Finished water disinfection with UV light: Overview of validation studies at American Water

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ABSTRACT

Finished water disinfection using two commercial ultraviolet light reactors and flows between 1 MGD and 13 MGD was assessed by MS2 bacteriophage biodosimetry and confirmed using bench-scale studies. An optimized cell culture IFA procedure for measuring *Cryptosporidium* oocysts inactivation indicated >4 mJ cm^{-2} of UV light resulted in >4 log inactivation of oocysts. These inactivation levels were similar to those expected from mouse infectivity assays.

Initial operational problems were encountered with both UV reactors, but both functioned reliably after the start-up phase. Using biodosimtery, lower (10 to 20 mJ cm^{-2}) computer generated doses were more accurately predicted for one reactor than for the other, however, both reactors demonstrated a high correlation between computer predicted and biodosimetry confirmed doses at 40 mJ cm^{-2}.

No impact was observed on water characteristics or disinfection by products following disinfection. Cost analysis at 40 mJ cm^{-2} was estimated to be approximately $10 per million gallons.

UV disinfection appears reliable and cost-effective for safeguarding public health from transmission of waterborne cryptosporidiosis.

INTRODUCTION

The upcoming Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) will require systems that use surface water or Ground Water Under the Direct Influence of surface water to conduct source water monitoring to determine average *Cryptosporidium* levels (USEPA 2003b). Concentrations greater than 0.075 oocysts per L will lead to system categorization in one of three bins according to their concentrations and these systems will need to demonstrate total *Cryptosporidium* treatment greater than 5 logs. In selecting additional treatment barriers to reduce waterborne disease transmission with this parasite, the Stage 2 Disinfectants and Disinfection Byproduct Rule (DBPR), intended to reduce peak DBP concentrations in the distribution system, also need to be taken into consideration by water utilities. Increasing chlorine levels can increase the oxidation of organic/inorganic compounds in the treated water to produce disinfection byproducts that can be potentially carcinogenic. The LT2ESWTR and Stage 2 DBPR are to be promulgated together to address the risk-risk trade off between the byproducts formed by commonly used disinfectants and effective microbial disinfection.

In addition to numerous waterborne outbreaks of human cryptosporidiosis worldwide, a recent study conducted at American Water (Aboytes and LeChevallier 2002) demonstrated the overall risk of *Cryptosporidium* infection in conventionally treated drinking water was 1/193 infections/yr (80% credible range of 1/84 to 1/1,110 infections/year). These findings are of significant concern as they illustrate that conventionally treated drinking water can exceed the United States Environmental Protection Agency (USEPA) defined annual "reasonable risk" of 1/10,000 infections from drinking water. Interest in UV disinfection of drinking water in the US was limited until the findings reported by Bukhari et al. (1999) that low levels of UV light effectively inactivated *Cryptosporidium* oocysts. While these findings have been corroborated by numerous independent studies at the bench scale level, limited experience exists in the US with full-scale UV disinfection of finished water. Industry concerns have revolved around the reliability of UV technology. Additional issues include determination of the performance efficiency of the reactors, effects of water quality characteristics on lamp sleeve fouling, effectiveness and reliability of lamp cleaning mechanisms, UV measurement sensors' stability, costs associated with retrofitting UV systems into existing water treatment plants, operation and maintenance costs associated with employment of UV disinfection, impact of lamp aging on delivery of target UV doses and impact of UV on disinfection by product (DBPs) formation or degeneration. Presently the Stage 2 M-DBP Agreement recognizes UV technology to be feasible and available and the USEPA is in the process of developing a UV Disinfection Guidance Manual that includes guidelines for UV reactor validation to help water utilities implement this technology in their multi-barrier approach to safeguarding the consumer from the risk of waterborne human cryptosporidiosis.

American Water, part of RWE's water division- serves 20 million people in 27 states and 4 Canadian provinces, has conducted two full-scale UV disinfection studies, utilizing finished water from two geographically distinct American Water systems and two commercially available UV reactors.

While recent evidence has indicated cell culture to be a promising *in vitro* alternative to mouse infectivity for measuring *Cryptosporidium* oocyst inactivation (Rochelle et al. 2003), gaps continue to exist in understanding the applicability of this methodology and, as a result, adoption of these procedures has been slow. Different treatments are likely to involve different mechanisms for oocyst inactivation and the mechanism of inactivation may, in turn, influence the outcome of the infectivity analysis. Realization of this has created a need for *in vitro* infectivity assays to be specifically optimized for measuring inactivation following UV disinfection and studies to define a user-friendly *in vitro* infectivity protocol for determining inactivation of UV treated *C. parvum* oocysts were performed also at American Water.

In the full scale validation studies, the Sentinel™ UV reactor, manufactured by the Calgon Carbon Corporation, which contained four 1 kW medium pressure mercury lamps, with a maximum flow rate of 700 gpm was evaluated at the Pennsylvania-American Hays Mine plant, whereas the Trojan UVSwift™, which contained eight 9.4 kW medium pressure-high output mercury lamps and a capacity of treating up to 12.8 MGD, was evaluated at the Missouri-American Central plant. In both studies the reactor installation was as depicted in Figure 1. The objectives were to develop UV dose response curves to validate performance of each UV system with MS2 bacteriophage as a biodosimetry surrogate, determine operational and maintenance costs and identify various operational issues associated with installation/operation of the UV systems. In addition, various chemical compounds (trihalomethanes (THM), haloacetic acid (HAA), UV254, total organic carbon (TOC), metals, nitrate, and nitrite) pre and post UV disinfection were measured to establish the impact UV treatment had on disinfection byproduct formation. In order to confirm the actual dose being delivered by the reactors, MS2 bacteriophage inactivation levels were compared with bench-scale inactivation experiments under controlled experimental conditions.

IN VITRO INFECTIVITY FOR MEASURING INACTIVATION OF UV TREATED *C. PARVUM* OOCYSTS

An in vitro infectivity assay (DiGiovanni et al. 1999) was optimized, following examination of various excystation triggers, incubation conditions and detection protocols to enable analysis of UV treated *C. parvum* oocysts. The fact that UV treated oocysts can undergo excystation and the sporozoites from UV treated oocysts maintain the potential for invading monolayers of HCT-8 cells to generate pinpoints of invasion was taken into to consideration to judicially select immunofluorescence based microscopy for quantification of infectivity. It was noted that spontaneous excystation by UV inactivated oocysts resulted in an errant signal being generated by certain molecular detection procedures such as the procedure described by DiGiovanni et al. (1999). In this particular case, the HSP 70 primers used in the cell culture-quantitative PCR assay were unable to discriminate between DNA originating from invasive sporozoites and infectious sporozoites. The optimized cell culture-IFA procedure developed in our laboratory enabled detection of less than 10 infectious oocysts.

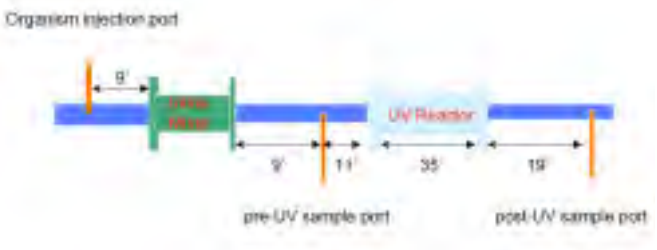

Figure 1: Diagrammatic layout of installed UV reactor

Using this optimized cell culture-IFA procedure in bench scale studies and application of a UV dose of 1 mJ cm^{-2} rendered 0.44 log inactivation of oocysts. Delivery of UV doses between 1 and 4 mJ cm^{-2} yielded a linear increase in oocyst inactivation, with 3 mJ cm^{-2} rendering 2.79-2.84 logs inactivation and 4-log inactivation occurring at 4 mJ cm^{-2}. Between 4 and 20 mJ cm^{-2}, measurements with the cell culture procedure continued to indicate that oocyst inactivation levels were greater than 4 logs (Figure 2).

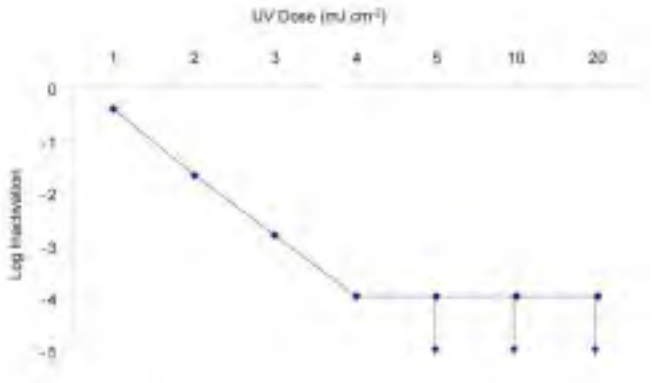

Figure 2: Inactivation of *C. parvum* oocysts with UV light, as determined by the cell culture-IFA procedure

Where these inactivation data could be compared with previously published data, using either tissue culture infectivity or mouse infectivity assays, an excellent agreement was observed (Figure 3). Numerous studies (Clancy et al. 2000; Craik et al. 2000; Landis et al. 2000; Shin et al. 2001; Clancy et al. 2004) have assessed levels of oocyst inactivation delivering UV doses ranging between 1 and <40 mJ cm^{-2}. Some variability exists in the data generated from these various studies, which may be associated with differences in oocyst preparation, disinfection conditions, and methods for infectivity measurements. Nonetheless, using UV doses between 1 and 3 mJ cm^{-2}, the oocysts inactivation data generated in American Water studies were within the range of inactivation data generated in the previous studies. The draft UV guidance manual (USEPA 2003a) indicates that 2.5 log or 3 log inactivation of *Cryptosporidium* would require a UV dose of 8.5 mJ cm^{-2} and 12 mJ cm^{-2} respectively, which appears to contain an approximate 3 to 4-fold safety factor based on the *C. parvum* inactivation data developed with the cell culture-IFA data described here. Additional safety factors related to validation and monitoring uncertainties increase the target Reduction Equivalent Dose to 28 mJ cm^{-2} and 36

mJ cm^{-2} for 2.5 log or 3 log inactivation, respectively, increasing the overall safety factor to ten-fold.

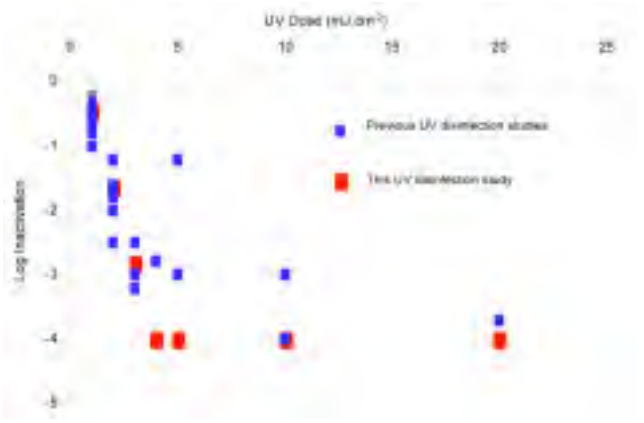

Figure 3: Inactivation of *C. parvum* oocysts with UV light, as determined by Infectivity

Currently American Water is collaborating with the USEPA and United Kingdom Water Industry Research Limited (UKWIR) to validate the cell culture-IFA procedure in "blind" trials to identify an alternative to mouse infectivity assays for measuring *C. parvum* oocysts inactivation following UV treatment. A positive outcome of these blind trials will be a tremendous asset for both American Water and the water industry as it would enable bench scale evaluation of oocyst inactivation using the same water matrix and target UV doses as those intended for full-scale validation using biodosimetry surrogate organisms.

FULL SCALE VALIDATION OF UV REACTORS

During the full-scale biodosimetry experiments conducted in Hays Mine, the target UV doses were achieved by selection of lamp configurations based on their pre-calibrated sensor readings as well as the computational fluid dynamics models used by the manufacturer. Lamps of operational age between 16 h and 5,800 h were used and the MS2 bacteriophage inactivation data for a given target UV dose were very similar irrespective of lamp operation time. Continuous operation of the reactor for up to 5,800 h did not demonstrate deterioration in the performance of the lamp cleaning mechanisms. The correlation between the full scale and bench scale log inactivation values was greatest at 40 mJ cm^{-2}; however, an increasing divergence in log inactivation values occurred between full and bench scale studies when the target UV dose values were reduced to 20 mJ cm^{-2} or 10 mJ cm^{-2} (Figure 4). At both of these lower UV doses, the levels of inactivation were higher in the full-scale studies compared to the bench scale studies. In the bench scale studies, both 10 mJ cm^{-2} and 20 mJ cm^{-2} demonstrated excellent reproducibility in organism inactivation, which confirms that the inactivation data were reliable and the full scale unit actually delivered higher UV doses when targeting low UV doses (i.e., 10 mJ cm^{-2} or 20 mJ cm^{-2}). In contrast to this, the St. Louis study utilized an algorithm in a UV Dosimeter™ to determine the applied UV dose and demonstrated a considerably improved prediction of the applied UV dose irrespective of whether the UV reactor was operated in an 8 lamp or 4 lamp configuration at UV doses from 10 to 60 mJ cm^{-2} (Figure 4) and flow rates of 4 or 13 MGD. The manufacturer of the latter full-scale UV reactor has factored MS2 bacteriophage biodosimetry data in their UV Dosimeter™ for optimizing the accuracy of the predicted UV doses. While the USEPA draft Guidance Manual contains provisions for validation of reactors that use different methods for predicting the applied UV dose (i.e., intensity measurements or dose algorithms), from a utility perspective it may be prudent to scrutinize the UV dose calculation procedures utilized in the test UV reactors in order to select reactors with the most robust procedure for determination of the applied UV dose. This will make it convenient for operators to ensure the regulatory standard for UV disinfection of finished water are being met reliably and will also allow fine adjustments of the applied UV dose (in response to changing water characteristics) to ensure optimal cost effectiveness during normal operation.

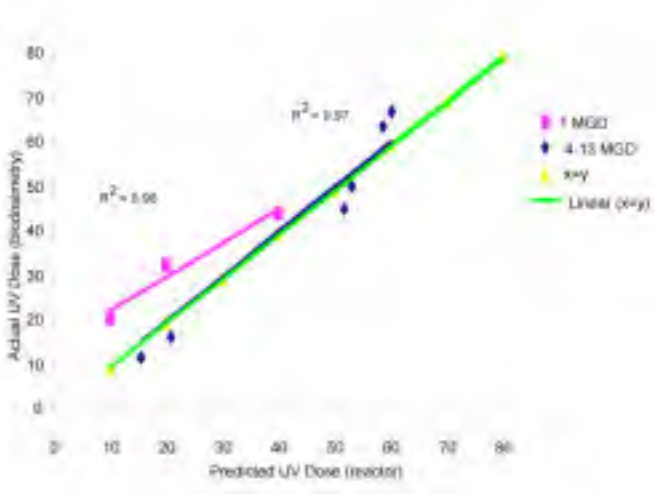

Figure 4: Verification of UV doses by MS 2 bacteriophage biodosimetry

IMPACT OF UV ON WATER QUALITY

In both the Hays Mine and St. Louis studies, total THM and HAA were examined for both the finished water influent to the reactor as well as the effluent from the UV reactor. These data indicated that disinfection by-product (DBP) values were below their respective maximum contaminant limit (MCL), but most importantly demonstrated that employment of UV disinfection did not alter existing DBP levels in the waters tested (Table 1).

Table 1: Chemical parameters at Pennsylvania-American Hays Mine plant

Compound	Pre-UV	Post-UV	MCL
THM (μg.L^{-1})	67.2	66.6	80
HAA (μg.L^{-1})	<5.0	<5.0	60
Nitrates (mg.L^{-1})	<1.0	<1.0	10
Nitrites (mg.L^{-1})	ND	ND	1

These data, which substantiate earlier findings, indicated that application of UV disinfection would be beneficial for utilities with recurring DBP issues in their finished water, where employment of UV disinfection would afford the utility an opportunity to reduce levels of existing chemical disinfectants. In this manner, the desirable disinfection credit for protozoan parasites could be attained using UV light, whereas the lowered levels of the chemical disinfectant would provide the benefit of reduced DBP formation. An additional benefit of using more than one disinfectant is their potential synergism for organism inactivation. That is, the level of inactivation achieved being greater than that obtained with using each disinfectant alone. Limited data on synergistic effects of UV light and various chemical disinfectants are available presently (Ballester and Malley 2003); however, usage of combined (or sequential) disinfectants seems rational primarily because UV disinfection occurs instantaneously and does not contribute a residual in the treated water. Absence of disinfectant residual can result in growth of biofilms within the distribution system (LeChevallier et al. 1996; Camper et al. 2000), in turn presenting a potential public health risk from regrowth of biofilm entrapped pathogens (i.e., *Legionella*, *Mycobacterium*). In addition, there is evidence to suggest that UV treated bacteria may be capable of repairing UV damaged DNA by employing dark or light repair processes (Oguma et al. 2001; Zimmer and Slawson 2002). Computational fluid dynamics modeling also indicates that the actual UV dose delivered to individual organisms passing through a UV reactor can vary (i.e. due to distance of organisms from UV lamps or organism velocity through the reactor). In order to reduce the likelihood of organisms damaged with low levels of UV light from undergoing various repair phenomena, use of a secondary chemical disinfectant (i.e., chlorine, chlorine dioxide, chloramines, ozone, ozone/peroxide) would oxidatively inactivate the organisms damaged by low levels of UV as well as oxidize organic and inorganic compounds thus depleting the nutrients that could favor organism regrowth (Solomon et al. 1998).

UV OPERATIONAL ISSUES

Both the Hays Mine and St. Louis studies accrued information on the reliability and cost effectiveness of employing UV disinfection. UV reactors from two different manufacturers demonstrated their own specific operational issues, with majority of these being minor. These issues were resolved easily by replacing or repairing faulty components (fuses, reed switch, sleeve bolts, home switch and magnet) or by performing simple corrective actions (i.e. relocation of turbidimeters on plant effluents to improve access to the mercury lamps and quartz sleeves).

The most significant problem with the reactor at Hays Mine was the malfunctioning of the third party compressor used to drive the hydraulics on the lamp cleaning mechanism. In the St. Louis study the lamp cleaning assembly was also the source of the problem; however in this case it was due to a design flaw, which was subsequently corrected by the manufacturer. The replacement prototype wiper assembly functioned without additional operational problems. In both studies, correction of the problems experienced during the commissioning and start-up phase was followed by normal operation requiring minimal maintenance.

Both these studies were of a short duration (<12 months) and the US water industry currently lacks experience with long-term application of UV technology. Information will need to be gathered on various factors including frequency of parts replacement and longevity of UV reactors to fully understand the reliability of this technology. While gaps may still exist in our knowledge on the reliability of long-term application of UV technology, validation trials performed by American Water indicate this technology has the potential to meet the microbial disinfection needs required by state and federal regulatory agencies. In order to achieve this, the UV reactors will require either onsite or off site validation using USEPA guidelines (USEPA 2003a). Usually these validation trials can be performed in concert with the reactor manufacturer, who can assist utilities to troubleshoot operational issues during the commissioning phase and help to develop an experimental design for the validation studies.

ESTIMATED COSTS OF UV DISINFECTION

American Water has performed capital cost analysis in a study reported by Hubel et al. (2001). Using medium pressure UV reactor costs from one vendor and a nominal dose of 40 mJ cm^{-2}, detailed take-off construction contract cost estimates were prepared and also accounted for earthwork, concrete, masonry, other building elements, pipe, valves, mechanical equipment, process equipment and electrical work including supplemental instrumentation. Capital costs were estimated for 78 American Water plants to be $5,000,000 (for 5 MGD systems) with economies of scale affecting the cost of higher and lower capacity plants. For a given target UV dose, it is important to optimize flow rate to make the disinfection process cost effective with respect to power consumption. The treatment plant needs to consider both the plant production capacity and the degree of reactor redundancy required (to allow for off spec time during routine maintenance) when selecting UV reactors for use in treating finished water. In the St. Louis study (8L24 Trojan UVSwift™ reactor), using power consumption and lamp replacement data and operating lamps at 70% power (to simulate ageing), the daily costs for power and lamp replacement were estimated to be $99 per day, which would enable a maximum flow rate of 10.2 MGD at a target a dose of 40 mJ cm^{-2}. Based on these estimates, a cost of $9.70 per MG was determined for 8L24 Trojan UVSwift™, which compared well to the cost estimates of $17.40 per MG generated for the Catskill and Delaware study where approximately two times greater capacity reactor was used (Valade et al., 2003). Similarly the data in the St. Louis study compared favorably with the operational and maintenance (O&M) cost estimates generated in an earlier study (Cotton et al. 2001) This study utilized annual costs for lamp replacement, sensor calibration, maintaining inventory of spare parts and cleaning chemicals/ cleaning activities for non-automated systems as well as power consumption and indicated a range between $5.90 - $16.60 per MG for a medium sized (average flow 13 MGD) systems. The O&M

costs increased with reducing flow rates and/or poorer water quality characteristics and were calculated to range from $7.20 to $18.70 per MG at an average flow rate of 8.8 MGD (Cotton et al. 2001).

Data from the American Water Hays Mine study indicated that increasing hours of lamp operation resulted in an associated increase in power consumption costs with lamp operation times between 2,200 h and 3,000 h increasing in power consumption costs by 67% compared to lamps operating at <2,200 h. Further studies are required to compare these power consumption costs with lamp replacement costs to determine optimal time for lamp replacements.

In conclusion, inactivation of waterborne *Cryptosporidium* oocysts and reduction of DBPs have been significant challenges for the water industry for almost two decades. Employing UV disinfection can be a reliable and cost-effective means for the water industry to attain a realistic potential to safe guarding public health from transmission of waterborne protozoan parasites, particularly human cryptosporidiosis.

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