Approach for Achieving Sustainable Operation of the 2-bgd Catskill/Delaware UV disinfection Facility

Matthew T. Valade, P.E.[1], Steven Farabaugh[2] Paul D. Smith, P.E.[3], Gary Kroll, P.E.[4]

[1]Hazen and Sawyer, P.C., 24 Federal Street, Suite 302, Boston, MA 02129

[2]Hazen and Sawyer, P.C., 498 Seventh Avenue, 11th Floor, New York, NY 10018

[3]NYC Dept. of Env. Protection, 96-05 Horace Harding Expy, Corona, NY 11368

[4]CDM, Raritan Plaza 1, Raritan Center, Edison, NJ 08817

ABSTRACT

Recent advances in testing methods are being applied to the validation of NYC's Catskill/Delaware UV equipment. These advanced methods will allow the full scale facility to operate in a more sustainable manner with up to 50% reduction in operating power requirements (and corresponding reduction in carbon dioxide emissions) and savings of over $1 million annually.

Key Words: UV disinfection, Dyed microspheres, Validation, Sustainable

INTRODUCTION

The design of the Catskill/Delaware UV disinfection facility commenced in 2001, concurrent with the development of the Long Term 2 Enhanced Surface Water Treatment Rule (LT2). The intent of the LT2 is to ensure protection of public health, particularly regarding infection by *Cryptosporidium*. The New York City Department of Environmental Protection (NYCDEP) has specifically undertaken the design and construction of the Catskill/Delaware UV facility in order to meet the requirements of LT2. At the time of design and validation testing, the LT2 was not final, nor was the UV Disinfection Guidance Manual (UVDGM), which prescribes the validation protocol. Therefore, not only was the design criteria for the UV facility conservative, but also the validation testing because NYCDEP wanted to ensure that the UV facility would meet the requirements of the rule when finalized. Essentially, the conservative design criteria and validation testing impacted the applied dose and capacity of the UV equipment, both of which directly affect the size of the UV units and therefore the footprint of the UV disinfection facility. NYCDEP is currently conducting additional validation testing with dyed microspheres (DMS) and other advanced surrogates, allowing for increased certainty of the applied dose, while reducing the power required to achieve proper disinfection by over 18,500 kW-hrs per day – enough energy to power nearly 1,000 homes. This paper presents the results of the validation testing and the approach the City of New York is taking to ensure a sustainable operation of the Catskill/Delaware UV Disinfection Facility.

BACKGROUND

NYCDEP is implementing UV disinfection in the Catskill/Delaware Water Supply System in compliance with the United States Environmental Protection Agency's (USEPA) Filtration Avoidance Determination (FAD) – the UV facility is scheduled to be online in 2012. UV disinfection in combination with chlorine disinfection, which is currently in place, provides a multiple disinfection barrier against bacteria, viruses, and protozoa like *Cryptosporidium* and *Giardia*. The Catskill/Delaware system is required under LT2 to provide disinfection for 2-log inactivation of *Cryptosporidium*, 3-log inactivation of Giardia and 4-log inactivation of viruses. The doses required by LT2 to achieve inactivation of *Cryptosporidium* are shown in Table I. The Catskill/Delaware system is conservatively designed to achieve a 3-log inactivation of *Cryptosporidium* with UV disinfection alone, a 3-log inactivation of Giardia through a combination of UV and chlorine disinfection and 4-log inactivation of viruses with chlorine disinfection.

Table 1: Experimental conditions for uv/h_2o_2 treatment of synthetic water

	Log Inactivation of *Cryptosporidium*		
	2.0	2.5	3.0
Regulatory Dose Requirement (mJ/cm^2)	5.8	8.5	12

USEPA Approach to Validation

In order to effectively and safely verify the effectiveness of UV equipment and establish the disinfection effectiveness, referred to as the reduction equivalent dose (RED), testing (i.e. validation) is required and furthermore is mandated by the LT2. Surrogate organisms are typically used because there are inherent dangers and challenges of validating equipment with the target organism, in the case of Catskill/Delaware – *Cryptosporidium*. However, using a surrogate results in inherent differences compared to the target organism – mainly because the target organism and the surrogate organism exhibit different sensitivities to UV light. The validation protocol set forth in the UVDGM accounts for these differences through the RED bias factor to ensure the RED achieved correlates properly to the required UV dose – as set forth in the LT2 – for the target organism.

Until recently, the surrogate microbe MS2 was the industry standard in the United States for establishing disinfection effectiveness through validation testing of a UV unit. The general consensus in the United States was that MS2 was easier to work with and the best surrogate to conservatively estimate the disinfection efficacy for larger capacity (i.e., greater than 5 mgd) UV units – despite the use of other types of surrogates for validation testing in Europe, like *Bacillus subtilis*. Only recently (i.e., post-2005) have other, more efficient surrogates such as Q-beta and T1 been identified and used for validating UV equipment in the US. The 2003 USEPA Draft UVDGM established guidelines for an RED approaching 40 mJ/cm^2 for 3-log inactivation of *Cryptosporidium*. Therefore, an RED of 40 mJ/cm^2 was selected as the design criteria for the Catskill/Delaware UV facility design. However, the final UVDGM, issued in 2006, changed how the RED bias was calculated and the manual permitted validation with surrogates other than MS2, such as Q-beta, which exhibits a sensitivity towards UV light that is more similar to *Cryptosporidium* and therefore, could significantly reduce the RED bias of a UV unit. In order to do so, the RED bias and other uncertainties encountered during a validation are calculated and incorporated into an overall 'uncertainty factor of validation' or what is referred to as the Validation Factor. To ensure the regulated dose is achieved, the following equation is applied:

Required Regulated Dose $\leq$	$\frac{\text{Validated RED}}{\text{Validation Factor (VF)}}$	[1]
Whereas, $VF = RED_{bias} \times (1 + U_i)$ U_i = Uncertainty of Validation (%)		

More recently, advances have been made in the application of chemical actinometry, which uses non-biological surrogates, such as DMS, to provide a greater understanding of the treatment characteristics of a unit.

Lagrangian Actinometry

Researchers at Purdue University, led by Professor Ernest R. Blatchley III of the School of Civil Engineering, developed a method known as Lagrangian actinometry (LA) that allows direct measurement of the dose distribution. (Shen, *et al.*, 2005; Blatchley, *et al.*, 2006) The actinometry process uses dyed microspheres that correlate dose measurement at a physical scale to that of an individual microorganism. The microspheres, which have size and density characteristics similar to the target organism, mimic the trajectories of individual microorganisms in actual treatment settings. The dye undergoes a photochemical reaction when exposed to UV radiation, yielding a stable, fluorescent compound that can be easily and accurately differentiated from the non-fluorescent parent compound (**Figure 1**). The fluorescence measurements are carried out in a flow cytometer, an instrument that can develop accurate fluorescence measurements for thousands of microspheres in a matter of minutes. Methods for characterization of a UV unit by DMS is similar to the methods with biological surrogates and consist of introducing a population of DMS upstream of a UV unit and collecting effluent samples for analysis of fluorescence among the captured microspheres. The significant benefit of DMS is that by measuring the actual dose distribution delivered by a UV unit, the RED bias is eliminated and therefore the Validation Factor can be significantly reduced through increasing the certainty of the delivered dose.

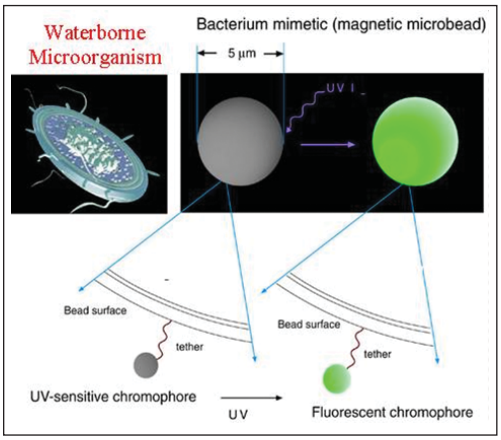

Figure 1: Representation of the Dyed-Microspheres Actinometry Process

Catskill/Delaware UV Unit Selection

As no UV units with capacities greater than 20 mgd were commercially available, the NYCDEP undertook a novel equipment selection and procurement process to ensure the best UV units would be used for the Catskill/Delaware UV Facility. The NYCDEP procured a single UV unit from two UV system suppliers - and validated both at the New York Validation and Research Center of New York. The validation was conducted by HydroQual Inc. and was performed according to the UV Disinfection System Validation Work Plan which was prepared based on the Draft UVDGM and provided to the New York State Department of Health (NYSDOH) for approval prior to the validation. The details of procurement and testing were reported by Valade, et al (2005).

The selected design capacity for the UV units was 40 mgd largely due to validation testing facility limitations; at the

time, the largest validation facility had a test capacity of 20 mgd. The design UV transmittance (UVT) selected was 87%, which represents the 5th percentile of historical Catskill/Delaware water quality UVT data. Validation testing was performed in 2005 to ensure the UV units selected were able to provide the required dose at the design flow and UVT. While both UV units met the design requirements and delivered a nominal dose of 40 mJ/cm^2, the NYCDEP selected Trojan Technologies Inc. as the sole-source supplier based on a life cycle cost analysis.

UV Facility Description

Each Trojan UV unit is a stainless steel pressure vessel and contains arrays of low pressure high output (LPHO) lamps mounted in a cross flow configuration and is outfitted with UV intensity sensors. A UV unit (**Photo 1**) contains 210 LPHO UV lamps mounted inside the unit but is capable of containing up to 240 lamps. For operational purposes the 210 lamps in the UV unit are separated into three banks and the unit was validated to operate with 90, 150, or 210 lamps online. Each lamp is protected by a quartz sleeve.

The UV Facility contains four UV modules for the Catskill/Delaware water supply. Each UV module is connected to a separate raw water header and consists of 14 UV units for a total of 56 UV units within the UV Facility. Each of the 56 UV units was designed to treat 40 mgd at the design conditions of 87% UVT, achieving the maximum design capacity of 2,020 mgd for the UV facility, with five standby UV units available, equivalent to 10% UV unit redundancy at the maximum design capacity. Each process train consists of an upstream isolation butterfly valve and magnetic flow meter, UV disinfection unit, and a downstream butterfly control/isolation valve.

Photo 1: Installation of UV Lamp Sleeves in Catskill/Delaware UV Unit

Catskill/Delaware Validation

Validation testing of the Trojan UV unit conducted in 2005 was performed with both MS2 and Q-beta as surrogates. A large set of data set for the Trojan unit was established over a wide range of operating conditions. Flows between 20 and 60 mgd and UVT's of 85, 90 and 95% were used. In order to allow efficient operation of a UV unit over the wide range of flow and UVT, the number of lamps in operation was also varied. Nearly100 discrete operating points were evaluated in order to develop a robust operating range of the Catskill/Delaware UV unit. As part of the initial testing of the Trojan UV unit, testing using dyed microspheres was conducted during the preliminary development of the Lagrangian Actinometry testing procedures.

Based on the current requirements of NYSDOH to achieve an RED of 40 mJ/cm^2, the maximum Validation Factor that would be allowed to ensure the regulated dose is achieved is 3.33 based on Equation 1.

12 mJ/cm^2 ≤	40 mJ/cm^2
	Validation Factor
Maximum Validation Factor based on 40 mJ/cm^2 MS2 Requirement	≤ 3.33

At the time of the development of validation protocol for the Catskill/Delaware UV unit, significant investigations were on-going into alternate validation surrogates that more closely represent the dose response characteristics of *Cryptosporidium*. (Clancy, 2004) The most significant benefit of using a surrogate that more closely mimics the dose response of the actual target organism (i.e. *Cryptosporidium*) is that a reduction in the RED bias will be achieved and therefore a reduction in the Validation Factor that must be applied to the validated dose to ensure the appropriate regulated dose is achieved. As input power to a UV unit is directly proportional to delivered does, reducing the Validation Factor of a UV unit allows less power to be used to achieve a specific regulated dose, as the certainty of the validation results has been increased. (Fallon, 2007) If a Validation Factor is reduced by 50 percent, the resulting power required to achieve the same regulatory log inactivation of a target organism will be reduced by a corresponding 50 percent. This would result in significant operating cost savings for utilities without adversely impacting public health.

Due to the success of these early tests, NYCDEP is currently undertaking additional validation testing that will provide a validation dataset using DMS, as well as additional data for T1 as the surrogate, across the full operating range tested in 2005. The benefits to New York City of using these additional surrogates are presented below.

Results of Catskill/Delaware Validation

Validation factors were calculated for MS2 and Q-beta, based on the validation testing of the Trojan UV unit in 2005. Factors were also estimated for DMS as only limited data was available from the 2005 testing. The DMS Validation Factors were estimated using similar uncertainty values as the MS2 and Q-beta results. Although the validation factors developed for the biological surrogates vary with the target log inactivation and UVT, conservative estimates are provided herein for discussion purposes. At the

design UVT of 87%, the estimated Validation Factors are:

	2-log	3-log
MS2	2.77	2.42
Q-beta	2.11	1.77
DMS	1.20	1.20

Because these validation factors are significantly lower than the maximum required by the current 40 mJ/cm^2 RED requirement, more efficient and sustainable operation of the UV unit could be achieved while still meeting and exceeding the federal regulations (i.e., the LT2). **Table II** details the power required to operate the Trojan UV unit at various flow rates for 3-log *Cryptosporidium* inactivation levels, and 91% UVT (the average historical Catskill/Delaware UVT), and the same end of lamp life conditions as the basis of design, which is 91 percent of the new lamp output.

Table II: Power required for 3-log *Cryptosporidium* Inactivation with Catskill/Delaware UV Unit

	Power Required per Unit (kW)			
Q (mgd)	MS2	QB	DMS	40 mJ/cm^2
20	14.53	12.30	9.93	17.34
40	21.02	17.79	14.36	29.98
60	31.19	26.39	17.82	41.85

Evaluation of UV Unit Capacity Impact on Capital Cost

The layout of the Catskill/Delaware UV Facility is based on a UV unit capacity of 40 mgd, resulting in a sizeable footprint and capital cost exceeding $1 billion. Theoretically, using higher capacity UV units would have resulted in a smaller footprint and a corresponding reduction in the capital cost. The theoretical UV unit treatment capacity was calculated based on MS2 and Q-beta validation data (**Table III**). Validation data from the Trojan unit shows that 3-log inactivation of Cryptosporidium can theoretically be achieved with flow rates of at least 80 mgd and 2-log inactivation can be achieved for flows well in excess of 90 mgd. These results are based on testing with Q-beta as the surrogate following the UVDGM procedures. A capacity of 60-mgd per unit would allow for a reduction to 10 units per module from the design of 14 units per module, resulting in a significant reduction in footprint from the current design.

Theoretically a capacity of at least 80 mgd can be achieved with the Trojan unit as configured while still maintaining greater than 3-log inactivation of Cryptosporidium, although validation testing has not been performed at this flow rate and would need to be conducted to achieve regulatory approval. This would allow for a reduction to 9 units per module and an even greater reduction in the footprint of the facility.

Even higher capacities could be achieved by using DMS as the validation surrogate. Table IV provides theoretical

Table III: Performance Characteristics of Catskill/Delaware UV Unit for MS2 and Q-beta Validation Surrogates

Flow (mgd)	Validated RED (mJ/cm^2)	MS2				Q-beta				Duty Units Required	Units per Module**	Headloss (in.)
		Validated Dose* (mJ/cm^2)		Validated: Regulated Dose Ratio†		Validated Dose* (mJ/cm^2)		Validated: Regulated Dose Ratio†				
		2-log	3-log	2-log	3-log	2-log	3-log	2-log	3-log			
40	42.5	15.3	17.6	2.75	1.28	20.1	24.0	3.46	2.00	51	14	14.5
50	34.2	12.3	14.1	2.13	1.03	16.2	19.3	2.79	1.61	41	12	21.2
60	**28.6**	**10.3**	**11.8**	**1.78**	**0.86**	**13.5**	**16.1**	**2.33**	1.34	**34**	**10**	**29.0**
70	24.6	8.9	10.2	1.53	0.74	11.6	13.9	2.01	1.16	29	9	38.0
80	21.6	7.8	8.9	1.34	0.65	10.2	12.2	1.76	1.02	26	8	48.2
90	19.3	7.0	8.0	1.20	0.58	9.1	10.9	1.57	0.91	23	7	59.7

* Validated dose = RED/VF; †Validated:Regulated Dose Ratio Values greater than 1.0 meet regulatory requirements

Table IV: Performance Characteristics of Catskill/Delaware UV Unit for DMS Validation Surrogate

Flow (mgd)	Validated RED (mJ/cm^2)	DMS				Duty Units Required	Headloss (in.)
		Validated Dose* (mJ/cm^2)		Validated: Regulated Dose Ratio†			
		2-log	3-log	2-log	3-log		
40	42.5	35.4	35.4	6.11	2.95	51	14.5
50	34.2	28.5	28.5	4.91	2.37	41	21.2
60	28.6	23.8	23.8	4.11	1.99	34	29.0
70	24.6	20.5	20.5	3.54	1.71	29	38.0
80	21.6	18.0	18.0	3.10	1.50	26	48.2
90	19.3	16.1	16.1	2.77	1.34	23	59.7
100	17.4	14.5	14.5	2.50	1.21	21	72.3
110	15.8	13.2	13.2	2.28	1.10	19	86.1
120	14.5	12.1	12.1	2.09	1.01	17	101.2
130	13.5	11.2	11.2	1.93	0.93	16	117.4
140	12.5	10.4	10.4	1.80	0.87	15	134.8

* Validated dose = RED/VF; †Validated:Regulated Dose Ratio Values greater than 1.0 meet regulatory requirements

treatment capacities of the UV unit based on extrapolation of the existing validation data.

Although the Trojan UV units could, theoretically, be rated for up to 120-mgd and still achieve 3-log inactivation credit, the headloss at flow rates higher than 50 mgd is substantial, exceeding the design criteria of 18 inches, and not feasible for Catskill/Delaware. As only 18-inches of head is available to be lost through the UV units at the maximum flow plant flow rate of 2,020-mgd; this headloss is equivalent to a flow rate of approximately 46 mgd through the Trojan UV unit. Therefore, only a minimal reduction in the number of UV units could be achieved. Furthermore, as with most UV facilities, the hydraulic elements of the facility, which enable water to flow to and from the UV equipment, represent the largest portion of the capital cost of a facility and more than 80% of the Catskill/Delaware facility capital costs. Therefore, significant capital cost savings would not be realized by increasing the capacity of the units.

The benefit of lower Validation Factors for the Catskill/Delaware UV Facility is that the operation of the UV units could be performed with fewer lamps on-line and therefore lower power consumption, thereby reducing operational costs as compared to the MS2 Validation Factors.

Evaluation of Validation Surrogate Impact on Catskill/Delaware UV Operations

Under the requirements of LT2 and the UVDGM, there is no prescribed minimum Validation Factor that the installed equipment must have. However, NYSDOH has currently imposed a minimum RED of 40 mJ/cm^2, which essentially requires that the Validation Factor for the Catskill/Delaware UV equipment be 3.33. The Catskill/Delaware equipment meets this requirement at the original design capacity of 40-mgd, but the lower Validation Factors that are allowed under the federal guidance would allow for significant reductions in the number of lamps required to achieve the Catskill/Delaware UV disinfection requirements and consequently a corresponding reduction in the power usage and UV unit consumables (e.g., ballasts, lamps, sleeves, sensors, etc.). Additionally, with fewer lamps required to achieve the required level of disinfection, the Facility could be operated with fewer UV units in service under many conditions, thereby requiring a lower number of UV units to be cleaned each month and reducing the volume of cleaning chemicals required. The reduction in power, consumables and cleaning chemicals will directly result in reduced operating costs and carbon footprint of the facility, thereby providing for a more sustainable operation of the Catskill/Delaware UV facility.

The power requirement, the number of UV units and lamps in operation and the associated operating costs were calculated based on the MS2, Q-beta and DMS using the UVDGM protocols, as well as the current 40 mJ/cm^2 requirement, in order to evaluate the impact of the validation surrogate on the Catskill/Delaware operations. Operating costs were developed based on expected average monthly plant flows and water quality for the initial year of operation (2012) and future operation (2045) (**Figure 2**). All costs are reported 2009 dollars.

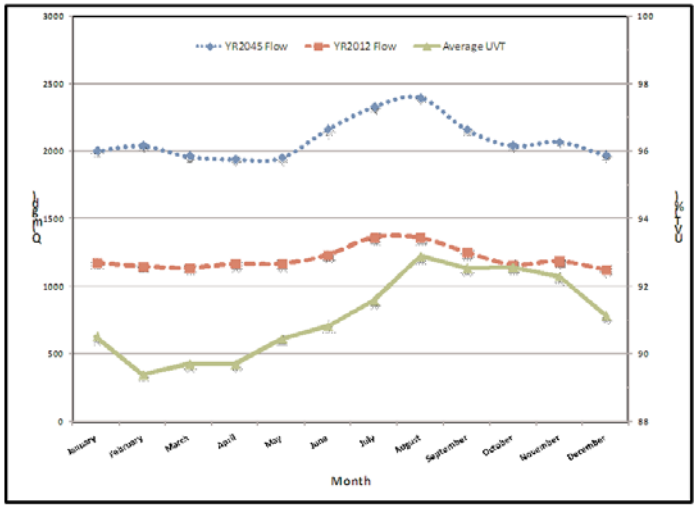

Figure 2: Average UVT and Flow Rates for Years 2012 and 2045

For the Catskill/Delaware facility, the requirement for using an RED of 40 mJ/cm^2 (based on MS2) in lieu of applying the USEPA recommended protocols will cost an additional $165,000 in electric power costs in the first year of operation alone. The costs savings would increase to $280,000 and $380,000 if Q-beta or DMS were used, respectively, and nearly double by the year 2045 (**Figure 5**). Although significant power savings could be achieved through use of one of the advanced surrogates, other

operational savings would be realized as well. As less power is required to achieve the required level of disinfection, fewer UV unit consumables such as lamps, sleeves and ballasts would be required. In addition, as fewer UV units would need to be on-line in order to achieve disinfection of the plant flow, cleaning of few reactors each month we need to be performed each month, thereby reducing the volume of cleaning chemical consumed. The estimated annual operating costs (including power) based on the

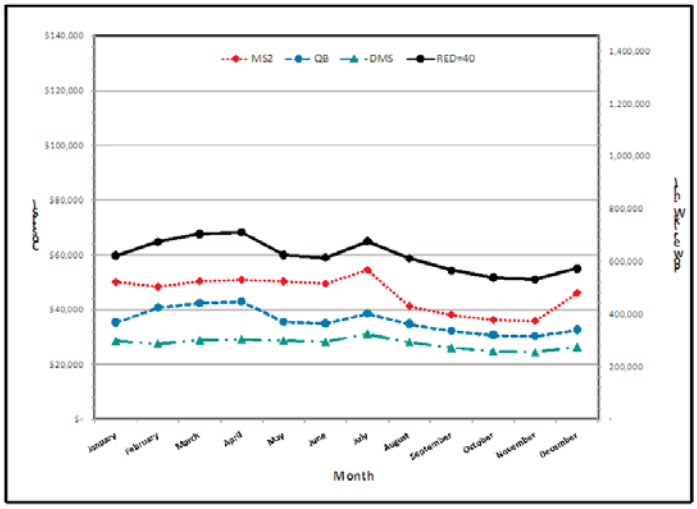

Figure 3: Monthly Power Costs for Various Surrogates – Year 2012 (in Year 2009 dollars)

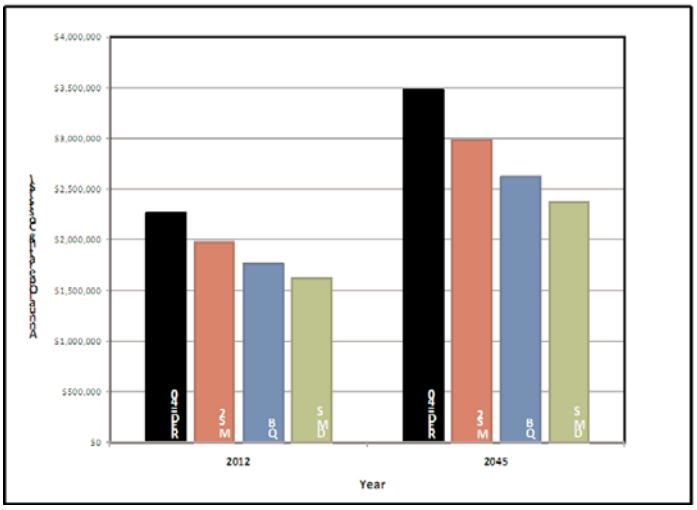

Figure 6: Annual Operating Costs (in Year 2009 dollars)

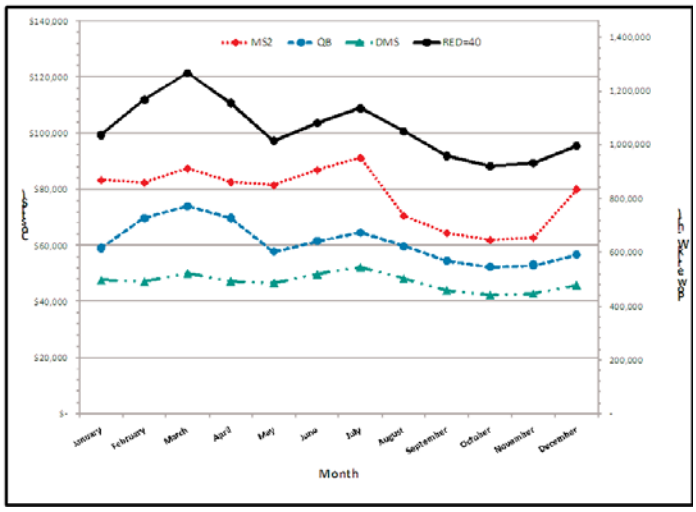

Figure 4: Monthly Power Costs for Various Surrogates – Year 2045 (in Year 2009 dollars)

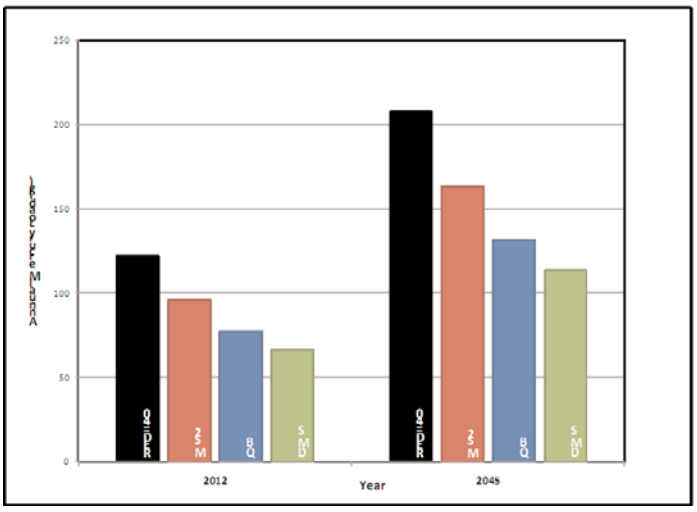

Figure 7: Annual Mercury Consumption)

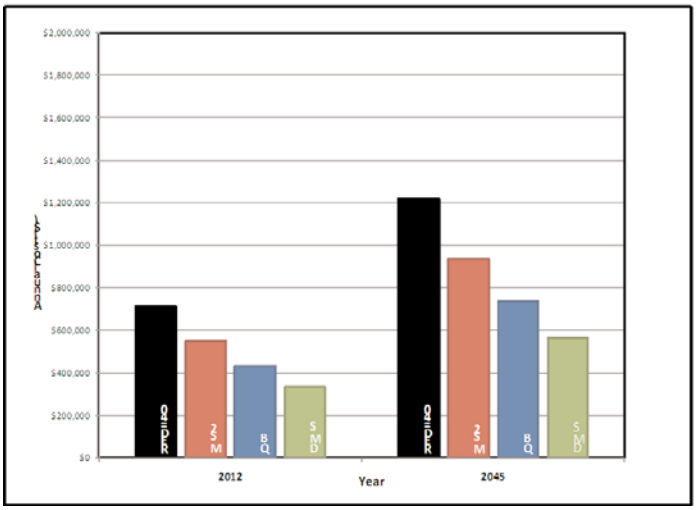

Figure 5: Annual Power Costs (in Year 2009 dollars)

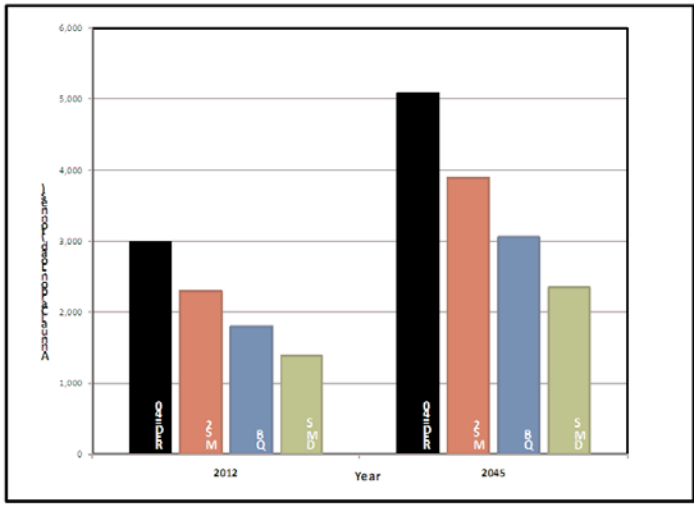

Figure 8: Annual Carbon Loading

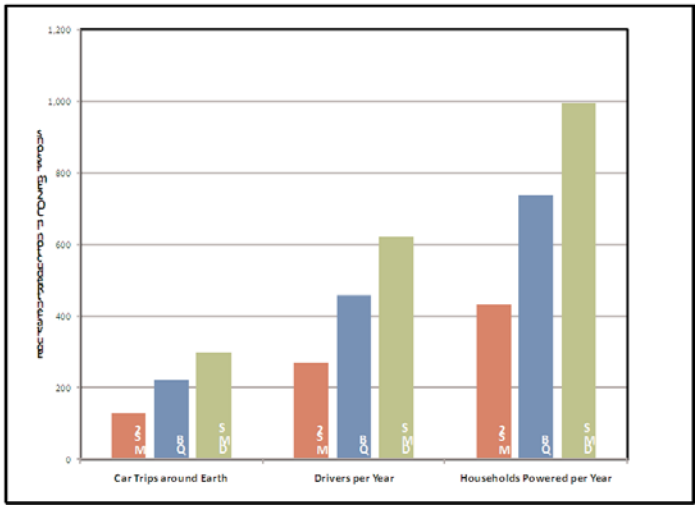

Figure 9: Annual Carbon Emissions Equivalents

various validation protocols are summarized in **Figure 6** for the initial year of operation (2012), as well as in the future (Year 2045).

An annual operating savings of at least $250,000 would be realized in the first year of operation by using the USEPA recommended protocols in lieu of the 40 mJ/cm2 requirement, even if MS2 was used as the surrogate. With dyed microspheres, the savings in the first year of operation would increase to over $600,000 and be over $1 million by the year 2045.

Although cost savings is a significant factor, the benefits to using the advanced surrogates go beyond simple economics. By reducing the power requirements for achieving full disinfection, significant reductions in the environmental and carbon footprint of the Catskill/Delaware facility can be achieved, without compromising public health in the slightest. The reduction in power requirements will reduce the number of lamps consumed by the facility. As the UV lamps contain mercury, reducing the number of lamps consumed will reduce the amount of mercury used in the facility (**Figure 7**). Reductions of between 21 and 45 percent can be achieved through use of the USEPA recommended guidelines instead of the required 40 mJ/cm^2 RED. By reducing the number of lamps used the potential for release of mercury into the environment through accidental lamp breakage would also be significantly reduced.

Although reducing the potential for mercury release will help the environment, the greatest impact on the environment that the use of advanced surrogates will have is through a reduction in the facility's carbon footprint (Figure 8). As shown above, the use of DMS will reduce the electrical power requirement of the facility by as much as 1.2 MW-hrs per year, which is enough electricity to power nearly 1,000 homes in New York State (**Figure 9**). This reduction in power use would have the same impact of carbon emissions in New York if 619 cars were to be removed from the roadways. The resulting carbon emissions that will be caused by the additional electricity required to power the Catskill/Delaware UV units based on a 40 mJ/cm^2 RED requirement compared to an RED based on MS2 or DMS is equivalent to driving a car around the earth 129 or 297 times every year, respectively

CONCLUSIONS

Significant advancements have been made in the understanding of UV disinfection validation testing surrogates over the past five years. Use of these advanced surrogates such as Q-beta or dyed microspheres would allow for a more sustainable operation of New York City's 2-bgd Catskill/Delaware UV Facility. Reduction in annual power usage would exceed 1.2 MW-hr, enough electricity to power nearly 1,000 homes, and save up to $1 million per year in operating costs. Furthermore, the use of these surrogates will have a positive impact to the environment by lowering the risk of mercury contamination, as well as the carbon footprint of the facility.

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