EXECUTIVE SUMMARY

Conventional UV disinfection is a physical disinfection process that uses commercially available lamps, which emit UV light in the wavelengths of 200 nm to 300 nm. These so-called germicidal wavelengths cause damage to DNA and RNA by dimerizing bases such as thymine and uracil. The damaged nucleic acids prevent replication thus rendering the potential pathogen sterile and unable to cause infection.

UV disinfection has had widespread use in the wastewater treatment field throughout North America. However, it has long been believed that UV was incapable of inactivating protozoan cysts or oocysts such as *Giardia lamblia* cysts and *Cryptosporidium parvum* oocysts at cost-effective dosages (Rice and Hoff, 1981; Campbell, 1995). More recently, however, it was discovered that the analytical methods commonly used to detect cyst and oocyst viability after UV dosage experiments, chemical excystation and vital stains, were incapable of predicting the effectiveness of UV disinfection since UV does not kill or inactivate the target pathogen rather it renders it incapable of infecting a cell.

Recent research by Clancy et al. (1998) and Bukhari et al. (1999) using mouse infectivity as the measure of viability showed that UV is highly effective at inactivating *Cryptosporidium parvum* oocysts. This work was confirmed by three other research groups using animal infectivity or cell culture techniques (Finch and Belosevic, 1999; Mofidi et al., 1999; Linden and Sobsey, 1999). Similar work using *Giardia* cysts also has shown that UV can effectively inactivate these cysts (Finch and Belosevic, 1999; and Linden and Sobsey, 1999). As a result, the U.S. EPA may propose that UV can be used as a best available technology for treating drinking water supplies.

A draft cost document by Malcolm Pirnie, Inc. for U.S. EPA evaluated a scenario in which a UV dose of 40 mJ/cm² could be granted inactivation credit of 2-logs for *Giardia* cysts and 2-logs for *Cryptosporidium*. If UV is granted these levels of inactivation credit by the regulatory community, its widespread use in drinking water disinfection in North America is likely since it can be as low as one-fifth the cost of ozone or one-tenth the cost of membrane filtration (MF size) and it would require a very small fraction (about one thousandth) of the space that these other technologies require. UV system costs (2000 U.S. dollars) were found to range from $0.05 to $0.08 per gallon of installed capacity for capital costs and from $0.005 to $0.03 per thousand gallons treated for annual operation and maintenance costs.

Key factors which affect UV design include in the order of importance: number and type of UV lamps used; UV reactor hydraulics and hydrodynamics (turndown ratios must be carefully considered); target organism(s) and level of inactivation required; location of UV in the treatment train degree of required redundancy; water quality characteristics such as: UV attenuation by the water, turbidity/particles, minimum temperature for lamp operation and degree of lamp fouling from inorganic constituents particularly iron and hardness; number and type of UV sensors; UV reactor types, configurations and materials; and system instrumentation and controls.

Key issues in UV operation and maintenance include the need for frequent calibration and/or replacement of UV sensor(s). Many UV sensors tested were found to have operating problems, easily lose calibration or become completely insensitive rapidly. The importance of proper UV lamp and sleeve cleaning and periodic replacement was found in all studies. The type of UV system cleaning selected will directly affect UV system headloss, UV system operation and maintenance costs and UV system reliability. Developing detailed day-to-day performance monitoring protocols including continuous monitoring of UV system equipment readings (sensors, flow, lamp out indicators, lamp hours, electronics/ballast temperatures and finished water microbiological monitoring plans is critical to gaining regulatory acceptance of UV technologies.

KEY WORDS

Ultraviolet disinfection; UV; *Giardia* cysts; *Cryptosporidium* oocysts; drinking water treatment; surface water treatment; operation and maintenance

INTRODUCTION

Conventional ultraviolet (UV) disinfection is a physical disinfection process that uses commercially available lamps, which emit UV light in the wavelengths of 200 nm to 300 nm. These
so called germicidal wavelengths cause damage to DNA and RNA by dimerizing bases such as thymine and uracil. The damaged nucleic acids prevent replication thus rendering the potential pathogen sterile and unable to cause infection. UV disinfection has had widespread use in the wastewater treatment field throughout North America. However, it has long been believed that UV was incapable at inactivating protozoan cysts or oocysts such as *Giardia lamblia* cysts and *Cryptosporidium parvum* oocysts at cost-effective dosages (Rice and Hoff, 1981; Campbell, 1995). Recent findings in North America that conventional, continuous wave ultraviolet (UV) disinfection can inactivate *Cryptosporidium parvum* as well as many other human pathogens of concern in drinking water at cost-effective dosages has spurred tremendous excitement and research throughout the U.S. and Canada. Pending regulations focus on simultaneously protecting the public health from microbial risks such as those from *Giardia*, *Cryptosporidium* and viruses and the potential chemical health risks from disinfection by-products has posed a difficult problem for the drinking water industry. In the U.S. negotiations are underway between all stakeholders to adopt the Stage 2 Microbial and Disinfection By-Product regulations. Concerns exist that if tighter *Cryptosporidium* inactivation requirements are imposed then drinking water systems will need to shift to more costly technologies such as long ozonation CxT times or membrane filtration. In addition, if DBP regulations for bromate or individual brominated organics are imposed, then ozone may not be an optimal solution. The potential that UV disinfection processes could be used to inactivate microbes of concern while reducing or as a minimum not adding to DBP disinfection processes could be used to inactivate microbes of concern while reducing or as a minimum not adding to DBP disinfection requirements.

**UV DISINFECTION EFFECTIVENESS**

Drinking water disinfection requirements have been driven in recent years by concerns about the risks from *Giardia lamblia*, *Cryptosporidium parvum* and human enteric viruses. In the U.S., the 1986 Surface Water Treatment Rule (SWTR) mandated a 3-log removal/inactivation of *Giardia* and a 4-log removal/inactivation of viruses. More recently, the Interim Enhanced SWTR essentially added a 2-log removal of *Cryptosporidium* through an optimized filtration requirement.

Figure 1 shows the effectiveness of UV for inactivation of *Cryptosporidium parvum* oocysts and *Giardia* cysts. These data reflect the recent understanding that UV effectiveness for inactivating protozoan cysts or oocysts must be evaluated using animal infectivity or cell tissue culture methods (Bukhari et al., 1999). The *Cryptosporidium* data shows that a UV dose of 10 mJ/cm² inactivated up to 4-logs of oocysts in most cases. Finch and Belosevic, 1999 observed a tailing effect in their results, but concluded that a UV dose of 10 mJ/cm² would reliably achieve a 2-log inactivation. By contrast older literature suggested that doses of hundreds or thousands of mJ/cm² would be required to inactivate protozoan cysts (Campbell, 1995). It is also interesting to note that the *Cryptosporidium* data based on animal infectivity generated by Bukhari et al., 1999 and by Finch and Belosevic, 1999 corresponds well with the *Cryptosporidium* data based on cell tissue culture generated by Linden and Sobsey et al., 1999 and Mofidi et al., 1999.

The *Giardia* data suggests that greater than 2-logs inactivation of cysts can be achieved at a dose of 10 mJ/cm². Finch and Belosevic, 1999 working with *Giardia muris* cysts noted a tailing effect which was not observed by Sobsey and Linden, 1999 who were using *Giardia lamblia* cysts. In either case, the data sets both demonstrate that a UV dose of 10 mJ/cm² or less will effectively inactivate at least 2-logs of *Giardia* cysts.

The effectiveness of UV for inactivating virus is well documented but it is important to note that there is a wide variety of virus strains that may be of concern in drinking water and their relative susceptibility to UV can vary widely. Table 1 summarizes the effects of UV on the major virus strains currently of interest to the drinking water industry. These data are compiled from work done by the authors on a variety of water qualities and data available in the current literature. These data suggest that Adenovirus, a double stranded (DS) DNA virus, may be the most resistant to UV inactivation. This finding would be consistent with earlier reports that Adenovirus has the capability to repair enzymatically damage to the DNA. Aside from Adenovirus data, which is currently undergoing further study and verification, it has been generally accepted that the surrogate MS-2 phage is a conservative indicator of human enteric virus inactivation by UV. If future work supports the
### Table 1. UV effectiveness for virus inactivation.

<table>
<thead>
<tr>
<th>Virus</th>
<th>UV Dose (mJ/cm²) for Inactivation of:</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2-log</td>
<td>3-log</td>
</tr>
<tr>
<td>Adenovirus 40</td>
<td>59</td>
<td>90</td>
</tr>
<tr>
<td>Adenovirus 41</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>Cox sackievirus B5</td>
<td>14</td>
<td>21</td>
</tr>
<tr>
<td>Hepatitis A HM-175</td>
<td>4-5</td>
<td>11-13</td>
</tr>
<tr>
<td>Poliovirus Type 1</td>
<td>8-11</td>
<td>15-19</td>
</tr>
<tr>
<td>Reovirus Type 1</td>
<td>36</td>
<td>-</td>
</tr>
<tr>
<td>Rotavirus WA</td>
<td>25-32</td>
<td>35-46</td>
</tr>
<tr>
<td>Rotavirus SA-11</td>
<td>19</td>
<td>25</td>
</tr>
</tbody>
</table>

Adenovirus data then the UV dose for 2-log credit would likely be increased to about 60 mJ/cm².

### EFFECTS OF WATER QUALITY MATRIX ON UV PERFORMANCE

Water quality conditions can affect all disinfection processes. In the case of UV these effects are broken into direct and indirect effects. Direct effects include water quality constituents that attenuate or block UV light and thus reduce the moles of photons of UV light which reach the nucleic acid of target pathogen. Indirect effects are water quality conditions which can affect lamp performance, foul UV lamp quartz sleeves and UV sensors or cause organisms to surface-associate with particles or aggregate (clump) thus making them more UV-resistant.

Direct effects can be the result of dissolved solutes such as iron, sulfites, natural organic matter (color or TOC) and synthetic organic compounds or the result of particles (turbidity) and suspended solids. It is well documented that UV disinfection is not directly affected by pH and temperature. Snicer et al., 2000 performed a study funded by the AWWARF in which 30 groundwaters, 15 conventionally treated surface waters and 18 synthetic waters were examined to determine which water quality parameters directly affected the ability of UV to inactivate human enteric viruses and the surrogate MS-2 bacteriophage virus. Examples of these data are shown in Figure 2. The study showed that the parameters, which significantly affected UV performance, were the dissolved iron concentration, the UV absorbance measured at 254 nm (resulting from dissolved organic matter or iron) and the nature and type of particles. The effects of dissolved solutes can be accounted for by using the UV absorbance measurements to adjust the UV dose provided to the water. However, the degree to which the UV dose can be increased to account for background absorbance is limited by practical space and cost considerations.

Effects of particles (often measured by turbidity) or suspended solids on UV performance are a function of their nature, type and concentration as well as their interaction with the target organism. Experiments looking at the effects of three different particles on the ability of UV to inactivate MS-2 are shown in Figure 3. In these studies, samples of wastewater effluent (representing amorphous biological particles); settled conventional drinking water (representing amorphous inorganic (alum) floc); and conventional filter effluent which had breakthrough of discrete inorganic clay like particles were collected and spiked with MS-2. After 8 hours of mixing, these samples were subjected to batch bench-scale collimated beam UV tests to determine the dose required to inactivate 2-log of MS-2. These data show that amorphous solids have a much more dramatic effect on UV performance. Further, the particles passed through conventional filtration did not significantly affect performance until levels above 3 NTU were obtained. These data suggest that the type and nature of particles will be important. In addition, these data suggest that placing UV post-filtration rather than prior to filters is the optimal location in a conventional drinking water plant. Additional work is on-going to determine how the nature of particles, which may contain high levels of organic matter or algae, will affect UV.

These types of particles often are encountered in unfiltered water supplies and in conventional filter plant effluents that are treating highly colored waters or algae-laden reservoirs.

The most significant indirect effects of water quality parameters were found to be sleeve and sensor fouling by dissolved iron, hardness or minerals and the effects of water temperature on lamp stability. Iron and minerals were found to significantly increase the rate of UV lamp sleeve fouling especially in medium pressure UV lamp systems due to their increased operating temperatures. Water temperature was found to significantly affect low pressure and low pressure high output UV lamps systems, likely because these lamp systems typically operate at internal temperatures of 40 to 60°C.
Treating surface drinking water supplies in northern climates with UV is one of the first applications in which waters entering the UV system may be at temperatures as low as 0.5°C. At these lower temperatures the UV lamps may have unstable output or take longer to reach a stable operating level. Therefore, designers must account for these effects when selecting lamp types, quartz sleeve designs and operating procedures. Temperature effects on medium pressure UV lamp systems were not found likely due to the fact that MP UV lamps operate at internal temperatures of 400 to 600°C.

**KEY FACTORS AFFECTING UV SYSTEM DESIGN**

As shown in Figure 4, there are several factors which must be considered when designing UV systems. One critical factor is minimum UV dose which is affected by UV lamp design (type, number and orientation), UV reactor hydraulics, and water quality parameters. As previously discussed, the target...
organism and the degree of inactivation desired also will strongly influence the minimum design dose, since organisms vary in their resistance to UV. The importance of water quality also has been demonstrated in this paper.

Figure 4. UV reactor schematic and key design factors.

UV sensors are critical to the day to day operation and performance verification of UV systems. Concerns over UV sensor reliability remain the largest obstacle to UV acceptance by regulatory officials and water utility operators. The author has found that the precision, accuracy and stability of UV sensors varies widely. An initial survey of UV sensors in place at over 100 wastewater UV disinfection facilities found that 80% of them were unreliable and hence not used. In wastewater UV systems, day to day performance can be verified by measuring effluent coliform organisms; however, in drinking water treatment there is no acceptable surrogate that is always present in the water and UV sensors will be critical. Increased emphasis by UV manufacturers on developing reliable sensors has led to improvements. Recent AWWARF research performed by the author has shown that reliable UV sensors for low pressure systems now are in use. However, effective sensors for medium pressure UV systems are less common. All sensors must be properly maintained and calibrated frequently (at least quarterly) to produce meaningful results.

CONCLUSIONS

UV disinfection systems have been found to effectively inactivate Giardia cysts, Cryptosporidium oocysts and human enteric viruses at cost-effective dosages. This result combined with earlier findings that UV does not increase concentrations of disinfection by-products or contribute to regrowth problems in distribution systems makes it an attractive technology for meeting emerging water quality regulations in the U.S. UV system design and performance is a function of lamp design and reactor hydraulics as well as key water quality parameters such as UV absorbing constituents, particles and solids, and constituents that can foul UV quartz sleeves and sensors. UV sensors are critical to the day to day performance monitoring of UV systems and the sensors must be carefully maintained and calibrated frequently to ensure reliability.

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REFERENCES


