Cryptosporidium Risk Analysis and UV Disinfection System Reliability

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ABSTRACT

Databases on *Cryptosporidium* occurrence in filtered surface water supplies can be used to estimate the benefit of providing UV disinfection and the consequences of an interruption of the UV disinfection system operation. Calculations show that a conventional treatment plant could operate without UV disinfection for 7 days per year (or an average of 14 hours per month) before exceeding the 1/10,000 annual risk of *Cryptosporidium* infection. However, the down time would be limited to only 3.67 hours per month during the spring months, when *Cryptosporidium* levels are the highest. The results demonstrate that UV disinfection systems can be brought back on-line within a practical time frame (i.e., several hours) after a power outage or equipment malfunction and that brief interruptions of a UV disinfection system would not create an unacceptable risk assuming continued operation of an upstream conventional treatment process. A similar approach was used to estimate the limits of operation when a UV system was performing outside of its validated operating criteria, and for unfiltered water systems. Although data are limited, and additional data are needed to refine the analysis, the study concludes that continuous operation of UV systems is not needed to achieve acceptable risk goals and that extra-ordinary measures to increase UV disinfection system reliability (e.g., provision of UPS) provide marginal benefit provided a backup power source is available.

INTRODUCTION

Ultraviolet disinfection is expected to be used by a significant number of water utilities to reduce the risk of *Cryptosporidium* infection, especially since the USEPA has published draft guidance on its application (USEPA 2003b) and proposed regulations requiring additional *Cryptosporidium* treatment (USEPA 2003a). The Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) has a goal of reducing the annual risk due to *Cryptosporidium* in treated drinking water to a level of less than 1 infection in 10,000 people per year.

Off-specification operation of a UV disinfection system occurs when any of the critical operating parameters (e.g., flow rate) is outside of the range of conditions used to validate the performance of the reactor. Downtime is when the operation of a UV disinfection system is interrupted (e.g., power failure) while water still is flowing through the reactor. In the USEPA draft UV Disinfection Guidance Manual (UVDGM, USEPA 2003b) downtime is considered a subset of off-specification operation. The proposed LT2ESWTR requires that for unfiltered surface water supplies, at least 95% of the monthly flow into the point of entry (POE) of the drinking water system undergo UV disinfection within the range of validated conditions. Unfiltered systems would need to apply UV doses sufficient to inactivate 2 or 3 logs of *Cryptosporidium* oocysts, depending on the source water quality. Therefore, assuming constant flow, unfiltered water system UV reactors could be out of service, bypassed or operate “out of specification” (beyond their validated conditions) for 36 hours per month.

The basis for the “out of service” or “out of specification” criteria for UV performance for unfiltered systems was designed to be similar to the requirements for Giardia and virus inactivation as specified by the Surface Water Treatment Rule (USEPA 1989). However the impact of this specification on meeting the 1/10,000 infection goal is not clear, because if source water *Cryptosporidium* risks are greater than 1/100 infections/year, treatment of 95% of the water would not be adequate. Recently LeChevallier et al. (2003) reported the risk of infectious *Cryptosporidium* in an unfiltered source water ranged between 1/42 to 1/95 infections per year, depending on the method of analysis.

The LT2ESWTR addresses filtered water supplies very differently by suggesting that primacy agency (States) define the “out of service and “out of specification” limits. A concern is that without additional guidance or information, some States may impose more stringent limits for filtered water supplies than for unfiltered water supplies. Again, using the Surface Water Treatment Rule as a model (USEPA 1989), which requires continuous disinfection of filtered drinking water, States would be inclined to require application of continuous UV disinfection.

Because UV disinfection system performance is highly dependant on power quality, water quality, flow rate, and other operational parameters (Cotton et al. 2003), the occurrence of “out of service” and “out of specification” conditions is expected in real world applications. Additional redundancy and uninterruptible power supplies can be provided to increase the overall reliability of UV disinfection systems, but increase the cost by 10% or more. For 78 American Water surface water supplies, this would represent a capital cost increase of $25 million (Hubel 2001).

The USEPA accepted public comment on the proposed LT2ESWTR and the UVDGM through January 9, 2004. The final LT2ESWTR and UVDGM are expected in 2005. Lacking in the discussions was the consideration of the current level of *Cryptosporidium* removal via conventional treatment and the risk consequences of UV disinfection system failure. This paper examines the risk of *Cryptosporidium* infection in filtered and unfiltered surface water supply systems, and estimates the amount of time UV systems can be out of service before acceptable risk levels are exceeded. Using several *Cryptosporidium* databases, it is shown that UV systems can be out of service for certain periods of time without an unacceptable increase in risk.

RISK OF INFECTION

As developed by the National Academy of Sciences, risk analysis is dependent on the three basic elements: hazard identification, exposure assessment, and risk assessment. Several risk assessments of *Cryptosporidium* in drinking water have been performed (Perz et al. 1998; Fewtrell et al. 2001; Messner et al. 2001). The hazard identification for *Cryptosporidium* is complicated because data on the occurrence of the organism in water frequently lack species or genotype characterization. In addition, until recently, data were lacking on the viability and infectivity of waterborne isolates. Data on drinking water exposure assessment have most commonly used source water studies and adjusted the data with estimates of treatment efficacy. These assumptions resulted in broad-range estimates of occurrence in finished drinking water supplies. Human dose-response data necessary to determine a risk assessment have been gathered for three *C. parvum* bovine genotype isolates, and a Meta analysis of the data has been completed (Messner et al. 2001) to calculate the infectious dose for an unknown isolate (Table 1). The resulting risk of infection has ranged from 5% for strain TAMU to 0.04% for strain UCP (Table 1). Meta analysis of the data has estimated the risk of infection from an unknown *Cryptosporidium* isolate to be 2.8%.

Table 1. Summary of the Risk of Infection from Ingestion of One Oocyst*

Risk of Infection from One Oocyst

Isolate	Mean	80% Credible Interval
Iowa	0.0053	0.0034 to 0.0074
TAMU	0.048	0.022 to 0.081
UCP	0.00038	0.00023 to 0.00055
Mix of all three	0.018	0.009 to 0.029
Unknown Isolate	0.028	0.005 to 0.066

*Based on human feeding studies from Messner et al. 2001

To determine the concentration of infectious oocysts in water, the number of oocysts must be adjusted for the recovery efficiency of the detection technique. To calculate the daily risk of infection from *Cryptosporidium*, the volume of drinking water consumed daily (1.2 L/ day) is multiplied by the concentration of oocysts, times the risk of infection from a single oocyst:

$$\text{Daily Risk} = 1.2\ \text{L / day} * \text{oocysts / L} * 0.028\ \text{infections / oocyst}$$

The annual risk is determined by:

$$\text{Annual Risk} = 1 - (1 - \text{DR})^{350}$$

The factor of 350 accounts for days when water is consumed from other sources. The USEPA is using these analyses as the basis for its risk assessments in the pending LT2ESWTR. The Agency has established an annual acceptable risk of microbial infection in drinking water at 10^{-4} infections per person (Regli et al. 1999). To achieve a $<10^{-4}$ infection per person per year level, infectious *Cryptosporidium* oocysts would have to be absent in 290,000 L ($<3 \times 10^{-6}$ / L) of drinking water (assuming a 40% recovery efficiency).

CRYPTOSPORIDIUM OOCYST OCCURRENCE IN WATER SUPPLIES

Numerous studies have demonstrated that surface water supplies are frequently contaminated with *Cryptosporidium* oocysts (LeChevallier and Norton 1995; McTigue et al. 1998; Di Giovanni et al. 1999; Connell et al. 2000; LeChevallier et al. 2002). The Information Collection Rule and the accompanying Supplemental Survey provided one of the largest studies of *Cryptosporidium* oocysts in surface water sources. A Bayesian analysis of the resulting data showed a median (50th percentile) concentration of 0.02 oocysts per liter (Connell et al. 2000).

A number of studies have examined the occurrence of *Cryptosporidium* oocysts in filtered drinking water (Table 2). Detection frequencies ranged from 10% to 40%. All these studies were conducted using the IFA method, so the occurrence of infectious oocysts is not known. LeChevallier and Norton (1995) reported detecting *Cryptosporidium* oocysts in approximately half of the 71 surface water treatment plants sampled with an average of 0.033 oocysts/L for positive samples. McTigue et al. (1998) examined 100 surface water treatment plants and detected *Cryptosporidium* in 15% of the systems at a median concentration of 0.0006 oocysts/L for positive samples[MLC2]. In one of the most detailed studies to date, the United Kingdom Drinking Water Inspectorate requirement for daily testing of 1000 L plant effluent samples by water utilities vulnerable to source water revealed that *Cryptosporidium* were detected in 70% of the systems in the range of 0.1 - 1 oocysts/100 L. (DWI 2002). When data are combined for multiple years, 84% of the 207 tested systems detected some oocysts, and two-thirds of the detected oocyst concentrations were between 0.001 and 0.01/L (personal communication, DWI 2003). The median number of occasions when *Cryptosporidium* was detected was 7 (mean 29 times).

Other variables in Table 2 include the variety of treatment processes and range of treatment conditions for the different studies, although all of the samples were taken from filtered water systems. Although there is ample evidence that low levels of *Cryptosporidium* oocysts can occur in drinking water, one problem with these databases is that the immunofluorescence (IFA) method does not indicate the viability or infectivity of oocysts in drinking water. Cell culture methods have been developed that can detect infectious oocysts in water (Di Giovanni et al. 1999; Rochelle et al. 1997; Slifko et al.

1997). Di Giovanni et al. (1999) detected infective oocysts in 6 of 25 (24%) source water sites and in 6 of 122 (4.9%) source water samples. LeChevallier et al. (2002) detected infective oocysts in 22 of 560 (3.9%) source water samples. By comparing cell culture and IFA results, both studies have estimated that 37% of the source water oocysts were infectious (Di Giovanni et al. 1999; LeChevallier et al. 2002; LeChevallier et al. 2003). The occurrence of oocysts had a bimodal seasonal occurrence, with detection frequencies highest in the fall and spring.

Table 2. Detection of *Cryptosporidium* parvum in finished water by immunofluorescence (IFA)

% Positive	Oocysts Level Range (100 L)	Study
26.8	0.13-48	LeChevallier et al., 1991
17.0	0.5-1.7	Rose et al., 1991
36.7	1-4.1	LeChevallier and Norton, 1992
13.4	0.29-57	LeChevallier and Norton, 1995
15	0.04-0.80	McTigue et al., 1998
1	40*	Solo-Gabrielle et al., 1998
46.2	22.1**	Hsu, et al. 2001
9.1	0.1-15	Rouse M. 2001, DWI 2001
3.28	0.1 - 1	DWI, 2002
35.0	0.05-0.8	Hashimoto et al., 2002

* Maximum value.
** Mean value

The study by Di Giovanni et al. (1999) was informative because it also examined spent filter backwash samples by the cell culture and polymerase chain reaction (CC-PCR) method. A total of 9 of 121 (7.4%) samples were positive for infectious oocysts. These data were significant because they were the first to demonstrate that live *Cryptosporidium* oocysts were penetrating the treatment process, at least up to the filters. The authors speculated that there existed a possibility that some of these oocysts could breakthrough the filters and enter the finished water.

American Water conducted studies of filtered drinking water using the CC-PCR technique to detect live, infectious *Cryptosporidium* in finished drinking water (Aboytes and LeChevallier 2003). To determine the concentration of live *Cryptosporidium* in drinking water, the number of positive samples (24) was divided by the total volume analyzed (169,000 L) and was adjusted for the recovery efficiency (32.3%). The daily risk of infection was determined by multiplying the average concentration of oocysts (0.00044 oocysts/L) times the average daily volume of water consumed (1.2 L) and the risk of infection from a single oocyst (0.028 infections/oocyst). The daily risk of *Cryptosporidium* infection was determined to be 1.5×10^{-5} infections/day, which translates into an annual risk of 1 infection in 193 years (80% credible interval of 1 infection in 84 to 1,110 years) as presented in Table 3.

Because there was a strong seasonal distribution of the *Cryptosporidium* occurrence in drinking water, similar calculations were made for monthly data. The highest monthly risk was in April, when the *Cryptosporidium* daily risk was 5.52×10^{-5} or annualized to 1/50 infection per year (Figure 1). These results correspond to a recently completed AwwaRF study of raw water samples that also showed more infectious *Cryptosporidium* during the spring (LeChevallier et al. 2002). Reasons for the seasonal occurrence may be due to environmental factors (increased rainfall or snow melt), source water occurrence, or a greater degree of oocysts passage through the treatment barriers due to changes in water temperature. An example of a seasonal phenomenon has been reported for rapid sand filters, where oocyst breakthrough increased when water temperatures were lower than 15°C and was associated with a decrease in the efficiency of particle removal (Hashimoto et al. 2002).

Table 3. Risk of *Cryptosporidium* Infection from Conventionally Treated Drinking Water

Factors and Assumptions
24 positives of 1,690 100-L samples
Assume 1 oocyst per positive sample
Recovery efficiency by Method 1622 = 32.3%

Estimated concentration (C) of oocysts in finished water
C = (Positives/total samples) (1/recovery efficiency)
C = (24/169,000) (1/0.323)
C = 4.4×10^{-4}

Daily Risk (DR) = (1.2 L/day) (C) (infection index for unknown strain)

DR = (1.2) (0.00044) (0.028)
DR = 1.5×10^{-5} infections

Annual Risk (AR) = 1 – (1 – DR)350
AR = 1 – [1 – (1.5×10^{-5})350]
AR = 1 – (1 – 0.0053)
AR = 1 – (0.995)
AR = 0.005 infections/yr (range 0.012 to 0.0009)
AR = 1/193 infections/yr (range 1/84 to 1/1,110)

From Aboytes and LeChevallier (2003).

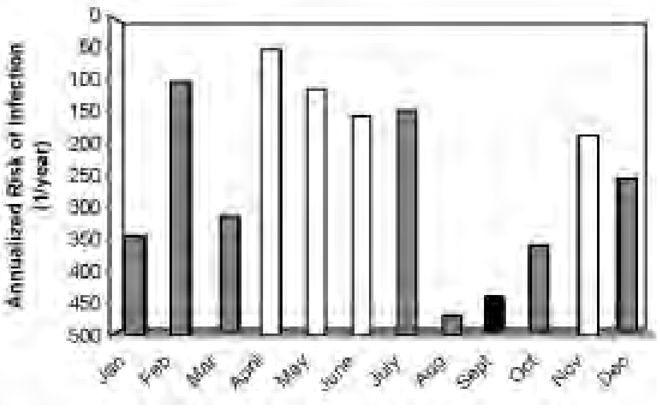

Figure 1. Distribution of *Cryptosporidium* Risk by Month. Dark shaded bars represent the limit of risk detection (e.g., no oocysts were detected). From Aboytes and LeChevallier (2003).

UV DISINFECTION SYSTEM RELIABILITY ASSESSMENT

Once the concentration of infectious *Cryptosporidium* is estimated in filtered drinking water the benefit of additional treatment, such as UV disinfection, can be assessed. Equally, the consequence of a failure of the UV treatment system can be determined. For example, using the range of oocyst concentrations observed in the UK monitoring (0.001 to 0.01/L), the annual risk of infection is between 1/100 to 1/10 (assuming 40% recovery and 37% infectivity). Should UV disinfection be implemented in these systems, a UV dose (fluence) >12 mJ/cm^2 (plus any added safety factors) would result in an additional >3 logs of inactivation (USEPA 2003a), reducing the risk to >10^{-4} to >10^{-5} annual risk of *Cryptosporidium* infection.

The relationship between UV disinfection system down time and *Cryptosporidium* inactivation credit was debated during the public comment period for the USEPA UVDGM. For the purpose of this analysis, it is assumed that UV disinfection systems operating under validated conditions achieve 2 log inactivation, and so are able to achieve the 10^{-4} annual risk goal, while no protection is provided when the UV unit is off-line (with water still flowing). Monthly down time then is limited to not more than 0.6 to 6.4 hours (Table 4), and the UV disinfection system would have to function under validated conditions 99% to 99.9% of the time, respectively, to maintain an overall 10^{-4} annual risk of infection with the UK data (Table 4).

Table 4. Permissible UV disinfection system down time before annual risk of *Cryptosporidium* infection exceeds 1/10,000 assuming conventional treatment upstream

Study	% Positive	Oocyst level (per 100 L)	Daily risk of infection	UV disinfection system down time[1]
DWI, 2002	3.28	0.1	0.000031[2]	6.4
		1.0	0.00031[2]	0.64
American Water	1.4	0.044	0.000015	13.3
	5.3[3]	0.16	0.000055	3.6

[1] Hours/month to exceed 1/10,000 annual risk assuming conventional treatment upstream and monthly reporting requirement.

[2] Values are adjusted for an estimated 40% recovery efficiency and 37% infectivity rate.

[3] Data for highest monthly (April) occurrence.

The UK monitoring data represent higher than normal risk because only those water systems that are deemed vulnerable to *Cryptosporidium* contamination are required to monitor. In addition, the upper range of oocyst occurrence (bracketed between 0.1 and 1.0 oocysts/100 L) was used in the risk calculation. Detailed data on individual *Cryptosporidium* samples were not available, but it is expected that these data would result in a lower annual risk of infection, and a higher acceptable down time for UV disinfection.

Using the database of infectious *Cryptosporidium* developed by American Water, similar calculations show that a conventional treatment plant could operate without UV disinfection for 7 days per year (or an average of 14 h per month) before exceeding the 1/10,000 annual risk level. However, the down time would be limited to only 3.67 hours per month during the spring months, when *Cryptosporidium* levels are highest.

UV disinfection systems can be brought back on-line within a practical time frame (i.e., several hours) after a power outage or equipment malfunction without an unacceptable risk increase. Brief interruptions of a UV disinfection system caused by power quality excursions (Cotton et al. 2003) would not create an unacceptable risk assuming continued operation of an upstream conventional treatment process. For example, power supply interruptions causing a UV disinfection system to shut down for 10-15 minutes would not significantly increase risk assuming the interruptions are relatively infrequent. Stand-by power would be needed for longer interruptions.

OUT OF SPECIFICATION PERFORMANCE

A similar approach could be used to estimate the limits of operation when a UV system is performing outside of its validated operating criteria. These "out of specification" parameters could include excursions in flow rate, UV transmittance, power quality, sensor calibration, etc. Because the causes for these "out of specification" parameters are variable, and data are not currently available to determine the magnitude of effect of these parameters on *Cryptosporidium* inactivation, some assumptions were made to determine acceptable risk limits. These assumptions can be revised as additional data become available.

It is assumed that the cause of "out of specification" performance does not result in total failure of the UV system (otherwise the value would be the same as down time). Under these conditions it is assumed that the UV disinfection system still delivers at least 1 log of *Cryptosporidium* inactivation. In this case, the risk calculations in Table 4 can be shifted by a factor of 10, and the acceptable "out of specification" time could be increased 10-fold. This would mean that UV disinfection systems should not operate "out of specification" for more than 69 days per year, on average, or more than 37 h per month during times of highest risk (spring) assuming conventional treatment upstream.

Additional data are needed to refine this analysis, but the assumption of 1 log of *Cryptosporidium* inactivation is reasonable considering research demonstrating oocysts to be highly sensitive to low UV doses. The UVDGM reported that a 1 log *Cryptosporidium* inactivation was achieved at 2.5 mJ cm^{-2} in bench-scale studies (USEPA 2003b). It is reasonable therefore that some level of oocyst inactivation would be achieved if a UV reactor was functional, even though it was operating "out of specification." Research studies should be performed to compare "out of specification" conditions (UV transmittance, flow rate, lamp age, power, etc.) to optimal performance to determine the degree of impaired reactor operation.

UNFILTERED SYSTEMS

Similar procedures can be used to set design criteria for unfiltered surface water systems. LeChevallier et al. (2003) reported infectious *Cryptosporidium* data for an unfiltered watershed in Oregon (Table 5). These data show that the design of a UV disinfection system should not allow more than 3-7 h of down time per month to meet the 1/10,000 annual risk of *Cryptosporidium* infection. Additional data are needed for a variety of unfiltered systems before generalized guidelines can be developed for unfiltered systems.

Table 5. *Cryptosporidium* data for the unfiltered watershed[3]

Study	No. of Samples	No. Positive	Conc. of Infectious Oocysts (per 100 L)	Daily risk of infection	UV disinfection system down time[1]
Method 1623	97	9	0.21[2]	0.00007	2.9
CC-PCR	89	2	0.09	0.00003	6.7

[1] Hours/month to exceed 1/10,000 annual risk without conventional treatment upstream and assuming monthly reporting requirement

[2] Value adjusted for a 72% recovery efficiency and 37% infectivity rate.

[3] Data based on LeChevallier et al. 2003.

CONCLUSIONS AND RECOMMENDATIONS

Microbial risk assessment can be used to develop a rational and defensible policy regarding UV disinfection down time and performance. UV systems for both filtered and unfiltered supplies can be out of service for short periods of times without impacting the utility's goal of meeting a 1/10,000 annual risk of *Cryptosporidium* infection. Although additional studies are necessary, the conclusion of this study does not support the USEPA draft proposal (USEPA 2003a) of allowing 5% of the monthly flow to by-pass UV disinfection for unfiltered water systems. Importantly, this study provides guidance for Primacy Agencies to develop reasonable policies for application of UV disinfection to filtered surface water systems. These policies have significant cost implications if extra redundancy and/or uninterruptible power supplies are required by the Primacy Agencies even if not supported by the risk analysis.

The results of this study indicate that “out of specification” operation of UV systems is not likely to pose a significant *Cryptosporidium* health risk provided that the on-line UV disinfection system remains functional. Assuming proper operation of the upstream conventional treatment, UV disinfection systems should not operate “out of specification” for more than 69 days per year, or more than 37 hours per month during times of highest risk (spring). Clearly there is an important research need to establish reasonable guidelines for UV disinfection system reliability, and studies of “out of specification” operation of UV systems are strongly recommended.

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