UV Disinfection as Best Available Technology (BAT) for Drinking Water

The removal or inactivation of pathogenic organisms in water and wastewater is an important step toward protecting the public health against waterborne outbreaks associated with potable and recreational waters. In the United States, the 1996 Amendments to the Safe Drinking Water Act have mandated the development of new regulations governing potable water treatment that achieve an appropriate balance between disinfection byproducts (DBPs) formed during chemical disinfection and microbial risk.

To meet this challenge, the U.S. EPA has set up a M/DBP (Microbial/Disinfection ByProducts) Advisory Committee under the Federal Advisory Committee Act (FACA) consisting of stakeholder groups from industry, government, public and environmental health groups to negotiate new rules governing DBPs and microbial risks. The first stage of this process has led to the promulgation of the Stage 1 Disinfectant/Disinfection By-Product (D/DBP) Rule and the Interim Enhanced Surface Water Treatment Rule (IESWTR). The second stage, currently being negotiated, will lead to the promulgation of the Stage 2 D/DBP Rule and the Long Term 2 Enhanced SWTR some time during 2001-2002.

The negotiators are challenged to use sound science to establish requirements that provide additional public health protection. The main issues are Cryptosporidium oocysts and DBPs. Cryptosporidium is responsible for waterborne outbreaks causing diarrheal infections. In some cases, infection leads to death for the old, young or immuno-compromised. Cryptosporidium is quite resistant to chlorine and an order of magnitude more resistant to ozone than are Giardia cysts. Water treatment plants that do not use ozone or chlorine dioxide must reduce Cryptosporidium risk using filtration and watershed control.

DBPs, on the other hand, have been linked to cancer and birth defects. Reducing levels of DBPs may only be achieved by controlling DBP precursors, lowering chemical disinfectant concentrations, moving the disinfectant point more toward the end of the treatment process or changing the disinfectant. However, lowering DBP levels by modifying chemical disinfection poses a dilemma — public health benefits achieved through reducing DBP level must not be at the expense of increased microbial risk. While the present debate assumes a tradeoff — reducing the risk from one agent results in an increased risk from another — a more appropriate strategy would be to ask what combination of technologies allows one to meet acceptable risk levels for both agents.

With the discovery that UV disinfection readily inactivates Giardia cysts and Cryptosporidium oocysts at doses well below current guidelines (see UV News, 1(1):18-22 (1999)), UV disinfection has come under the spotlight as a potential BAT for drinking water disinfection. Backed by six decades of peer reviewed science and a track record based on thousands of installations treating groundwater, surface water, reclaimed water, and wastewater, UV disinfection is a cost-effective, established, and increasingly popular alternative to chemical disinfectants. UV disinfection is effective against a wide range of pathogenic waterborne bacteria and viruses. Furthermore, unlike chemical disinfection, microbe inactivation by UV radiation is not a function of the water temperature and pH. UV disinfection produces negligible levels of disinfection byproducts and no increase in water carcinogenicity and mutagenicity. Applied either as an add-on technology to inactivate Cryptosporidium and Giardia, or as a primary disinfectant followed by a chemical disinfectant residual, UV disinfection holds great promise for enhancing public health protection and solving the dilemma facing the current round of regulatory negotiations.

The Need for UV Reactor Validation/Certification

While the ultimate goal of public health protection through the reduction and inactivation of pathogens is the same for wastewater and drinking water disinfection, regulations governing how this goal is achieved varies notably between these two media. With wastewater disinfection, regulations specify a target level of indicator microbes (e.g., 200 fecal coliforms per 100mL as a 30-day geometric mean). Compliance to target levels and validation of equipment performance can be assessed easily by sampling the wastewater effluent after disinfection and enumerating the concentration of indicator microbes. On the other hand, indicator microbe and pathogen concentrations in finished drinking water prior to disinfection often are at or below the detection limits of the microbiological assay. Concentrations after disinfection can be expected to be
below detection limits, and microbial methods cannot be used to assess the performance of drinking water disinfection unit operations. Accordingly, drinking water regulations mandate a target reduction of waterborne pathogens and provide guidance on how to achieve that reduction using various disinfection technologies.

Guidance for compliance with the disinfection requirements of the SWTR currently are provided in the form of CT tables (U.S. EPA, 1989). The SWTR mandates that water treatment achieve overall 3-logs removal/inactivation of Giardia cysts and 4-logs removal/inactivation of enteric viruses. CT tables for the inactivation of Giardia cysts and virus by various log removals are published as a function of water temperature and pH for free chlorine, chloramine, chlorine dioxide, and ozone. In the case of chemical disinfectants, CT is defined as the product of measured residual disinfectant concentration and contact time. CT tables for UV disinfection also are published for virus inactivation, wherein CT for UV inactivations is defined as UV dose, the product of UV intensity and exposure time. These CT values are based on the UV inactivation of Hepatitis A virus and incorporate a safety factor of 3. Since rotavirus and adenovirus both are more UV-resistant than Hepatitis A, current regulatory talks may redefine the viral targets for UV. Guidance for the UV inactivation of Giardia and Cryptosporidium currently are under development.

The issue of UV dose delivery by a UV reactor is controversial. Several models for dose delivery by a UV reactor exist. The simplest model assumes that a UV reactor performs hydraulically as a plug flow reactor with complete mixing across UV intensity gradients. Under these conditions, each fluid element leaving the reactor experiences the same UV dose, defined as the product of the average UV intensity within the reactor and the theoretical contact time. In a more advanced model (Qualls and Johnson, 1985), the residence time distributions (RTDs) through UV reactors were multiplied by the average UV intensity to define a distribution of delivered UV doses which in combination with microbe inactivation kinetics could be used to define net inactivation by the reactor. In an alternative version of this approach (Scheible, 1985), a longitudinal dispersion coefficient derived from the RTD was combined with the average intensity and inactivation kinetics to define reactor performance. The most advanced model to date for UV reactor performance (Do-Quang et al., 1997; Lyn et al., 1997) uses computational fluid dynamics to define the flow paths of microbes as they pass through the UV reactor. UV dose experienced by each microbe is defined as the integration of UV intensity over exposure time. Since no two particles take the same path when traversing through a UV reactor, each microbe receives a different dose. Dose delivery by the reactor can be presented as a histogram of UV doses delivered to the microbes and can be combined with microbe inactivation kinetics to predict net inactivation by the reactor.

All of these models use flow rate through the reactor, UV absorbance of the water, and UV sensor output as input variables. Flow rate through the reactor combined with reactor geometry is used to define UV exposure time(s). UV absorbance of the water is used to define UV intensity profiles within UV reactors. UV sensor measurements are used to estimate UV lamp output and quantify any impacts of lamp aging and quartz sleeve fouling.

While performance models for UV reactors are useful tools for providing guidance in designing and sizing UV disinfection systems, they have limited value from a regulatory perspective. First, since the models rely on information provided by the manufacturer on the performance of various components within the UV disinfection system, they cannot be used to provide an independent assessment of dose delivery by the UV reactor. Second, since the models rely on assumptions, all models need to be validated experimentally by comparing predicted inactivation to measured inactivation.

As an alternative to using models to gauge UV dose delivery, microbial inactivation performance curves for a UV reactor can be established as a function of flow rate, UV absorbance, and UV sensor output. Performance curves can be used to identify a range of reactor operating conditions under which the reactor meets the disinfection objectives. Performance curves incorporated into an on-line command and control system ensure actions are taken should dose delivery be jeopardized by excessive water flow rate, high UV absorbance, or reduced UV intensity caused by lamp aging, lamp failure, lamp sleeve fouling, or power failures. Appropriate actions could include increasing the power setting of the lamps, initiating a lamp sleeve cleaning sequence, controlling or shutting off water flow, and triggering alarms to warn plant operators. Certification of UV reactor performance by an independent third party provides a guarantee to the end user that the UV disinfection system will provide and maintain target levels of microbial inactivation and meet regulatory requirements.

### Validation/Certification Protocols

The German DVGW Standard W294 (DVGW, 1997) describes a validation/certification process involving four areas – support documentation, UV sensors, command and control, and UV dose delivery. Support documentation supplied by the manufacturer on assembly and installation, operation and maintenance, cleaning procedures, UV lamps, sleeves, and sensors is examined. UV lamp documentation must include the lamp type, electrical operation, and UV spectral output. With UV disinfection systems using polychromatic lamps, documentation must show that UV radiation below 240 nm penetrating the water does not exceed 2% of the radiation between 240 and 290 nm. Sleeve documentation must include the sleeve material, dimensions, and UV transmittance.
spectrum. Sensor documentation must include the sensor’s operating range in W/m², spectral selectivity, measurement uncertainty, linearity, temperature and long term stability, and recalibration requirements.

A UV reactor must have at least one on-line sensor. On-line UV sensors must provide continuous monitoring of UV lamp output with measurements verifiable using a reference sensor. The properties of on-line and reference sensors are defined in detail (see Table 1). A sensor port with defined physical dimensions and a quartz viewing window also is defined. If the on-line sensor provides a UV irradiance measurement that deviates from the reference sensor measurement by more than the measurement uncertainty, the on-line sensor must be either cleaned, recalibrated, or replaced. Sensors must be tested and recalibrated every 15 months. The distance between the sensor window and the lamp being monitored must be chosen by the manufacturer to provide a similar sensitivity to changes in UV lamp output and changes in the UV absorbance of the water.

The UV disinfection system’s on-line command and control continuously monitors water flow rate and UV sensor output, and responds to ensure UV dose delivery is maintained during system operation. UV dose delivery is ensured when the UV sensor indicates an irradiance above a set point. The set point is defined as the sensor reading required to achieve the objective dose delivery as determined using biodosimetry plus the sensor’s measurement uncertainty. The on-line command and control system must respond to lamp failure and low sensor output by activating safety devices and triggering alarms.

German drinking water regulations require at least a 4-log inactivation of waterborne pathogens achieved using a UV dose of 40 mJ/cm². Ideally, the UV disinfection system should be challenged using a microbe that demonstrates a 4-log inactivation at a dose of 40 mJ/cm². Lacking such a microbe, Standard W 294 requires UV systems to be challenged using two microbes – Bacillus subtilis spores and E. coli. B. subtilis inactivation is used to demonstrate a dose of 40 mJ/cm², while E. coli inactivation followed by photoreactivation is used to demonstrate a 4-log inactivation.

The challenge test involves seeding the challenge microbe into the UV disinfection unit and measuring the inactivation achieved by the reactor. Static mixers are used upstream and downstream of the unit to ensure that seeded microbes are properly mixed and that microbial samples are representative. Challenge tests are performed at the minimum and maximum flow through the UV unit with the UV sensor reading at the set point. The set point is achieved using two methods – by lowering the lamp output with the water UV absorbance unchanged and by increasing the water UV absorbance with the lamps at maximum output. A UV dose equivalent is assigned to the UV reactor by comparing the inactivation achieved by the reactor to a UV dose-response curve for the challenge microbe obtained using a collimated beam apparatus (see Figure 1). In a collimated beam apparatus, the inactivation of a challenge microbe is measured as a function of applied UV dose under controlled laboratory conditions. In the German standard, the collimated beam apparatus may use either a low or medium pressure mercury arc lamp as a source. Furthermore, the microbial suspension irradiated must not be stirred and must be sampled from the center of the suspension using a small volume.

All tests are performed at a facility capable of evaluating sensors, performing challenge tests, and evaluating one-line command and control strategies. Validated UV disinfection systems are certified with a registration number and a period of validity.

Leuker (1999) and Sommer et al (1997) reported on UV reactor validation using Austrian Standard ÖNORM M 5873, a standard similar to the German DVGW standard. The certification process, performed at a test facility, identifies conditions of flow rate, UV absorbance, and UV sensor output that provide for a dose equivalent of 40 mJ/cm². Challenge tests are performed using B. subtilis spores. Static mixers upstream and downstream of the UV reactor are used and the test stand is designed with a 90° elbow located immediately upstream of the reactor. The UV absorbance of the water is increased by seeding the influent with a UV absorbing chemical such as sodium thiosulfate or fluorescein. UV lamp intensity is reduced to the level expected at the end of its useful service life. If the sensor output falls below a target level, the system must react by increasing lamp output, activating redundant lamps, or restricting flow. Alarms are sounded and shutoff valves activated if dose delivery is in jeopardy.

NSF/ANSI Standard 55-1991 outlines a certification protocol that uses B. subtilis spores to challenge UV reactors designed to deliver 38 mJ/cm² and Saccharomyces cerevisiae to challenge UV reactors designed to deliver 16 mJ/cm². S. cerevisiae, having a greater UV sensitivity than B. subtilis spores, is a more appropriate challenge microbe for the lower dose requirement of 16 mJ/cm². The UV dose-response of the challenge microbe is measured using a collimated beam apparatus in which a stirred sample is irradiated using UV light from a low pressure mercury arc lamp. The UV dose delivery must be challenged at the UV sensor set point, obtained either by reducing the lamp intensity or by increasing the water UV absorbance through addition of parahydroxybenzoic acid (PHBA).
Table 1. Sensor characteristics defined in German DVGW Standard W 294

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<thead>
<tr>
<th>Property</th>
<th>On-line sensor</th>
<th>Reference sensor</th>
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<tbody>
<tr>
<td>Output</td>
<td>W/m²</td>
<td>W/m²</td>
</tr>
<tr>
<td>Measurement uncertainty</td>
<td>&lt; ±10%</td>
<td>&lt; ±5%</td>
</tr>
<tr>
<td>Selectivity</td>
<td>&gt;90% for 240-290 nm</td>
<td>&gt;95% for 240-290 nm</td>
</tr>
<tr>
<td>Opening angle</td>
<td>30°</td>
<td>30°</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>&gt;90% over 15°</td>
<td>&gt;90% over 15°</td>
</tr>
<tr>
<td></td>
<td>&lt;5% from 15 to 30°</td>
<td>&lt;5% from 15 to 30°</td>
</tr>
<tr>
<td>Linearity</td>
<td>±5%</td>
<td>±5%</td>
</tr>
<tr>
<td>Temperature stability</td>
<td>±10% from 5 to 25°C</td>
<td>±10% from 5 to 25°C</td>
</tr>
<tr>
<td>Long term stability</td>
<td>±5% over 5000 hrs</td>
<td>±5% over 5000 hrs</td>
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Figure 1. A UV dose equivalent is assigned to the UV reactor by comparing the inactivation achieved by the reactor to a UV dose-response curve for the challenge microbe obtained using a collimated beam apparatus.

Issues

While UV reactor validation/certification protocols currently exist and have been applied successfully, advances in the understanding and application of UV disinfection challenges conventional wisdom. Cabaj et al. (1996) showed that the UV dose equivalent obtained when challenging a UV reactor depends on the UV dose distribution delivered by the reactor and on the kinetics of inactivation of the challenge microbe. The measured dose equivalent decreases with a broader dose distribution and decreases as the UV sensitivity of the challenge microbe increases. However, shoulders in the UV inactivation kinetics may increase the measured dose equivalent. Figure 2 demonstrates the dependency of the dose equivalent on the microbe’s first order inactivation constant for a UV reactor with a dose distribution as indicated.

A number of rules of thumb may be used when evaluating the results of microbial challenge tests given these dependencies on dose distribution and inactivation kinetics. First, if a challenge test using two microbes of differing UV sensitivity gives the same dose equivalent, the reactor is performing with near ideal hydraulics and UV dose may be expressed as the product of average UV intensity and exposure time. If a non-ideal reactor is challenged by a single microbe, microbes that are more UV sensitive than the challenge microbe will have a log reduction at least equal to that experienced by the challenge microbe. On the other hand, microbes less sensitive will experience a UV dose at least equal to that experienced by the challenge microbe. For example, if an MS2 challenge shows a log reduction of 2.8 and a UV dose equivalent of 50 mJ/cm², one can argue that *E. coli*, a microbe with a UV sensitivity greater than that of MS2, will experience at least a 2.8-log removal. On the other hand, adenovirus, a microbe more UV resistant than MS2, will experience a dose equivalent of at least 50 mJ/cm².

These arguments demonstrate the importance of choosing a challenge microbe with an appropriate UV sensitivity. Table 2 presents a list of target pathogens and their UV sensitivity, and suggests appropriate challenge microbes. The challenge
microbe used as a surrogate for UV-resistant rotavirus should differ from the challenge microbe used as a surrogate for UV sensitive Cryptosporidium.

Differences exist in the methodology used to obtain UV dose-response curves with a collimated beam device. Some protocols allow the use of polychromatic UV sources. Dose calculation with a polychromatic source requires data on the spectral output of the source, the action spectrum of the microbe being irradiated, and the UV absorbance spectrum of the water. The dose calculation sums the dose delivered at each wavelength weighted by the microbe’s action spectrum and normalizes that sum to give a dose equivalent expected at 254 nm. On the other hand, dose calculations with low pressure mercury arc lamps are simplified by the monochromatic nature of the source and are based on readily measured UV intensities. Given that UV dose delivery requirements are based on inactivation data originally derived using low pressure mercury arc sources, using such a source within a collimated beam apparatus is justified and preferred.

While some collimated beam protocols require stirred suspensions, others require the sample to be quiescent. By stirring the sample, dose delivery to all fluid elements within the suspension is uniform. This is very important when the intensity gradients across the suspension are large due to high UV absorbance. Collimated beam protocols need to recognize that some waters will have significant UV absorbances necessitating stirred suspensions.

UV absorbing chemicals (e.g., PHBA) used during a challenge test may significantly change the characteristic shape of the UV absorbance spectrum of the water. Under such conditions, the results of a challenge test on a polychromatic UV disinfection system may not be reflective of real world conditions and an alternate chemical then must be used.

Validation protocols without reference to a collimated beam dose-response curve have been proposed. However, UV dose-respon se is a function of the culture methods used to grow the microbes and the assay methods used to quantify inactivation. Measuring the UV dose-response of the challenge microbes ensures that the appropriate UV dose-response is used to calibrate the reactor.

Prescribing an on-line sensor technology verifiable using a reference sensor provides health inspectors a means for checking the performance of an installed UV disinfection system. However, specific UV sensor requirements could restrict technology innovation and advancement. Validation/certification protocols should be written to allow technology advancement that does not compromise public health protection.

Summary and Conclusions

UV disinfection is positioned to become a BAT for drinking water disinfection in the United States. Key to the acceptance of UV disinfection is the development of validation/certification protocols that provide a guarantee to the end-user that the UV disinfection system installed meets disinfection objectives reliably. Certification/validation protocols for UV disinfection currently are being used by Germany and Austria for UV disinfection systems designed for municipal drinking water disinfection and currently exist in the United States for Point-of-Entry and Point-of-Use UV disinfection systems. These protocols share many features – the establishment of UV reactor performance curves as a function of flow, UV absorbance, and UV sensor output and validation of low dose safeguards. While advancements in the understanding and application of UV disinfection has identified issues that require resolution, a framework exists whereby UV disinfection system validation/certification can be incorporated into guidelines for drinking water disinfection in the United States.

References

DVGW (1997) UV-Disinfection devices for drinking water supply – requirements and testing. DVGW Deutscher Verein des Gas- und Wasserfaches e.V., Bonn, Germany.


<table>
<thead>
<tr>
<th>Table 2. Target Pathogens and Suggested Challenge Microbes</th>
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<tr>
<td><strong>Target Pathogen</strong></td>
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<tr>
<td>Cryptosporidium</td>
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<tr>
<td>Hepatitis A virus</td>
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<tr>
<td>Rotavirus</td>
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<tr>
<td>Adenovirus</td>
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**Figure 2.** With an ideal UV reactor where each microbe receives the same UV dose, the dose equivalent obtained with different challenge microbe is the same. However, if the reactor delivers a range of doses, the dose equivalent depends on the shape of the dose distribution and the inactivation kinetics of the challenge microbe. Shown in this figure is a theoretical dose distribution curve and the associated bioassay dose equivalent for organisms of different UV sensitivities.