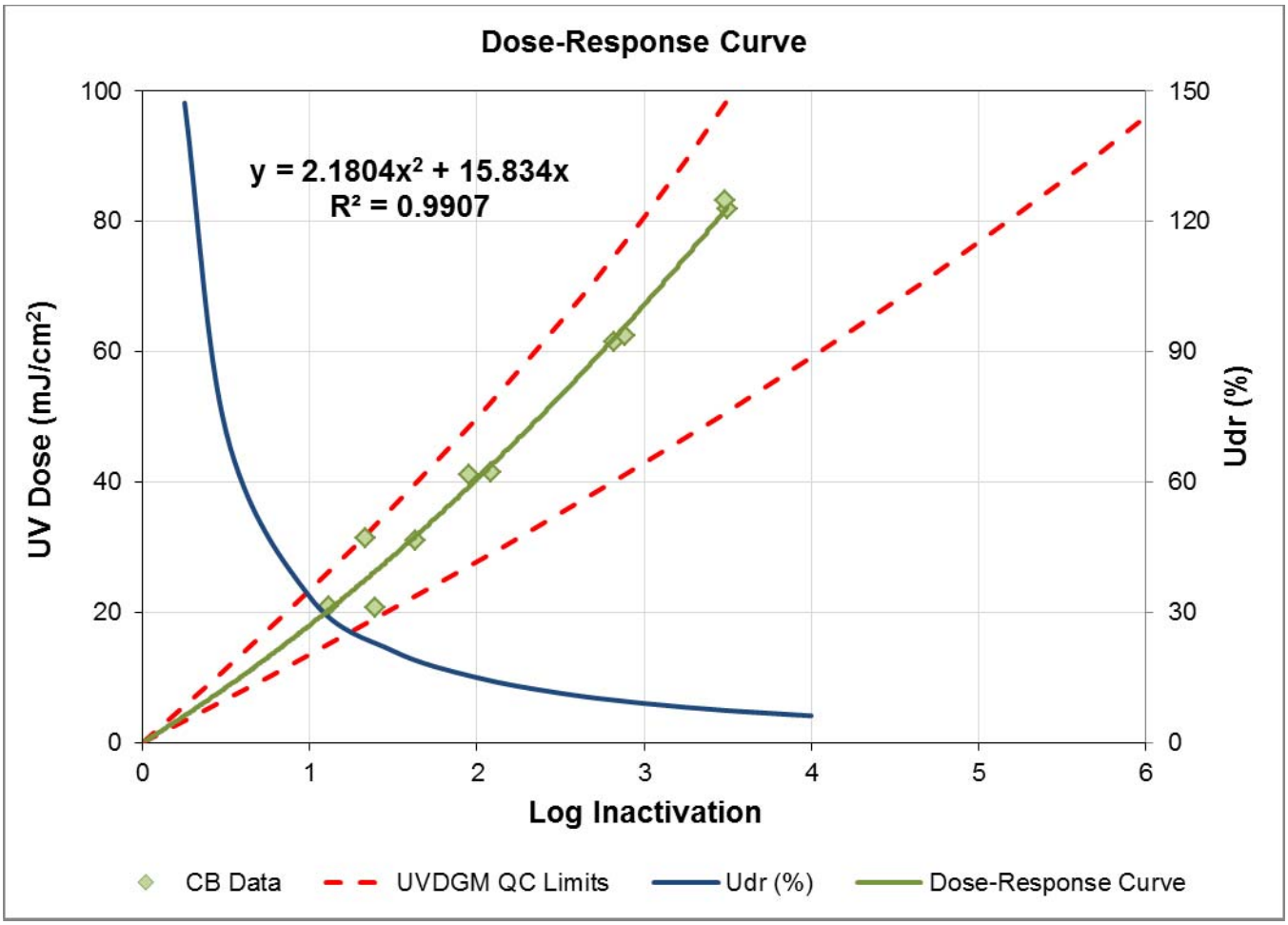

Figure 4-8 Dose response - log I versus dose UVT 97% (September 2012)

4.5 MS and Operational Flow Test Data

The operational data (flow rate, UVT, lamp power and UV sensor intensity measurements) are presented in Table 4-7. UVT was monitored continuously by an in-line analyzer. Flow rate, UVT, and intensity were recorded when each sample was collected, thus providing five data points for each test run. These values were then used to obtain an average flow rate, UVT, and intensity for each test run.

The first influent and effluent samples for MS2 determination were taken simultaneously beginning after approximately 2-3 minutes of steady state operation. Subsequent influent and effluent samples were collected simultaneously after an additional two to three minutes of operation, yielding five sets of samples over a ten to twelve minute period. The MS2 concentration data for each test run are shown in Table 4-8.

For each test condition replicate (i.e., each of the five influent and effluent samples), the log inactivation (log I) was calculated using the following equation:

$$\log I = \log (N_o / N)$$

Where:

N_o = Challenge microorganism concentration in influent sample (pfu/mL);

N = Challenge microorganism concentration in corresponding effluent sample (pfu/mL).

The log of the influent and effluent concentration is shown in Table 4-9. Table 4-10 shows the Log Inactivation results. For each test condition replicate the RED_{meas} was determined using the measured log inactivation (log I) and the collimated beam test dose-response curves for each day of testing (See Figures 4-5 through 4-8). The five replicate RED_{meas} values were then averaged to produce one RED_{meas} for each test run and its duplicate. The calculated RED_{meas} results in mJ/cm^2 are shown in Table 4-11.

All of the flow rate tests at 50, 75, and 100 gpm, with feed water at 78%, 89%, and 93% UVT or the equivalent reduced power tests, achieved a minimum RED_{meas} of 40 mJ/cm^2. The results from the additional flow test at 175 gpm and the minimum RED_{meas}, standard deviation (SD_{RED}) and the uncertainty of the set point (U_{sp}) shown in Table 4-11 were used in the example validated dose calculation for *Cryptosporidium* shown in Section 4.7.

The RED_{meas} for two of the test runs exceeded the maximum collimated beam dose of 80 mJ/cm^2. These runs showed calculated RED between 90.9 and 93.2 mJ/cm^2. The RED cannot be quantitatively determined if the measured RED exceeds the top range of the collimated data and can only be quantified as being >80 mJ/cm^2. For informational purposes, these data are presented as calculated even though they exceeded the maximum collimated beam dose of 80 mJ/cm^2 and would normally be reported at >80 mJ/cm^2. The two RED values above 80 mJ/cm^2 should be considered as estimates only.

Table 4-7. ETS UV *Model ECP-113-5* Operational Data

Test Condition	Run	% of Full Power[(1)]	UVT (%)	Flow (gpm)	Intensity (W/m^2)
Lowered UVT - Full Power (SPt 1)	22	100	78.3	50	82
Lowered UVT - Full Power Duplicate (SPt 1)	23	100	78.4	51	82
Lowered UVT - Full Power (SPt 2)	4	100	89.3	75	84
Lowered UVT - Full Power Duplicate (SPt 2)	5	100	89.3	75	84
Lowered UVT - Full Power (SPt 3)	6	100	93.4	101	104
Lowered UVT - Full Power Duplicate (SPt 3)	7	100	93.4	100	105
Lowered Power - High UVT (SPt 1)	24	45	97.9	50	81
Lowered Power - High UVT Duplicate (SPt 1)	25	45	97.9	51	81
Lowered Power - High UVT (SPt 2)	26	74	97.9	76	89
Lowered Power - High UVT Duplicate (SPt 2)	15	74	96.8	75	87
Lowered Power - High UVT (SPt 3)	16	83	97.2	100	105
Lowered Power - High UVT Duplicate (SPt 3)	17	83	97.2	101	105
High Flow Rate Test for 3-log *Cryptosporidium* inactivation demonstration					
Lowered UVT - Full Power (SPt 4)	8	100	93.5	175	104
Lowered UVT - Full Power Duplicate (SPt 4)	9	100	93.4	175	103
Lowered Power - High UVT (SPt 4)	18	45	97.3	176	105
Lowered Power - High UVT Duplicate (SPt 4)	19	45	97.4	175	105

(1) % of full power less than 100% estimated based on measured amperage for the system, where amperage at reduced power is divided by sensor intensity at full power.

SPt = Set Point Condition

Table 4-8. ETS UV *Model ECP-113-5* MS2 Concentration Results

Test Condition	Run	Influent (pfu/mL)					Effluent (pfu/mL)				
		Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5
Lowered UVT - Full Power (SPt 1)	22	5.14E+05	4.01E+05	4.34E+05	4.06E+05	3.80E+05	8.47E+02	1.07E+03	1.11E+03	8.27E+02	9.57E+02
Lowered UVT - Full Power Dup (SPt 1)	23	5.51E+05	5.75E+05	4.80E+05	3.23E+05	5.46E+05	9.80E+02	9.97E+02	8.97E+02	8.73E+02	1.17E+03
Lowered UVT - Full Power (SPt 2)	4	7.33E+04	8.77E+04	7.67E+04	5.20E+04	5.37E+04	2.03E+02	1.30E+02	1.52E+02	1.32E+02	1.20E+02
Lowered UVT - Full Power Dup (SPt 2)	5	9.00E+04	1.07E+05	7.20E+04	9.40E+04	9.13E+04	4.03E+02	4.03E+02	3.03E+02	5.13E+02	3.73E+02
Lowered UVT - Full Power (SPt 3)	6	1.48E+05	1.27E+05	1.53E+05	1.43E+05	2.14E+05	9.50E+02	6.67E+02	8.63E+02	6.93E+02	7.73E+02
Lowered UVT - Full Power Dup (SPt 3)	7	3.30E+05	2.86E+05	3.20E+05	3.10E+05	3.30E+05	8.63E+02	8.63E+02	no data	9.17E+02	9.67E+02
Lowered Power - High UVT (SPt 1)	24	8.17E+05	6.13E+05	7.10E+05	7.93E+05	6.73E+05	1.30E+02	1.51E+02	1.21E+02	9.70E+01	1.08E+02
Lowered Power - High UVT Dup (SPt 1)	25	1.08E+06	1.43E+06	6.63E+05	7.13E+05	1.04E+06	1.61E+02	1.12E+02	1.42E+02	1.02E+02	1.71E+02
Lowered Power - High UVT (SPt 2)	26	5.77E+05	4.67E+05	4.07E+05	6.13E+05	4.63E+05	1.22E+03	1.35E+03	1.08E+03	9.80E+02	7.50E+02
Lowered Power - High UVT Dup (SPt 2)	15	2.84E+05	2.91E+05	2.85E+05	3.62E+05	2.68E+05	5.63E+02	4.77E+02	4.37E+02	4.83E+02	5.83E+02
Lowered Power - High UVT (SPt 3)	16	1.89E+05	1.97E+05	1.98E+05	1.90E+05	1.99E+05	3.57E+02	2.90E+02	4.37E+02	3.53E+02	4.47E+02
Lowered Power - High UVT Dup(SPt 3)	17	2.46E+05	2.00E+05	2.39E+05	2.42E+05	2.56E+05	5.63E+02	6.87E+02	6.07E+02	5.30E+02	5.30E+02
High Flow Rate Test for 3-log *Cryptosporidium* inactivation demonstration											
Lowered UVT - Full Power (SPt 4)	8	2.30E+05	2.31E+05	2.85E+05	2.97E+05	2.77E+05	3.07E+03	5.37E+03	3.17E+03	5.13E+03	2.67E+03
Lowered UVT - Full Power Dup (SPt 4)	9	2.83E+05	2.57E+05	2.45E+05	2.27E+05	2.33E+05	7.90E+03	4.80E+03	6.90E+03	5.03E+03	3.57E+03
Lowered Power - High UVT (SPt 4)	18	2.23E+05	1.78E+05	2.38E+05	2.65E+05	2.41E+05	1.37E+03	1.49E+03	1.15E+03	2.50E+03	2.78E+03
Lowered Power - High UVT Dup (SPt 4)	19	1.31E+05	1.90E+05	1.25E+05	7.87E+04	1.19E+05	3.90E+03	3.99E+03	2.85E+03	3.02E+03	3.76E+03

SPt = Set Point Condition

Table 4-9. ETS UV *Model ECP-113-5* MS2 Log Concentration for Influent and Effluent Samples

Test Condition	Run	Log Influent Concentration					Log Effluent Concentration				
		Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5
Lowered UVT - Full Power (SPt 1)	22	5.71	5.60	5.64	5.61	5.58	2.93	3.03	3.05	2.92	2.98
Lowered UVT - Full Power Dup (SPt 1)	23	5.74	5.76	5.68	5.51	5.74	2.99	3.00	2.95	2.94	3.07
Lowered UVT - Full Power (SPt 2)	4	4.87	4.94	4.88	4.72	4.73	2.31	2.11	2.18	2.12	2.08
Lowered UVT - Full Power Dup (SPt 2)	5	4.95	5.03	4.86	4.97	4.96	2.61	2.61	2.48	2.71	2.57
Lowered UVT - Full Power (SPt 3)	6	5.17	5.10	5.18	5.16	5.33	2.98	2.82	2.94	2.84	2.89
Lowered UVT - Full Power Dup (SPt 3)	7	5.52	5.46	5.51	5.49	5.52	2.94	2.94	no data	2.96	2.99
Lowered Power - High UVT (SPt 1)	24	5.91	5.79	5.85	5.90	5.83	2.11	2.18	2.08	1.99	2.03
Lowered Power - High UVT Dup (SPt 1)	25	6.03	6.16	5.82	5.85	6.02	2.21	2.05	2.15	2.01	2.23
Lowered Power - High UVT (SPt 2)	26	5.76	5.67	5.61	5.79	5.67	3.09	3.13	3.03	2.99	2.88
Lowered Power - High UVT Dup (SPt 2)	15	5.45	5.46	5.46	5.56	5.43	2.75	2.68	2.64	2.68	2.77
Lowered Power - High UVT (SPt 3)	16	5.28	5.29	5.30	5.28	5.30	2.55	2.46	2.64	2.55	2.65
Lowered Power - High UVT Dup(SPt 3)	17	5.39	5.30	5.38	5.38	5.41	2.75	2.84	2.78	2.72	2.72
High Flow Rate Test for 3-log *Cryptosporidium* inactivation demonstration											
Lowered UVT - Full Power (SPt 4)	8	5.36	5.36	5.46	5.47	5.44	3.49	3.73	3.50	3.71	3.43
Lowered UVT - Full Power Dup (SPt 4)	9	5.45	5.41	5.39	5.36	5.37	3.90	3.68	3.84	3.70	3.55
Lowered Power - High UVT (SPt 4)	18	5.35	5.25	5.38	5.42	5.38	3.14	3.17	3.06	3.40	3.44
Lowered Power - High UVT Dup (SPt 4)	19	5.12	5.28	5.10	4.90	5.08	3.59	3.60	3.46	3.48	3.57

SPt = Set Point Condition

Table 4-10. ETS UV *Model ECP-113-5* MS2 Log Inactivation Results

Test Condition	Run	Log Inactivation				
		Rep 1	Rep 2	Rep 3	Rep 4	Rep 5
Lowered UVT - Full Power (SPt 1)	22	2.78	2.57	2.59	2.69	2.60
Lowered UVT - Full Power Dup (SPt 1)	23	2.75	2.76	2.73	2.57	2.67
Lowered UVT - Full Power (SPt 2)	4	2.56	2.83	2.70	2.60	2.65
Lowered UVT - Full Power Dup (SPt 2)	5	2.35	2.42	2.38	2.26	2.39
Lowered UVT - Full Power (SPt 3)	6	2.19	2.28	2.25	2.31	2.44
Lowered UVT - Full Power Dup (SPt 3)	7	2.58	2.52	no data	2.53	2.53
Lowered Power - High UVT (SPt 1)	24	3.80	3.61	3.77	3.91	3.79
Lowered Power - High UVT Dup (SPt 1)	25	3.83	4.11	3.67	3.84	3.78
Lowered Power - High UVT (SPt 2)	26	2.67	2.54	2.58	2.80	2.79
Lowered Power - High UVT Dup (SPt 2)	15	2.70	2.79	2.82	2.87	2.66
Lowered Power - High UVT (SPt 3)	16	2.72	2.83	2.66	2.73	2.65
Lowered Power - High UVT Dup(SPt 3)	17	2.64	2.46	2.60	2.66	2.68
High Flow Rate Test for 3-log *Cryptosporidium* inactivation demonstration						
Lowered UVT - Full Power (SPt 4)	8	1.88	1.63	1.95	1.76	2.02
Lowered UVT - Full Power Dup (SPt 4)	9	1.55	1.73	1.55	1.65	1.81
Lowered Power - High UVT (SPt 4)	18	2.21	2.08	2.31	2.02	1.94
Lowered Power - High UVT Dup (SPt 4)	19	1.53	1.68	1.64	1.42	1.50

SPt = Set Point Condition

Table 4-11. ETS UV *Model ECP-113-5* MS2 Observed RED Results

Test Condition	Run	RED (mJ/cm2) Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Average	SD(RED)	U_{SP}
Lowered UVT - Full Power (SPt 1)	22	60.58	54.60	55.11	57.92	55.30	56.70	2.52	12.34
Lowered UVT - Full Power Dup (SPt 1)	23	59.61	59.93	58.99	54.44	57.29	58.05	2.26	10.82
Lowered UVT - Full Power (SPt 2)	4	55.27	63.09	59.44	56.38	57.92	58.42	3.05	14.49
Lowered UVT - Full Power Dup (SPt 2)	5	49.52	51.57	50.25	47.22	50.61	49.84	1.64	9.11
Lowered UVT - Full Power (SPt 3)	6	45.39	47.65	46.85	48.60	52.07	48.11	2.51	14.46
Lowered UVT - Full Power Dup (SPt 3)	7	55.98	54.25	no data	54.49	54.60	54.83	0.78	4.53
Lowered Power - High UVT (SPt 1)	24	91.60	85.53	90.63	95.33	91.48	90.91(1)	3.51	10.73
Lowered Power - High UVT Dup (SPt 1)	25	92.52	101.78	87.45	93.10	91.14	93.20(1)	5.28	15.71
Lowered Power - High UVT (SPt 2)	26	57.95	54.26	55.26	61.32	61.16	57.20	3.16	15.34
Lowered Power - High UVT Dup (SPt 2)	15	53.96	56.05	56.82	58.32	52.97	55.62	2.16	10.80
Lowered Power - High UVT (SPt 3)	16	54.53	57.23	52.84	54.68	52.63	54.38	1.85	9.43
Lowered Power - High UVT Dup (SPt 3)	17	52.42	48.11	51.31	52.88	53.49	51.64	2.13	11.45
High Flow Rate Test for 3-log *Cryptosporidium* inactivation demonstration									
Lowered UVT - Full Power (SPt 4)	8	37.31	31.52	39.27	34.54	40.82	36.69	3.72	28.18
Lowered UVT - Full Power Dup (SPt 4)	9	29.64	33.76	29.58	31.96	35.81	32.15	2.69	23.23
Lowered Power - High UVT (SPt 4)	18	42.15	39.04	44.54	37.85	35.91	39.90	3.45	23.97
Lowered Power - High UVT Dup (SPt 4)	19	27.09	30.28	29.54	24.86	26.61	27.68	2.22	22.22

SD - Standard Deviation

U_{SP} - Uncertainty of the Set Point {[(Student t * SD)/RED_{ave}]*100}

SPt - Set Point Condition

(1) These RED values exceeded the highest dose in the collimated beam tests and therefore should be considered estimates. Since they are above the maximum dose in the collimated beam test, the results can only truly be quantified as being >80 mJ/cm^2.

U

4.6 Set Line for a Minimum RED of 40 mJ/cm^2

The three set point conditions selected for this validation all achieved a minimum RED_{meas} of 40 mJ/cm^2, which was the target minimum RED_{meas} for developing the set line. Figure 4-9 shows the set line. The unit is validated for a minimum RED_{meas} of 40 mJ/cm^2 for any combination of flow rate and intensity above and to the left of the set line. The maximum flow rate demonstrated was 100 gpm. A UV system cannot operate above the highest validated flow rate and claim a 40 mJ/cm^2 RED_{meas}. The lowest intensity demonstrating a RED_{meas} of 40 mJ/cm^2 was 82 W/cm^2. A UV system cannot operate below the lowest validated irradiance and claim a 40 mJ/cm^2 RED.

Set Point 1 – 50 gpm; 82 W/m^2
Set Point 2 – 75 gpm; 89 W/m^2
Set Point 3 – 100 gpm; 105 W/m^2

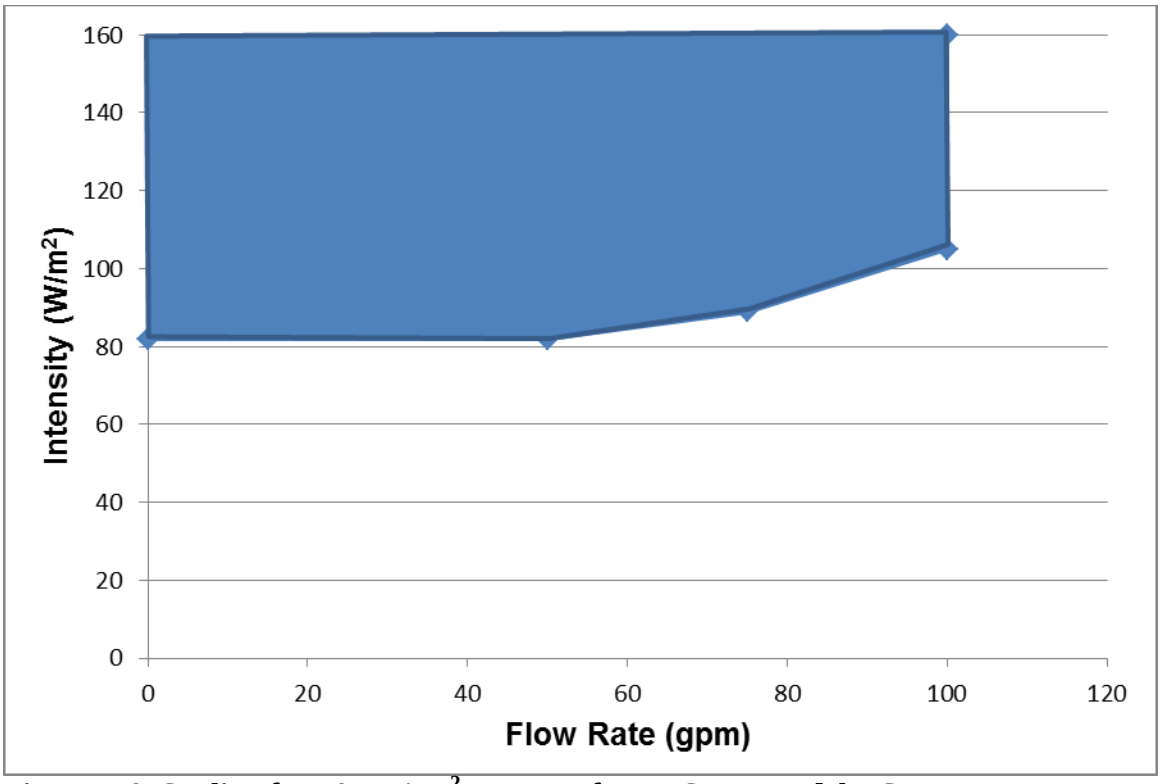

Figure 4-9. Set line for 40 mJ/cm^2 RED_{meas} for ETS UV *Model ECP-113-5.*

4.7 Deriving the Validation Factor and Log Credit for *Cryptosporidium*

4.7.1 Validation Factor Definition

Several uncertainties and biases are involved in using experimental testing to define a validated dose and validated operating conditions such as challenge microorganism UV sensitivity, and sensor placement or variability. The validation factor (VF) for *Cryptosporidium* was determined quantitatively to account for key areas of uncertainty and variability. The equation for the VF is shown below.

$$VF = B_{RED} \times [1+ (U_{Val} / 100)]$$

Where:

VF = Validation Factor;
B_{RED} = RED bias factor;
U_{Val} = Uncertainty of validation expressed as a percentage.

The data used for the VF calculations and final results are presented in the following section.

4.7.2 RED Bias (B_{RED})

The RED bias factor (B_{RED}) is a correction factor that accounts for the difference between the UV sensitivity of a selected target pathogen and the UV sensitivity of the challenge microorganism (MS2). If the challenge microorganism is more resistant (less sensitive) to UV light than the target pathogen, the RED measured during the validation will be greater than the RED that would be measured for the target pathogen. In this case the RED bias would be greater than 1.0. If the challenge microorganism is less resistant (more sensitive) to UV light than the target pathogen, then RED measured by the validation will be less than the RED that would be measured for the target pathogen.

A target pathogen must be selected to calculate the RED bias factor. For this test, the target pathogen *Cryptosporidium* was selected for use in presenting an example calculation of RED bias as it is a common pathogen that is evaluated for drinking water applications. *Cryptosporidium* was also selected because the EPA's LT2ESWTR requires UV reactors be validated to demonstrate a log inactivation for *Cryptosporidium*. A target of 3-log inactivation of *Cryptosporidium* was selected as water utilities in the highest risk category or "bin" may need this maximum level of inactivation. The RED bias tables in Appendix G of the UVDGM-2006 were used for determining the RED bias. The RED bias is determined from the Tables based on the sensitivity calculated for each test run replicate at a given set point (test condition) and the UVT of the water. Sensitivity is calculated as:

$$\text{Sensitivity (mJ/cm}^2\text{ per log I)} = \text{RED/ Log I}$$

Per the GP-2011 and UVDGM-2006, the sensitivity is calculated for each test replicate (five per test run, 20 samples total per set point). The highest B_{RED} value found among the replicates at a given set point is then selected for the B_{RED} value for use in the VF calculation per the UVDGM-2006 requirement. Table 4-12 shows the data for the replicates at each set point. The highest

RED bias at each set point is used in the validation factor calculations shown later in Section 4.7.3.

Table 4-12. RED Bias Factor for Each Set Point for *Cryptosporidium*

Sample Number	Test Run	UVT	Sensitivity (mJ/cm2 per Log I)			B_{RED} 4 log crypto	B_{RED} 3.5 log crypto	B_{RED} 3.0 log crypto
		%	RED	Log I	Sensitivity			
22-1	22	78.3	60.58	2.78	21.8	1.97	2.35	2.54
22-2	22	78.3	54.60	2.57	21.2	1.97	2.35	2.54
22-3	22	78.3	55.11	2.59	21.3	1.97	2.35	2.54
22-4	22	78.3	57.92	2.69	21.5	1.97	2.35	2.54
22-5	22	78.3	55.30	2.60	21.3	1.97	2.35	2.54
23-1	23	78.4	59.61	2.75	21.7	1.97	2.35	2.54
23-2	23	78.4	59.93	2.76	21.7	1.97	2.35	2.54
23-3	23	78.4	58.99	2.73	21.6	1.97	2.35	2.54
23-4	23	78.4	54.44	2.57	21.2	1.97	2.35	2.54
23-5	23	78.4	57.29	2.67	21.5	1.97	2.35	2.54
4-1	4	89.3	55.27	2.56	21.6	1.77	2.01	2.10
4-2	4	89.3	63.09	2.83	22.3	1.84	2.01	2.10
4-3	4	89.3	59.44	2.70	22.0	1.84	2.01	2.10
4-4	4	89.3	56.38	2.60	21.7	1.77	2.01	2.10
4-5	4	89.3	57.92	2.65	21.9	1.77	2.01	2.10
5-1	5	89.3	49.52	2.35	21.1	1.77	2.01	2.10
5-2	5	89.3	51.57	2.42	21.3	1.77	2.01	2.10
5-3	5	89.3	50.25	2.38	21.2	1.77	2.01	2.10
5-4	5	89.3	47.22	2.26	20.9	1.77	2.01	2.10
5-5	5	89.3	50.61	2.39	21.2	1.77	2.01	2.10
6-1	6	93.4	45.39	2.19	20.7	1.61	1.75	1.78
6-2	6	93.4	47.65	2.28	20.9	1.61	1.75	1.78
6-3	6	93.4	46.85	2.25	20.8	1.61	1.75	1.78
6-4	6	93.4	48.60	2.31	21.0	1.61	1.75	1.78
6-5	6	93.4	52.07	2.44	21.3	1.61	1.75	1.78
7-1	7	93.4	55.98	2.58	21.7	1.61	1.75	1.78
7-2	7	93.4	54.25	2.52	21.5	1.61	1.75	1.78
7-3	7	93.4	N/A	N/A	N/A	N/A	N/A	N/A
7-4	7	93.4	54.49	2.53	21.5	1.61	1.75	1.78
7-5	7	93.4	54.60	2.53	21.6	1.61	1.75	1.78
24-1	24	97.9	91.60	3.80	24.1	1.55	1.70	1.73
24-2	24	97.9	85.53	3.61	23.7	1.55	1.70	1.73
24-3	24	97.9	90.63	3.77	24.1	1.55	1.70	1.73
24-4	24	97.9	95.33	3.91	24.4	1.55	1.70	1.73
24-5	24	97.9	91.48	3.79	24.1	1.55	1.70	1.73
25-1	25	97.9	92.52	3.83	24.2	1.55	1.70	1.73
25-2	25	97.9	101.78	4.11	24.8	1.55	1.70	1.73
25-3	25	97.9	87.45	3.67	23.8	1.55	1.70	1.73
25-4	25	97.9	93.10	3.84	24.2	1.55	1.70	1.73
25-5	25	97.9	91.14	3.78	24.1	1.55	1.70	1.73
26-1	26	97.9	57.95	2.67	21.7	1.36	1.40	1.39
26-2	26	97.9	54.26	2.54	21.4	1.34	1.38	1.38

Sample Number	Test Run	UVT	Sensitivity (mJ/cm2 per Log I)			B_{RED} 4 log crypto	B_{RED} 3.5 log crypto	B_{RED} 3.0 log crypto
		%	RED	Log I	Sensitivity			
26-3	26	97.9	55.26	2.58	21.5	1.34	1.38	1.39
26-4	26	97.9	61.32	2.80	21.9	1.36	1.40	1.39
26-5	26	97.9	61.16	2.79	21.9	1.36	1.40	1.39
15-1	15	96.8	53.96	2.70	20.0	1.34	1.38	1.38
15-2	15	96.8	56.05	2.79	20.1	1.36	1.40	1.39
15-3	15	96.8	56.82	2.82	20.2	1.36	1.40	1.39
15-4	15	96.8	58.32	2.87	20.3	1.36	1.40	1.39
15-5	15	96.8	52.97	2.66	19.9	1.34	1.38	1.38
16-1	16	97.2	54.53	2.72	20.0	1.34	1.38	1.38
16-2	16	97.2	57.23	2.83	20.2	1.36	1.40	1.39
16-3	16	97.2	52.84	2.66	19.9	1.34	1.38	1.38
16-4	16	97.2	54.68	2.73	20.0	1.34	1.38	1.38
16-5	16	97.2	52.63	2.65	19.9	1.34	1.38	1.38
17-1	17	97.2	52.42	2.64	19.9	1.34	1.38	1.38
17-2	17	97.2	48.11	2.46	19.5	1.34	1.38	1.38
17-3	17	97.2	51.31	2.60	19.8	1.34	1.38	1.38
17-4	17	97.2	52.88	2.66	19.9	1.34	1.38	1.38
17-5	17	97.2	53.49	2.68	19.9	1.34	1.38	1.38
Maximum B_{RED}		Set Point 50 gpm - 82 W/m^2				1.97	2.35	2.54
		Set Point 75 gpm - 89 W/m^2				1.84	2.01	2.10
		Set Point 100 gpm - 105 W/m^2				1.61	1.75	1.78
High Flow Rate Test for 3-log *Cryptosporidium* inactivation demonstration								
8-1	8	93.5	37.31	1.88	19.9	1.55	1.70	1.73
8-2	8	93.5	31.52	1.63	19.3	1.55	1.70	1.73
8-3	8	93.5	39.27	1.95	20.1	1.61	1.75	1.78
8-4	8	93.5	34.54	1.76	19.6	1.55	1.75	1.73
8-5	8	93.5	40.82	2.02	20.2	1.61	1.70	1.78
9-1	9	93.4	29.64	1.55	19.1	1.55	1.70	1.73
9-2	9	93.4	33.76	1.73	19.5	1.55	1.70	1.73
9-3	9	93.4	29.58	1.55	19.1	1.50	1.64	1.68
9-4	9	93.4	31.96	1.65	19.3	1.50	1.64	1.68
9-5	9	93.4	35.81	1.81	19.7	1.55	1.70	1.73
18-1	18	97.3	42.15	2.21	19.1	1.34	1.38	1.38
18-2	18	97.3	39.04	2.08	18.8	1.34	1.38	1.38
18-3	18	97.3	44.54	2.31	19.2	1.34	1.38	1.38
18-4	18	97.3	37.85	2.02	18.7	1.34	1.38	1.38
18-5	18	97.3	35.91	1.94	18.5	1.34	1.38	1.38
19-1	19	97.4	27.09	1.53	17.8	1.31	1.36	1.36
19-2	19	97.4	30.28	1.68	18.0	1.31	1.36	1.36
19-3	19	97.4	29.54	1.64	18.0	1.31	1.36	1.36
19-4	19	97.4	24.86	1.42	17.6	1.31	1.36	1.36
19-5	19	97.4	26.61	1.50	17.7	1.31	1.36	1.36
Maximum B_{RED}		Set Point 175 gpm - 105 W/m^2				1.61	1.75	1.78

N/A - sample not analyzed so RED and bias not determined

4.7.3 Uncertainty of Validation

The uncertainty of validation (U_{Val}) addresses many sources of experimental uncertainty. As the critical source of uncertainty, such as the sensor readings, or the fit of the dose-response curve, is unknown in advance of the validation testing, the USEPA developed a decision tree to assist in establishing U_{Val}. The GP-2011 equations and in accordance with Figure 5.4 of the UVDGM-2006, which are specific to a UV intensity set point approach, were used to determine U_{Val} in calculating the validated dose. Per the GP-2011 and the EPA's UVDGM-2006, any of the following equations may be used to establish the U_{Val}:

$$U_{Val} = (U_{SP}^2 + U_S^2)^{1/2}$$
$$U_{Val} = U_{SP}$$
$$U_{Val} = (U_{SP}^2 + U_{DR}^2)^{1/2}$$
$$U_{Val} = (U_{SP}^2 + U_S^2 + U_{DR}^2)^{1/2}$$

Where:

U_S = Uncertainty of sensor value, expressed as a fraction;
U_{DR} = Uncertainty of the fit of the dose-response curve;
U_{SP} = Uncertainty of set-point;
U_{Val} = Uncertainty of the validation

The QC objective for the duty sensor is that the measurements with the duty sensor should be $\leq$10% of the average of two or more reference sensors. If this objective is met, then it eliminates the need to calculate the U_S factor per the GP-2011 and UVDGM-2006, Section 5.4.4. The sensor met the 10% requirement, as shown in Tables 4-1 and 4-2, therefore U_S is not used in determining the uncertainty of validation.

The GP-2011 and UVDGM-2006 in Appendix C Section C4 show the formula and calculations for the uncertainty of the fit of the collimated beam dose response curve (U_{DR}).

The equation is:

$$U_{DR} = t * [SD/ \text{UV Dose}_{CB}] * 100\%$$

Where:

U_{DR} = Uncertainty of the UV dose-response fit at a 95% confidence level
UV Dose_{CB} = UV dose calculated from the UV dose-response curve for the challenge microorganism
SD = Standard deviation of the difference between the calculated UV dose response and the measured value
t = t-statistic at a 95% confidence level for a sample size equal to the number of test condition replicates used to define the dose-response.

The U_{DR} results are shown in Tables 4-3 and 4-6 for the low and high UVT waters for both the July 18 and 19, 2012 test runs and the September 11, 2012 test runs. The July U_{DR} results for low and high UVT waters (27.48% and 20.74%, respectively) are less than 30%, and therefore U_{DR} is not used in calculating U_{Val} for the test runs corresponding to these days of testing. The September U_{DR} results for low and high UVT waters were 26.99% and 33.46%, respectively. Since the U_{DR} was >30% at the UV dose corresponding to 1-log inactivation of the MS2 the uncertainty of the dose response (U_{DR}) is included in the calculation of uncertainty (U_{Val}) for the test runs performed in September. The 75 gpm flow rate test with the power turned down included one test run in July and one test run in September. The September test run had the highest U_{DR} of 33.46%. The highest Udr measured in September was applied to both test runs and was included in determining the uncertainty (U_{Val}) for both test runs.

The uncertainty in the set point value (U_{SP}) is based on a prediction interval at a 95% confidence level using the following procedure:

1. Calculate the average and standard deviation of RED_{meas} values for each test condition.
2. Calculate the uncertainty of the set point RED_{meas} using:

$$U_{SP} = [(t \times SD_{RED}) / (RED_{meas})] \times 100\%$$

Where:

RED_{meas} = Average RED_{meas} value measured for each test condition;

SD_{RED} = Standard deviation of the RED_{meas} values measured for each test condition;

t = t-statistic for a 95% confidence level defined as a function of the number of replicate samples, in this case 5 replicates were used for testing yielding a t value of 2.776 (n-1 = 4), except for test run 7 which had four valid replicates so the t value is 3.182.

3. Select the highest U_{SP} from the replicates at each set point for calculating the VF.

The U_{SP} results based on the RED_{meas} and standard deviation are shown in Table 4-11. In accordance with the GP-2011, the highest U_{SP} of the four test runs at each set point determines the U_{SP} for that set point. The highest U_{SP} for each set point is 15.71% (50 gpm set point), 15.34% (75 gpm set point), 14.46% (100 gpm set point) and 28.18% (175 gpm set point).

The uncertainty of the validation is equal to the highest U_{SP} at a set point when the U_{DR} is <30% (July test runs) or is calculated using the highest applicable U_{DR} (33.46%) and the highest U_{SP} at a set point for the September test runs using the equations:

$$U_{Val} = U_{SP}$$
$$U_{Val} = (U_{SP}^2 + U_{DR}^2)^{1/2}$$

Table 4-13 shows the U_{Val} values used for determining the uncertainty of the validation at each set point.

Table 4-13 Uncertainty of the Validation (U_{Val}) and B_{RED} Values for *Cryptosporidium*

Set Point	Max U_{DR} %	Max U_{SP} %	U_{Val} %	Max B_{RED} 4.0 log	3.5 log	3.0 log
50 gpm - 82 W/m^2	33.46	15.71	36.96	1.97	2.35	2.54
75 gpm - 89 W/m^2	33.46	15.34	36.81(1)	1.84	2.01	2.10
100 gpm - 105 W/m^2	27.48	14.46	14.46	1.61	1.75	1.78
175 gpm - 105 W/m^2	27.48	28.18	28.18	1.61	1.75	1.78

(1) The lowered UVT - full power runs were performed in July. U_{DR} for July is <30% for the U_{Val} for those two replicates is 15.34%. The low power test runs were in both July and September, so the highest U_{DR} applies from July and September is used and the U_{Val} is equal to 36.81% for the low power test run replicates.

4.7.4 Validated Dose and Set Line for *Cryptosporidium*

After establishing the U_{Val} and the RED bias as described above, the validation factor (VF) is calculated using the equation:

$$VF = B_{RED} \times [1+ (U_{Val} / 100)]$$

Where:

VF = Validation Factor;
B_{RED} = RED bias factor for *Cryptosporidium*
U_{Val} = Uncertainty of validation expressed as a percentage

The validated dose is then calculated as follows:

$$\text{Validated dose } (RED_{Val}) = RED_{meas} / VF$$

Table 4-14 shows the calculated Validation Factors (VF) for various *Cryptosporidium* log inactivation levels (3.0, 3.5, and 4.0 log inactivation).

Table 4-14 shows the RED_{Val} for *Cryptosporidium* for each test run using the validation factors for the various *Cryptosporidium* log inactivation levels. Table 4-14 shows the Validated Dose for each set point and a comparison to the dose required for various levels of inactivation of *Cryptosporidium*. As can be seen, the tests for the 75 - 89 W/m^2 and 100 gpm - 105 W/m^2 set points show a validated dose for *Cryptosporidium* that achieves a minimum of 4.0 log inactivation. The other set point (50 gpm - 82 W/m^2) achieved a minimum of 3.5 log inactivation for *Cryptosporidium*.

Table 4-14 also shows the RED_{Val} for the additional 175 gpm - 105 W/m^2 tests achieved a validated dose for *Cryptosporidium* that demonstrates a minimum of 3.0 log inactivation. Therefore, the higher flow rate set point achieved the objective to meet a minimum 3.0 log inactivation of *Cryptosporidium,* which may be required by the EPA's LT2ESWTR in cases where a utility is in the highest "bin" or risk category for *Cryptosporidium* in their source water.

Table 4-14 Validation Factors and Validated Dose (RED_{Val}) for *Cryptosporidium*

Condition	Run	Flow Rate	Intensity	Validation Factor			RED_{meas}	RED_{Val}		
		gpm	W/m^2	4.0 log	3.5 log	3.0 log	mJ/cm^2	4 log_2	3.5 log_2	3.0 log_2
								22[1] mJ/cm^2	15[1] mJ/cm^2	[1]
Lowered UVT - Full Power (SPt 1)	22	50	82	2.70	3.22	3.48	56.7 mJ/cm	21.0	**17.6**	16.3
Lowered UVT - Full Power Dup (SPt 1)	23	51	82	2.70	3.22	3.48	58.1	21.5	**18.0** 12	16.7
Lowered Power - High UVT (SPt 1)	24	50	81	2.70	3.22	3.48	90.9	**33.7**	28.2	
Lowered Power - High UVT Dup (SPt 1)	25	51	81	2.70	3.22	3.48	93.2	**34.5**	29.0 26.1	
Lowered UVT - Full Power (SPt 2)	4	75	84	2.12	2.32	2.42	58.4	**27.5**	25.2 26.8	
Lowered UVT - Full Power Dup (SPt 2)	5	75	84	2.12	2.32	2.42	49.8	**23.5**	21.5 24.1	
Lowered Power - High UVT (SPt 2)	26	76	89	2.52	2.75	2.87	57.2	**22.7**	20.8 20.6	
Lowered Power - High UVT Dup (SPt 2)	15	75	87	2.52	2.75	2.87	55.6	**22.1**	20.2 19.9	
Lowered UVT - Full Power (SPt 3)	6	101	104	1.84	2.00	2.04	48.1	**26.1**	24.0 19.4	
Lowered UVT - Full Power Dup (SPt 3)	7	100	105	1.84	2.00	2.04	54.8	**29.8**	27.4 23.6	
Lowered Power - High UVT (SPt 3)	16	100	105	1.84	2.00	2.04	54.4	**29.5**	27.1 26.9	
Lowered Power - High UVT Dup (SPt 3)	17	101	105	1.84	2.00	2.04	51.6	**28.0**	25.8 26.7	
High Flow Rate Test for 3-log *Cryptosporidium* inactivation demonstration										
Lowered Power - High UVT (SPt 4)	8	175	104	2.06	2.24	2.28	36.7	17.8	**16.4** 25.3	16.1
Lowered Power - High UVT Dup (SPt 4)	9	175	103	2.06	2.24	2.28	32.1	15.6	14.3	**14.1**
Lowered UVT - Full Power (SPt 4)	18	176	105	2.06	2.24	2.28	39.9	19.3	**17.8**	17.5
Lowered UVT - Full Power Dup (SPt 4)	19	175	105	2.06	2.24	2.28	27.7	13.4	12.3	**12.1**

(1) Required dose for log inactivation validation per the UVDGM-2006 Appendix G; SPt = Set Point Condition

The four set point tests demonstrating a minimum of 3 log inactivation for *Cryptosporidium* were plotted to form a set line. Figure 4-10 shows the set line.

The four set points are:

Set Point 1 - 50 gpm; 82 W/m^2
Set Point 2 - 75 gpm; 89 W/m^2
Set Point 3 - 100 gpm; 105 W/m^2
Set Point 4 - 175 gpm; 105 W/m^2

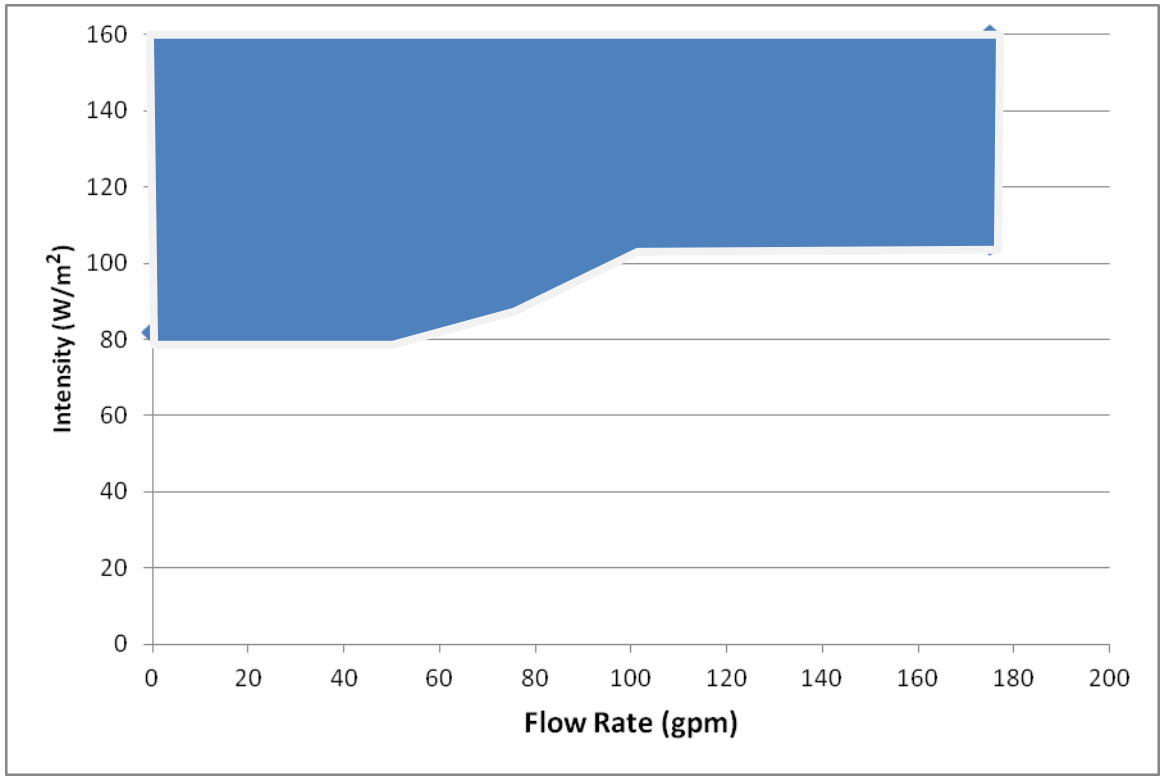

Figure 4-10. Set Line for Minimum 3-log *Cryptosporidium* Inactivation for ETS UV *Model ECP-113-5*.

4.7.5 Low Wavelength Medium Pressure Lamp Bias Correction

At the time of this testing, the UV industry was addressing a concern about MS2 susceptibility to low wavelength emission from medium pressure lamps. MS2 has action spectra at 254 nm and also at 220 nm and lower wavelengths. The UV industry comprising of manufacturers, engineers, water utilities and regulators have been conducting research and developing solutions to correct for the low wavelength bias in existing validations. When the work of the UV industry is completed, a correction factor will be necessary for the results presented herein. NSF understands that the NIPH requires a 30% correction factor and so does the California Department of Public Health.

One way for a MP UV reactor to use a germicidal sensor (250-280 nm), would be to validate the reactor with a lamp sleeve that does not transmit in the lower wavelengths during validation. So a sensor set point could be established using only the 250-280 nm wavelength emitted by the MP lamps. Another validation could occur with a lamp sleeve that does transmit at the other wavelengths. In this case, the difference in the UV dose could be observed and accounted for in a control strategy.

In the future, NSF will require all medium pressure lamps (with a polychromatic bias) to use a quartz sleeve designed to filter out the low wavelength when using MS2 to validate a reactor. NSF will also consider a challenge organism that demonstrates action spectra only for a small region near the 254 nm wavelength.

4.8 Validated Dose (RED_{Val}) for MS2 as the Target Organism

Some regulatory agencies, such as the NYDOH, have established a standard for spray parks and other applications based on a validated dose (RED_{Val}) of 40 mJ/cm^2 based on MS2 as the pathogen. The calculation of the validation factor for a validated dose based on MS2 is performed using B_{RED} set equal to 1.0. For MS2 validated dose calculations, B_{RED} is set equal to 1.0 because the pathogen selected, namely MS2, is the same as the test organism, so there is no bias correction. Therefore, the validation factor will not vary by the log inactivation level.

The U_{Val} is calculated in the same manner as described in Section 4.7.3.

The validation factor (VF) for evaluating validated dose (RED_{Val}) based on MS2 is calculated using the same formula as for other pathogens as follows:

$$VF = B_{RED} \times [1+ (U_{Val} / 100)]$$

Where:

VF = Validation Factor;
B_{RED} = RED bias factor (set equal 1.0)
U_{Val} = Uncertainty of validation expressed as a percentage.

The validated dose is then calculated as follows:

$$\text{Validated dose } (RED_{Val}) = RED_{observed} / VF$$

Table 4-15 shows the RED_{Val} based on MS2 for each test run.

Using the VF calculated for each set point, the RED_{Val} based on MS2 was calculated for each test run. All of the primary set point test runs (flow rates of 50, 75, and 100 gpm) achieved a 40 mJ/cm^2 validated dose based on MS2. The higher flow rate test did not achieve a 40 mJ/cm^2 RED_{Val} based on MS2. This was expected as this higher flow rate test (175 gpm - 105 W/m^2) was targeted at achieving a minimum 3 log inactivation for *Cryptosporidium* and 40 mJ/cm^2 RED_{meas}.

Table 4-15 Validation Factors and Validated Dose (RED_{Val}) based on MS2

Condition	Run	Flow Rate gpm	Intensity W/m^2	Validation Factor (1)	RED_{meas} mJ/cm^2	RED_{Val} based on MS2 mJ/cm^2
Lowered UVT - Full Power (SPt 1)	22	50	82	1.37	56.7	41.4
Lowered UVT - Full Power Dup (SPt 1)	23	51	82	1.37	58.1	42.4
Lowered Power - High UVT (SPt 1)	24	50	81	1.37	90.9	66.4
Lowered Power - High UVT Dup (SPt 1)	25	51	81	1.37	93.2	68.0
Lowered UVT - Full Power (SPt 2)	4	75	84	1.15	58.4	50.6
Lowered UVT - Full Power Dup (SPt 2)	5	75	84	1.15	49.8	43.2
Lowered Power - High UVT (SPt 2)	26	76	89	1.37	57.2	41.8
Lowered Power - High UVT Dup (SPt 2)	15	75	87	1.37	55.6	40.7
Lowered UVT - Full Power (SPt 3)	6	101	104	1.14	48.1	42.0
Lowered UVT - Full Power Dup (SPt 3)	7	100	105	1.14	54.8	47.9
Lowered Power - High UVT (SPt 3)	16	100	105	1.14	54.4	47.5
Lowered Power - High UVT Dup (SPt 3)	17	101	105	1.14	51.6	45.1
High Flow Rate Test for 3-log *Cryptosporidium* inactivation demonstration						
Lowered Power - High UVT (SPt 4)	8	175	104	1.28	36.7	28.6
Lowered Power - High UVT Dup (SPt 4)	9	175	103	1.28	32.1	25.1
Lowered UVT - Full Power (SPt 4)	18	176	105	1.28	39.9	31.1
Lowered UVT - Full Power Dup (SPt 4)	19	175	105	1.28	27.7	21.6

(1) B_{RED} equal to 1.0 as the target organism is MS2 the same as the test organism.; SPt – Set Point Condition

4.9 Water Quality Data

Samples were collected for general water quality characterization. Influent and effluent samples were collected during each flow test run and analyzed for temperature, pH, total chlorine, and free chlorine. An influent sample was collected from each flow test run and analyzed for turbidity, iron, and manganese.

An influent and effluent sample from each test run was also collected and analyzed for total coliform, *E. coli*, and heterotrophic plant count (HPC).

The general chemistry and microbiological results are presented in Tables 4-16 through 4-19.

Table 4-16. Temperature and pH Results

		Temperature (^{o}F)		pH (S.U.)	
Test	**Run #**	**Influent**	**Effluent**	**Influent**	**Effluent**
Reactor Blank	1	72.3	72.6	8.47	8.53
Reactor Blank	21	71.1	71.4	7.41	7.34
Lowered UVT - Full Power (SPt 1)	22	71.0	71.2	7.38	7.42
Lowered UVT - Full Power Dup (SPt 1)	23	70.9	71.1	7.37	7.41
Lowered UVT - Full Power (SPt 2)	4	72.4	72.6	8.60	8.60
Lowered UVT - Full Power Dup (SPt 2)	5	72.3	72.5	8.60	8.58
Lowered UVT - Full Power (SPt 3)	6	72.5	71.9	8.55	8.53
Lowered UVT - Full Power Dup (SPt 3)	7	72.2	72.1	8.54	8.54
Lowered UVT - Full Power (SPt 4)	8	71.9	72.3	8.54	8.55
Lowered UVT - Full Power Dup (SPt 4)	9	72.0	72.1	8.54	8.55
Reactor Blank	10	72.3	72.6	8.52	8.49
Reactor Control	11	72.2	72.3	8.51	8.48
Lowered Power - High UVT (SPt 1)	24	70.4	70.7	7.84	7.86
Lowered Power - High UVT Dup (SPt 1)	25	70.2	70.4	7.89	7.90
Lowered Power - High UVT (SPt 2)	26	70.0	70.2	7.90	7.89
Lowered Power - High UVT Dup (SPt 2)	15	72.1	72.3	8.50	8.46
Lowered Power - High UVT (SPt 3)	16	72.1	72.3	8.38	8.53
Lowered Power - High UVT Dup (SPt 3)	17	71.9	72.2	8.44	8.54
Lowered Power - High UVT (SPt 4)	18	72.0	72.2	8.45	8.57
Lowered Power - High UVT Dup (SPt 4)	19	71.8	72.0	8.48	8.58

Table 4-17. Total Chlorine, Free Chlorine and Turbidity Results

		Total Chlorine (mg/L)	Free Chlorine (mg/L)	Turbidity (NTU)
Test	**Run #**	**Influent**	**Influent**	**Influent**
Blank	1	0.03	<0.03	0.37
Blank	21	0.03	<0.03	0.75
Lowered UVT - Full Power (SPt 1)	22	<0.03	<0.03	0.80
Lowered UVT - Full Power Dup (SPt 1)	23	<0.03	<0.03	0.66
Lowered UVT - Full Power (SPt 2)	4	<0.03	<0.03	0.26
Lowered UVT - Full Power Dup (SPt 2)	5	<0.03	<0.03	0.37
Lowered UVT - Full Power (SPt 3)	6	<0.03	<0.03	0.30
Lowered UVT - Full Power Dup (SPt 3)	7	<0.03	<0.03	0.29
Lowered UVT - Full Power (SPt 4)	8	<0.03	<0.03	0.27
Lowered UVT - Full Power Dup (SPt 4)	9	<0.03	<0.03	0.30
Reactor Blank	10	<0.03	<0.03	0.18
Reactor Control	11	<0.03	<0.03	0.19
Lowered Power - High UVT (SPt 1)	24	<0.03	<0.03	0.38
Lowered Power - High UVT Dup (SPt 1)	25	<0.03	<0.03	0.38
Lowered Power - High UVT (SPt 2)	26	<0.03	<0.03	0.40
Lowered Power - High UVT Dup (SPt 2)	15	<0.03	<0.03	0.15
Lowered Power - High UVT (SPt 3)	16	<0.03	<0.03	0.33
Lowered Power - High UVT Dup (SPt 3)	17	<0.03	<0.03	0.26
Lowered Power - High UVT (SPt 4)	18	<0.03	<0.03	0.24
Lowered Power - High UVT Dup (SPt 4)	19	<0.03	<0.03	0.22

Note: Runs 21-23 with the addition of LSA to lower UVT to 79% showed higher readings for turbidity; suspect interference due to the LSA

Table 4-18. Iron and Manganese Results

		Iron	Manganese	UVT[(1)]	
		(mg/L)	(mg/L)	(%)	
Test	Run #	Influent	Influent	Influent	Effluent
Reactor Blank	1	<0.02	0.002	78	78
Reactor Blank	21	0.06	0.009	78	78
Lowered UVT - Full Power (SPt 1)	22	0.02	0.008	78	78
Lowered UVT - Full Power Dup (SPt 1)	23	0.09	0.009	78	78
Lowered UVT - Full Power (SPt 2)	4	0.02	0.001	89	89
Lowered UVT - Full Power Dup (SPt 2)	5	0.03	0.001	89	89
Lowered UVT - Full Power (SPt 3)	6	<0.02	<0.001	93	93
Lowered UVT - Full Power Dup (SPt 3)	7	0.04	<0.001	93	93
Lowered UVT - Full Power (SPt 4)	8	<0.02	<0.001	93	93
Lowered UVT - Full Power Dup (SPt 4)	9	<0.02	<0.001	93	93
Reactor Blank	10	<0.02	<0.001	95	95
Reactor Control	11	<0.02	<0.001	95	95
Lowered Power - High UVT (SPt 1)	24	0.09	0.003	97	97
Lowered Power - High UVT Dup (SPt 1)	25	<0.02	0.002	97	97
Lowered Power - High UVT (SPt 2)	26	<0.02	0.002	97	97
Lowered Power - High UVT Dup (SPt 2)	15	<0.02	<0.001	96	96
Lowered Power - High UVT (SPt 3)	16	0.02	<0.001	95	95
Lowered Power - High UVT Dup (SPt 3)	17	<0.02	<0.001	97	96
Lowered Power - High UVT (SPt 4)	18	<0.02	<0.001	97	97
Lowered Power - High UVT Dup (SPt 4)	19	<0.02	<0.001	97	97

(1)UVT on grab samples, measured in laboratory after tests; Five influent samples averaged; single effluent sample reported here; In- line UVT meter used for flow test results

Table 4-19. HPC, Total Coliform and *E. coli* Results.

		Total Coliform		*E. coli*		HPC	
		MPN/100mL		MPN/100mL		CFU/mL	
Test	**Run #**	**Influent**	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**
Reactor Blank	1	<1	<1	<1	<1	6.50E+02	2.60E+01
Reactor Blank	21	<1	<1	<1	<1	2.83E+03	5.60E+01
Lowered UVT - Full Power (SPt 1)	22	34	<1	<1	<1	3.56E+03	5.15E+01
Lowered UVT - Full Power Dup (SPt 1)	23	18	12	<1	1	4.20E+03	6.00E+01
Lowered UVT - Full Power (SPt 2)	4	<1	<1	<1	<1	9.55E+02	2.80E+01
Lowered UVT - Full Power Dup (SPt 2)	5	<1	<1	<1	<1	9.85E+02	7.50E+00
Lowered UVT - Full Power (SPt 3)	6	2	<1	<1	<1	3.35E+02	2.00E+00
Lowered UVT - Full Power Dup (SPt 3)	7	1	<1	<1	<1	5.30E+02	4.50E+00
Lowered UVT - Full Power (SPt 4)	8	3	<1	<1	<1	5.25E+02	2.15E+01
Lowered UVT - Full Power Dup (SPt 4)	9	4	<1	<1	<1	5.20E+02	3.50E+00
Reactor Blank	10	2	<1	<1	<1	3.09E+03	3.06E+02
Reactor Control	11	435	328	<1	<1	5.06E+03	5.35E+03
Lowered Power - High UVT (SPt 1)	24	10	<1	<1	<1	3.60E+03	2.11E+02
Lowered Power - High UVT Dup (SPt 1)	25	13	<1	<1	<1	1.98E+03	6.60E+01
Lowered Power - High UVT (SPt 2)	26	8	<1	<1	<1	2.41E+03	8.50E+01
Lowered Power - High UVT Dup (SPt 2)	15	1	<1	<1	<1	6.70E+02	5.30E+01
Lowered Power - High UVT (SPt 3)	16	10	<1	<1	<1	1.63E+03	4.90E+01
Lowered Power - High UVT Dup (SPt 3)	17	7	<1	<1	<1	6.35E+02	2.20E+01
Lowered Power - High UVT (SPt 4)	18	22	<1	<1	<1	1.03E+03	2.65E+01
Lowered Power - High UVT Dup (SPt 4)	19	5	<1	<1	<1	1.04E+03	2.25E+01

4.10 Headloss

Headloss was measured over the flow range of 50 to 200 gpm. Pressure at the inlet and outlet of the reactor was measured at several flow rates as shown in Table 4-20.

Table 4-20. Headloss Measurement Results.

Flow Rate	Inlet (psi)	Outlet (psi)	Headloss (psi)
50	1.949	1.903	0.046
100	2.155	2.025	0.130
150	2.506	2.212	0.294
200	2.954	2.525	0.429

4.11 Power Measurement

A power monitoring platform was connected to the unit. This monitoring platform provided continuous readout of the voltage and amperage being used by the unit for each test run. Volts and amperes were recorded during each flow test. A series of power measurements were also made to show the change in intensity at various power down levels. Table 4-21 presents the power measurements taken during the flow tests.

Table 4-21. Power Measurement Results

		Unit Volts	Unit Amperage	Unit Power
Test	Run #	(volts)	(amps)	(Watts)
Reactor Blank	1	206.8	6.6	1150
Reactor Blank	21	242.1	10.64	1960
Lowered UVT - Full Power (SPt 1)	22	242.1	10.62	1960
Lowered UVT - Full Power Dup (SPt 1)	23	241.8	10.62	1950
Lowered UVT - Full Power (SPt 2)	4	206.4	6.4	1110
Lowered UVT - Full Power Dup (SPt 2)	5	206.5	6.4	1120
Lowered UVT - Full Power (SPt 3)	6	204.6	6.3	1100
Lowered UVT - Full Power Dup (SPt 3)	7	205.9	6.4	1110
Lowered UVT - Full Power (SPt 4)	8	205.6	6.3	1100
Lowered UVT - Full Power Dup (SPt 4)	9	205.1	6.3	1090
Reactor Blank	10	207.7	3.3	560
Reactor Control	11	208.1	0.0	0.0
Lowered Power - High UVT (SPt 1)	24	207.5	4.85	800
Lowered Power - High UVT Dup (SPt 1)	25	207.0	4.78	790
Lowered Power - High UVT (SPt 2)	26	206.5	5.12	840
Lowered Power - High UVT Dup (SPt 2)	15	207.7	4.9	820
Lowered Power - High UVT (SPt 3)	16	206.1	5,5	950
Lowered Power - High UVT Dup (SPt 3)	17	206.2	5.5	960
Lowered Power - High UVT (SPt 4)	18	206.2	5.5	940
Lowered Power - High UVT Dup (SPt 4)	19	206.4	5.5	950

Chapter 5
Quality Assurance/Quality Control

5.1 Introduction

An important aspect of verification testing is the QA/QC procedures and requirements. Careful adherence to the procedures ensures that the data presented in this report is of sound quality, defensible, and representative of the equipment performance. The primary areas of evaluation were representativeness, accuracy, precision, and completeness.

Because this ETV was conducted at the NSF testing lab, all laboratory activities were conducted in accordance with the provisions of the NSF International Laboratories Quality Assurance Manual.

5.2 Test Procedure QA/QC

NSF testing laboratory staff conducted the tests by following a USEPA-approved test/QA plan[(1)] created specifically for this verification. NSF QA Department staff performed an audit during testing to ensure the proper procedures were followed. The audit yielded no significant findings.

5.3 Sample Handling

All samples analyzed by the NSF Chemistry and Microbiology Laboratories were labeled with unique identification numbers. All samples were analyzed within allowable holding times.

5.4 Chemistry Laboratory QA/QC

The calibrations of all analytical instruments and the analyses of all parameters complied with the QA/QC provisions of the NSF International Laboratories Quality Assurance Manual.

The NSF QA/QC requirements are all compliant with those given in the USEPA method or Standard Method for the parameter. Also, every analytical method has an NSF standard operating procedure.

The bench top UV spectrophotometer was calibrated with Holmium Oxide with each batch of samples analyzed and showed peaks at 241.1 nm, 250.0 nm and 278.1 nm within $\pm$ 0.2 nm of the actual peak. Dichromate standards were also run with each batch of samples and found to be within 1% of the true value.

5.5 Microbiology Laboratory QA/QC

5.5.1 Growth Media Positive Controls

All media were checked for sterility and positive growth response when prepared and when used for microorganism enumeration. The media was discarded if growth occurred on the sterility check media, or if there was an absence of growth in the positive response check.

5.5.2 Negative Controls

For each sample batch processed, an unused membrane filter and a blank with 100 mL of buffered, sterilized dilution water was filtered through the membrane, placed onto the appropriate media and incubated with the samples as negative controls. No growth was observed on any blanks.

5.5.3 Collimated Beam Apparatus and QA/QC

The petri dish factor was determined for the collimated beam apparatus prior to the start of the test program. Radiometers were calibrated and checked in accordance with operating procedure and UVDGM-2006 requirements. These procedures and data were reviewed as part of the NSF QA department review of the microbiological laboratory data.

The factors used in the collimated test shown below were evaluated against the protocol requirements and found to meet the QC objectives. The length (distance from the lamp centerline to the suspension) and the depth of suspension were fixed parameters. These measurements were made multiple times at the "fixed mark" on the collimated beam apparatus to estimate the precision of the measurements. The time was checked based on a stop watch with minimal uncertainty. The petri dish factor was measured several times prior to the start of the test. Absorbance uncertainty is based on spectrophotometer precision, as is the related reflectance factor. The average intensity is measured for every collimated beam test, as it is required that intensity be measured before and after each test.

To control for error in the UV dose measurement, the uncertainties of the terms in the UV dose calculation met the following criteria:

	Estimated	Required
• Depth of suspension (d)	<5%	≤ 10%
• Average incident irradiance (E_s)	2.5%	≤ 8%
• Petri Factor (P_f)	2.1%	≤ 5%
• L/(d + L)	0.7%	≤ 1%
• Time (t)	1.6%	≤ 5 %
• $(1 - 10^{-ad})/ad$	1.2%	≤ 5%

Trip blanks are normally performed to show that the phage stock solution does not change during shipment to and from the test site. The phage stock solution was delivered from the microbiology laboratory in the same building as the test rig before each test run and the samples were returned to the laboratory after each test run. Therefore trip blanks were not required for these tests, as all stock solution and test samples were received from and delivered to the microbiology laboratory before/after each test run. No shipping or long holding times was required. However, trip blanks were analyzed for this project to demonstrate that no change was occurring. The results are shown in Table 5-1.

Table 5-1. Trip Blank Results

	Trip Blank Lab Retained		Trip Blank Travel to Test Rig and Returned		Difference
Date	(PFU/mL MS2)	Log_{10}	(PFU/mL MS2)	Log_{10}	Log_{10}
July 18, 2012	2.10E+07	7.32	2.07E+07	7.32	0.00
July 19, 2012	5.93E+07	7.77	5.67E+07	7.75	0.02
September 11, 2012	4.98E+08	8.70	3.97E+08	8.60	0.10

Stability tests for MS2 are normally performed to show that the phage does not change during holding times when samples are shipped from the test site to the laboratory and/or held in the laboratory prior to analysis. However, for these tests, the test rig was located in the same building as the microbiology laboratory. Samples were delivered to the laboratory after each test run and the laboratory ran the samples within 4 to 6 hours of sample collection. Stability samples were run for informational purposes even though the holding time was very short.

Table 5-2. MS2 Stability Test Results

MS2 Stability Test Results					
High UVT 95%	**PFU/mL**	**Log_{10}**	**Low UVT 79%**	**PFU/mL**	**Log_{10}**
Influent 0 Hour	4.27E+02	2.63	Influent 0 Hour	3.47E+02	2.54
Influent 4 Hour	1.45E+02	2.16	Influent 4 Hour	2.31E+02	2.36
Influent 8 Hour	5.67E+02	2.75	Influent 8 Hour	7.30E+02	2.86
Influent 24 Hour	6.10E+02	2.79	Influent 24 Hour	1.02E+03	3.01
High UVT 95%	**Average**	**Log_{10}**	**Low UVT 79%**	**Average**	**Log_{10}**
Effluent 0 Hour	3.37E+02	2.53	Effluent 0 Hour	3.50E+02	2.54
Effluent 4 Hour	1.12E+02	2.05	Effluent 4 Hour	9.83E+01	1.99
Effluent 8 Hour	3.37E+02	2.53	Effluent 8 Hour	4.33E+02	2.64
Effluent 24 Hour	7.27E+02	2.86	Effluent 24 Hour	8.03E+02	2.90

5.6 Engineering Lab - Test Rig QA/QC

The flow meter for the test rig is part of the NSF tank, pump, and flow control system used for UV testing and other tests in the engineering laboratory. The flow meter is calibrated by the NSF QA staff at least annually. Calibration is performed by measuring the draw down volume from the calibrated feed tank over time. The tank was calibrated by filling with measured volumes of water and the corresponding depth measured. In addition to the annual calibration, the flow meter was calibrated prior to the start of these test runs. Calibration was performed at 50, 75, 100, and 175 gpm covering the range of expected flow rates. The flow meter accuracy fell within a range of 0.6 to 2.7% of the measured tank draw down rate over the range of test flow rates. The calibration data for the flow meter are shown in Table 5- 3 and achieved the requirement of +/- 5%.

Table 5-3. Flow Meter Calibration Results

Meter Flow Rate Read by meter	Volume from Tank	Run Time	Flow Rate Calculated	Percent Difference
(gpm)	(gallons)	(min:sec:millsec)	(gpm)	(%)
51.3	399.4	7:37:62	52.4	2.1
100.5	612.1	5:55:42	103.3	2.7
177.6	874.4	4:50:51	180.6	1.7
52.8	184.8	3:26:54	53.7	1.7
78.1	268.3	3:24:87	78.6	0.6

A reactor control and a reactor blank were performed as part of the validation. One reactor control, with MS2 coliphage injection, and the lamps off, was performed to demonstrate that the MS2 concentration was not changing as the seeded water passed though the reactor. A reactor blank was collected to demonstrate that the system was not accumulating or being contaminated with MS2 at levels that would interfere with the test.

Table 5-4 presents the results of the reactor control and reactor blanks. The reactor control had an average influent concentration of 5.23 $\log_{10}$ and an average effluent concentration of 5.26 $\log_{10}$ showing a difference of 0.03 $\log_{10}$ through the system with lamps off. This meets the criteria of less than a 0.2 $\log_{10}$ change through the unit with lamps turned off.

The reactor blank results showed no measureable MS2 in the system.

The results for the blank samples for HPC, total coliform, and *e. coli* were presented in Table 4-19.

5.7 Documentation

All laboratory activities were documented using specially prepared laboratory bench sheets and NSF laboratory reports. Data from the bench sheets and laboratory reports were entered into Microsoft™ Excel® spreadsheets. These spreadsheets were used to calculate the means and $\log_{10}$ reductions. One hundred percent of the data entered into the spreadsheets was checked by a reviewer to confirm all data and calculations were correct.

5.8 Data Review

NSF QA/QC staff reviewed the raw data records for compliance with QA/QC requirements. As required in the ETV Quality Management Plan, NSF ETV staff checked at least 10% of the data in the NSF laboratory reports against the lab bench sheets.

Table 5-4. Reactor Control and Reactor Blank MS2 Results

Test Condition	Test Run	UVT (%)	Flow (gpm)	Intensity (W/m^2)	Influent (pfu/mL)			Effluent (pfu/mL)		
					Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3
Reactor Blank	1	78.1	51.1	45	<1	<1	<1	<1	<1	<1
Reactor Blank	10	95.1	52.2	48	<1	<1	<1	<1	<1	<1
Reactor Blank	21	78.4	50.5	82	<1	<1	<1	<1	<1	<1
Reactor Control	11	95.0	50.1	0.0	1.86E+05	1.83E+05	1.46E+05	2.08E+05	1.65E+05	1.76E+05
Test Condition	**Test Run**	**UVT (%)**	**Flow (gpm)**	**Intensity (W/m^2)**	**Influent log_{10}**			**Effluent log_{10}**		
					Rep 1	Rep 2	Rep 3	Rep 1	Rep 2	Rep 3
Reactor Blank	1	78.1	51.1	45	0.0	0.0	0.0	0.0	0.0	0.0
Reactor Blank	10	95.1	52.2	48	0.0	0.0	0.0	0.0	0.0	0.0
Reactor Blank	21	78.4	50.5	82	0.0	0.0	0.0	0.0	0.0	0.0
Reactor Control	11	95.0	50.1	0.0	5.27	5.26	5.16	5.31	5.22	5.25

5.9 Data Quality Indicators

The quality of data generated for this ETV verification is established through four indicators of data quality: representativeness, accuracy, precision, and completeness.

5.9.1 Representativeness

Representativeness is a qualitative term that expresses "the degree to which data accurately and precisely represent a characteristic of a population, parameter variations at a sampling point, a process condition, or an environmental condition." Representativeness was ensured by consistent execution of the test protocol for each challenge, including timing of sample collection, sampling procedures, and sample preservation. Representativeness was also ensured by using each analytical method at its optimum capability to provide results that represent the most accurate and precise measurement each method is capable of achieving.

5.9.2 Accuracy

Accuracy was quantified as the percent recovery of the parameter in a sample of known quantity. Accuracy was measured through use of both matrix spikes of a known quantity, where applicable, and certified standards during calibration of an instrument.

The following equation was used to calculate percent recovery:

$$\text{Percent Recovery} = 100 \times [(X_{known} - X_{measured})/X_{known}]$$

Where:

X_{known} = known concentration of the measured parameter
$X_{measured}$ = measured concentration of parameter

Accuracy of the bench top chlorine, pH, and turbidity meters were checked daily during the calibration procedures using certified check standards. The in-line UVT monitor was calibrated daily with both a purchased UVT standard and with DI water at 99.9% UVT before the flow tests.

The NSF Laboratory Quality Assurance Manual establishes the frequency of spike sample analyses at 10% of the samples analyzed for chemical analyses. Laboratory control samples are also run at a frequency of 10%. The recovery limits specified for the parameters in this verification, excluding microbiological analyses, were 70-130% for laboratory-fortified (spiked) samples and 85-115% for laboratory control samples. The NSF QA department reviewed the laboratory records and found that all recoveries were within the prescribed QC requirements. Calibration requirements were also achieved for all analyses.

5.9.3 Precision

Precision refers to the degree of mutual agreement among individual measurements and provides an estimate of random error. One sample per batch was analyzed in duplicate for the iron and manganese measurement. At least one out of every ten samples for pH, total chlorine, free chlorine, temperature, and turbidity was analyzed in duplicate as part of the daily calibration

process. Precision of duplicate analyses was measured by use of the following equation to calculate RPD:

$$RPD = \left| \frac{S_1 - S_2}{S_1 + S_2} \right| \times 200$$

Where:

S_1 = sample analysis result; and

S_2 = sample duplicate analysis result.

Acceptable analytical precision for the verification test was set at an RPD of 30%. Field duplicates were collected at a frequency of one out of every 10 samples for each parameter, to incorporate both sampling and analytical variation to measure overall precision against this objective. In addition, the NSF Laboratory also conducted laboratory duplicate measurements at 10% frequency of samples analyzed. The laboratory precision for the methods selected was tighter than the 30% overall requirement, generally set at 20% based on the standard NSF Chemistry Laboratory method performance.

All RPD were within NSF's established allowable limits for each parameter.

5.9.4 Completeness

Completeness is the proportion of valid, acceptable data generated using each method as compared to the requirements of the TQAP plan. The completeness objective for data generated during validation testing is based on the number of samples collected and analyzed for each parameter and/or method, as presented in Table 5-5.

Table 5-5. Completeness Requirements

Number of Samples per Parameter and/or Method	Percent Completeness
0-10	80%
11-50	90%
> 50	95%

Completeness is defined as follows for all measurements:

$$\%C = (V/T) \times 100$$

Where:

%C = percent completeness;

V = number of measurements judged valid; and

T = total number of measurements.

One replicate sample for MS2 (influent and effluent) from test run 7 was not useable. The total number of test run replicates was 120 (not counting blanks and controls) yielding a completeness of 98.3%. All other scheduled samples and analyses were a hundred percent complete. All planned testing activities were conducted as scheduled, and all planned samples were collected for challenge organism and water chemistry analysis.

Chapter 6
References

1. Test/Quality Assurance Plan for The ETS UV Ultraviolet (UV) Reactor, Medium Pressure Lamps, June 2010

2. Generic Protocol for Development of Test/Quality Assurance Plans for Validation of Ultraviolet (UV) Reactors, NSF International, 7/2010.

3. Protocol for Development of Test / Quality Assurance Plans for Validation of Ultraviolet (UV) Reactors August 2011 10/01/EPADWCTR.

4. Ultraviolet Disinfection Guidance Manual For the Long Term 2 Enhanced surface Water Treatment Rule, Office of Water, US Environmental Protection Agency, November 2006, EPA 815-R-06-007

5. German Association for Gas and Water (DVGW) Technical Standard Work Sheet W 294-1,2,3 (June 2006)

6. Austrian Standards, ÖNORM M5873-2, Plants for the disinfection of water using ultraviolet radiation, Requirements and testing, Medium pressure mercury lamp plants (2003)

7. APHA, AWWA, and WEF (1999). *Standard Methods for the Examination of Water and Wastewater*, 20th Edition.

8. NSF International (2007). *NSF/ANSI Standard 55 – Ultraviolet Microbiological Water Treatment Systems*.

9. NSF International (2011). *NSF/ANSI Standard 50 – Equipment for Swimming Pools, Spas, Hot Tubs and Other Recreational Water Facilities*

10. Water Report 113, Safe, Sufficient and Good Potable Water Offshore: A guideline to design and operation of offshore potable water systems. 2nd edition. By Eyvind Andersen and Bjørn E. Løfsgaard.

11. Recommended Standards For Water Works, Policies for the Review and Approval of Plans and Specifications for Public Water Supplies, 2012 Edition, A Report of the Water Supply Committee of the Great Lakes--Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers

November 2013

Attachment 1

Model ECP-113-5 Operating and Technical Manual
Supporting Technical Data

Contact Mr. Bruce Bartley at 734-769-5148 or bartley@nsf.org for a copy of this document.

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Attachment 2

Model ECP-113-5 Sensor and Lamp Information

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Attachment 3

Standard 55 Annex A - Collimated Beam Apparatus

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Attachment 4

UVT Scans for Feed Water
High and Low UVT
(with and without LSA)

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