UV IN WATER TREATMENT ISSUES FOR THE NEXT DECADE

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ABSTRACT

The paper presents a 50,000 foot view of the UV technology field including where the field has been and where it may be going in the area of water treatment. Application of UV to wastewater was the initial and remains the most promising large long term market for the technology. Clearly the developing world will have numerous wastewater treatment challenges and UV will be widely used with a projection of up to 15,000 new facilities worldwide in the next decade. Challenges for wastewater UV includes much lower design UVT values; higher log inactivation requirements; and the need for tighter design requirements and validation. Applications of UV technology to conventional drinking water treatment should increase steadily in the next decade with projections of up to 7,000 new facilities worldwide.

Challenges for drinking water UV include insuring that significant health effects resulting from currently unregulated DBPs are not produced; determining effectiveness of UV for emerging pathogens; development of mercury free lamps; and refinement of validation procedures. Application of UV to water reuse is likely to grow at a slower rate in the next decade due to the complexity and costs of UV based AOPs with a projection of up to 100 new facilities worldwide using UV based AOPs in the next decade. Challenges of UV for reuse applications include those mentioned for disinfection and also include UV based AOP applications. UV based AOPs need a much closer examination since they are a much more complex technology often intended to meet multiple treatment objectives. The need for validation protocols and a detailed guidance manual for UV based AOPs will become more and more apparent as the number of full-scale systems put into use increase.

Key words: Ultraviolet Disinfection; Advanced Oxidation Processes; Wastewater UV; Drinking Water UV, UV for Reuse; and Future Trends

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INTRODUCTION

The purpose of this paper is to promote big picture thinking and discussion about the future of UV technology. This author began laboratory studies on UV technology in 1989 and during those efforts literature reviews identified significant publications on modern UV applications to wastewater treatment back to about 1969. So the period of this discussion will be nominally 50 years - from 1969 through 2019. Certainly the fundamentals of photochemistry, photobiology, optical physics and process engineering apply to UV technology regardless of the field it is applied. Similarly, some of the past, present and future issues with UV technology transcend and overlap a given applications. For organizational clarity, this paper breaks the discussion into three "market" areas: wastewater treatment, drinking water treatment and water reuse.

WASTEWATER TREATMENT APPLICATIONS

Past to Present

There are numerous reasons why UV technology was a very attractive fit for wastewater treatment applications: First, it is highly effective at inactivating bacterial pathogens as well as poliovirus and hepatitis virus. Second, it has a relatively small footprint and low headloss making a retrofit into a treatment plant easier. Third, its process performance could be based upon residual concentrations of total coliforms or fecal coliforms or *E. coli* in the same way chemical disinfectants were. Fourth, it produced no chemical residuals thus eliminating the need for chemical dechlorination as the wastewater industry became more and more concerned with whole effluent toxicity to the aquatic food chain. Despite these positive features, the widespread use and acceptance of UV technology for wastewater disinfection took about two decades to develop.

This slow development has within it some important lessons. The UV lamp technology common in the early 1970's was predominantly low pressure and this meant a large number of lamps, in the thousands, for large wastewater flow so it was deemed impractical for an operation and maintenance perspective. In addition, the early UV systems had many operational problems, many traced to poor electrical components and lack of water tight connections, with many treatment plants noting that once they installed UV disinfection they needed to employ a fulltime plant electrician and a fulltime operator just to keep the UV system running.

Another common problem noted was the lack of conservative designs in terms of the flow conditions, the total suspended solids and the UVT. Many wastewater channel systems to this day have very poor inlet hydraulics and very poor outlet hydraulic controls. In addition, the size of the UV system (number of lamps) was often too small to handle the actual TSS and the actual UVT of the water entering the UV system and the end result was numerous coliform permit violations. In most wastewater systems the UV sensors provided were quickly identified by the owners or operators as producing meaningless results and ignored. Lastly, there were numerous complaints about UV lamp fouling and the need for constant, time consuming cleaning which in those early days typically involved an air mixed, acid dip tank.

Thanks to the work of many dedicated engineers, scientists, operators and UV equipment manufacturers many of those early limitations on applying UV to wastewater were overcome. The LP lamp systems were often replaced with MP lamp systems and more recently with LPHO lamps systems. These new systems employed less lamps and allowed UV applications to be cost effective for higher design flows. The fewer lamps also reduced most of the operation and maintenance complaints and allowed for automatic wiper systems to handle the fouling issues. Many design engineers and UV manufacturers also began to focus on improving UV channel hydraulics and accounting for higher TSS levels in their selection of UV power and number of lamps.

The attractiveness of UV technology for wastewater disinfection also received an external boost from several factors. Concerns over whole effluent toxicity (WET), aquatic food chains and overall ecological health of receiving streams required most wastewater facilities that apply chlorine to use dechlorination. Regulations on the production, shipping, storage and application of toxic chemicals, such as chlorine and dechlorinating sulfites, increased the costs of using chemical systems. Increasing public concern about toxic chemicals in their communities and a desire for more natural or “green” solutions encouraged many wastewater plants to seek chemical free alternatives.

More recently there has been an interest and a move by the public toward making the sustainability of the treatment options we select a priority. The sustainability of UV technology is an issue in all applications of UV whether air, wastewater, drinking water, or water reuse. Sustainability and carbon footprint are usually linked and a large number of approaches to computing the carbon footprint of a given option have been developed. This paper CAUTIONS the reader about the temptation to conclude one technology is more sustainable than another without careful analysis. After review of numerous documents from PhD dissertations to peer reviewed publications to engineering sales literature it becomes very clear that a careful review of the input assumptions and variable for a sustainability analysis must be performed before a conclusion can be used with confidence.

For example, by manipulating the input variables and assumptions it is easy to conclude on any given project that the use of chlorine followed by dechlorination is more sustainable than the use of UV technology or to conclude the exact opposite. Clearly, the marketplace will be compelled to perform a sustainability analysis with a reasonable set of input assumptions and variables but still favors their product or technology. Rather than the concept of a “right” answer to the question of sustainable process selection, it is better to approach this issue by determining what input variables and assumptions are the most important to the stakeholders in a given project and then based on those inputs and assumptions determine which technology emerges from the analysis as the most sustainable.

When the issue of sustainability is discussed for UV technology applications it often turns to a discussion of power use. Clearly it is in the best interest of the profession to develop UV systems that are as energy efficient as possible. However, in almost all cases when an audit of the entire treatment facility focuses on improving energy efficiency, it becomes clear from the usage data that UV technology is a very small and almost insignificant part of the overall treatment plants power use. Facility owners and operators differ in their opinions on this issue but based upon the data, when a facility wishes to reduce their carbon footprint it is always in their best interest to focus efforts on improving the energy efficiency of their water pumping systems.

Future

The World Health Organization, International Water Association and World Bank at numerous conferences, workshops and public presentations identified the need for wastewater treatment improvements as the top environmental challenge and the area in most need of investment for the developing world including but not limited to the expanding populations of India and China. Therefore, it is a relatively sure prognostication that UV technology applications in wastewater treatment will rapidly expand around the world in the next decade. The number of new UV disinfection facilities for conventional wastewater treatment should be on the order of 15,000 worldwide in the next decade. In addition, there are tens of thousands of wastewater UV applications that will reach or exceed their design life in the next ten years.

The challenges facing this growing wastewater UV market will include the following items: First, wastewater UV applications lack a reasonable validation protocol which can lead to inadequate designs, poor equipment performance and poor public health protection. Efforts are underway through an IUVA committee to develop a wastewater UV validation protocol that can meet the needs of the international community. Second, there has been a widely accepted minimum wastewater UVT of 65% specified in many UV specifications and awarded contracts. Recent experience shows that the mean wastewater UVT of 100 composite samples of conventional wastewater treatment plants throughout the New England in the USA was 52% and these data ranged from 46% to 73%. The most common reason for the decreasing UVT values has been an increase in water conservation practices and a general reduction in collection system infiltration and inflow. For other wastewater systems there has been an increase in the use of UV absorbing organic chemicals by the contributing industries and citizens of the system. UV absorbing chemicals such as para-aminobenzoic acid and similar compounds are used in a wide array of industrial and commercial applications from chemical coatings to protecting printed circuit boards to sunglasses and personal care products like sunscreens. Third, there are increasingly stringent disinfection requirements being specified for conventional wastewater treatment plant effluents to insure greater public health protection. A review of discharge permits in the US has shown a downward trend from 1,000 total coliforms/100 mL to 200 fecal coliforms/100 mL and more recently to 100 E. coli/100 mL over the past 30 years. These tighter standards will require more robust wastewater UV disinfection system designs and performance.

DRINKING WATER TREATMENT APPLICATIONS

Past to Present

Many UV technology references begin by explaining that UV applications in drinking water treatment have been documented for almost 100 years and then went into a period of demise due to electrical and lamp operational challenges along with the rapid advances and the cost effectiveness of chemical disinfection using chlorine and ozone. The resurgence of interest in UV technologies for the disinfection of drinking water resulted from the understanding that low doses of UV were extremely effective at inactivation of *Cryptosporidium*. Interestingly, this result was not due to significant changes in our understanding of UV technology rather it was due to a better understanding of how to test for viability of *Cryptosporidium* and *Giardia* after it was dosed with UV. This finding combined with the fact that UV technology at disinfectant doses does not increase the production of regulated DBPs made final promulgation by USEPA of the LT2ESWTR and the Stage 2 D/DBPR economically acceptable. It is anticipated that these rules will results in 3,000 to 5,000 UV systems being installed in the U.S. at drinking water treatment plants using surface waters and/or groundwaters under the direct influence of surface waters in the U.S. by 2014 (the end of the implementation period). The USEPA also funded the largest single investment in a UV disinfection guidance manual (UVDGM) in the history of UV technology and as a result of that six year effort a copious document that significantly furthered our understanding of UV technology selection, design, validation, operation and maintenance was produced (www.epa.gov/safewater/disinfection/lt2/pdfs/guide_lt2_uvguidance.pdf).

The UVDGM drew upon and expanded past validation approaches developed in Germany and Austria as well as U.S. efforts by NWRI and AwwaRF. The UVDGM development process also highlighted two important aspects of UV technology applications to drinking water that remain important research issues. It underscored the importance of fully understanding the UV dose distribution of the UV reactor in order to have the most efficient system and the most accurate validation. As a result, work continues on using multiple test organisms to better understand dose distribution and on perfecting a system using dyed microspheres to directly determine the dose distribution of a UV reactor. The UVDGM also compiled and established the available, reputable UV dose response data for adenovirus serotypes resulting in a complete paradigm shift in the granting of virus inactivation credit for UV disinfection. The UV dose of 186 mJ/cm^2 for 4-log inactivation credit of virus (based on adenovirus) was developed during the UVDGM process and codified in the Federal Register as part of the LT2ESWTR. This represents a dose of over four times higher than the 40 mJ/cm2 value that had been used for years as the benchmark for insuring virus inactivation credit.

The de facto decision by USEPA to base 4-log virus inactivation credit for UV technology on adenovirus and on the available data set generated during the UVDGM had widespread ramifications in the U.S. for utilities that need to comply with the subsequent GWR also finalized in 2006. Groundwater systems that have serious concerns about using chlorination and wishing to use UV as a better means of improving overall public health protection are now faced with conflicting guidance since accepted protocols for validation of UV systems at high doses of 186 mJ/cm^2 are not available and it has been left to each state to make decisions on the applicability of UV technology for these groundwater systems. The issue of adenovirus and GWR compliance has led to several innovative and interesting UV projects including validation testing with live adenovirus to demonstrate that 4-log inactivation can be achieved and the related finding that the polychromatic UV light from MP UV systems is more effective at adenovirus inactivation than the monochromatic (254nm) UV light from LP and LPHO UV systems.

Impacts of polychromatic UV light versus monochromatic UV light systems have also been a concern in applying UV technology to drinking water treatment because of concerns with nitrogenous disinfection by products and their precursors. It is well know that polychromatic UV light systems have wavelengths which can effectively reduce nitrate to nitrite whereas monochromatic UV light at 254nm does not produce this reaction. Research is ongoing to determine the effects of UV light on nitrogenous DBPs and their precursors with reports that low levels of chloropicrin formation are enhanced following MP UV irradiation and chlorination of some water sources.

More recently there has been an interest and a move by the public toward making the sustainability of the treatment options we select a priority. The sustainability of UV technology is an issue in all applications of UV whether air, wastewater, drinking water, or water reuse. Sustainability and carbon footprint are usually linked and a large number of approaches to computing the carbon footprint of a given option have been developed. This paper CAUTIONS the reader about the temptation to conclude one technology is more sustainable than another without careful analysis. After review of numerous documents from PhD dissertations to peer reviewed publications to engineering sales literature it becomes very clear that a careful review of the input assumptions and variable for a sustainability analysis must be performed before a conclusion can be used with confidence. Clearly, the marketplace will be compelled to perform a sustainability analysis with a reasonable set of input assumptions and variables but still favors their product or technology. Rather than the concept of a "right" answer to the question of sustainable process selection, it is better to approach this issue by determining what input variables and assumptions are the most important to the stakeholders in a given project and then based on those inputs and assumptions determine which technology emerges from the analysis as the most sustainable.

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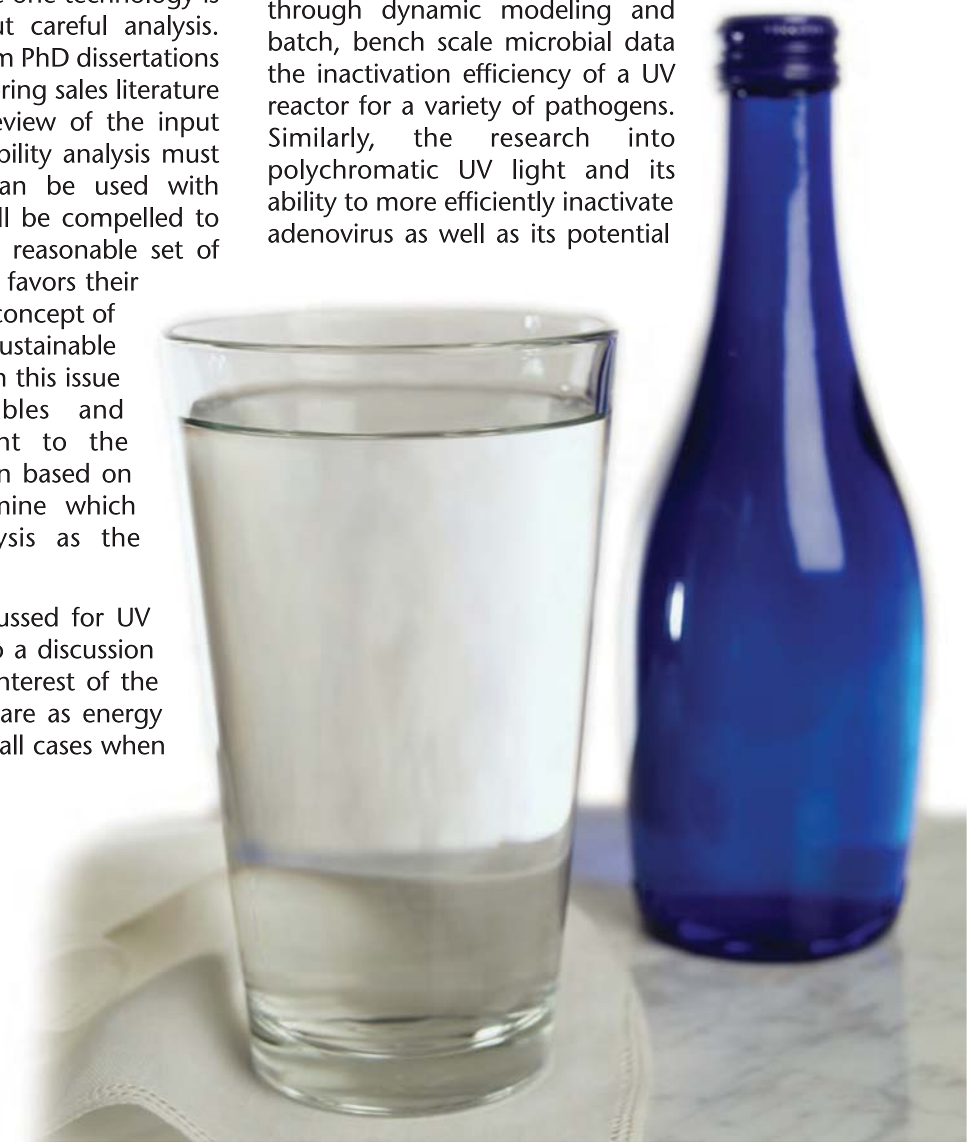
However, the growing number of installations of UV technology in drinking water treatment has allowed the field to identify areas that should be addressed to improve the technology. A particular focus is the need to make UV systems more sustainable and that implies improvements to existing UV lamp technologies both in terms of making them mercury free and in terms of increasing their energy efficiency.

Future

Widespread application of UV disinfection to drinking water treatment is expected to increase steadily worldwide for the next several decades. The number of new UV disinfection facilities for conventional drinking water treatment should be on the order of 7,000 worldwide in the next decade. It is anticipated that the current issues that have surfaced in the past decade will continue to be addressed through research through the coming decade. In particular, refinements to the UV validation process are expected that will identify the true UV dose distribution of a reactor and allow the accurate prediction through dynamic modeling and batch, bench scale microbial data the inactivation efficiency of a UV reactor for a variety of pathogens. Similarly, the research into polychromatic UV light and its ability to more efficiently inactivate adenovirus as well as its potential



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impact on nitrogenous DBPs or DBP precursors will continue until mechanisms and potential implications are adequately understood.

The search for more sustainable UV light sources will also continue with the hopes of finding a source that has longer life, significantly better energy efficiency and is free of toxic components such as mercury. The most promising new UV light sources are germicidal light emitting diode (LED) technology. This technology has numerous potential advantages including: extremely long lives on the order of hundreds of thousands of hours; energy efficiencies which can reach better than 50%; extremely durable components without mercury; and virtually no limitations on the potential geometry of the UV emission sources. However, UV LEDs are years away from widespread commercial use since the current generation of germicidal UV LEDs have very low outputs on the order of ten microwatts of germicidal UV and costs up to $400 U.S. These present UV LED cost are tens of millions of times more expensive that commercially available LP, LPHO and MP UV sources.

The drinking water treatment field for the past 40 years has experienced a series of alternating concerns between microbial risks from waterborne disease and chemical risks, in particular cancer and reproductive health effects, from the long term ingestion of DBPs. Currently, there are increasing interests in nitrogenous disinfection by-products and it can be anticipated that questions about the role of UV technology in the formation either directly or indirectly of emerging DBPs will be the subject of several future research projects. Similarly as new waterborne disease outbreaks occur or emerging pathogens are identified (either naturally or as the result of homeland security related activities) it should be expected that the UV dose response for these organisms will be identified and the ability of UV technology to attain disinfection credits for these organisms will be determined.

WATER REUSE APPLICATIONS

Past to Present

A wide variety of factors have contributed to a worldwide increase in water reuse applications including unprecedented population growth in regions with extremely limited water resources, record setting droughts and severe over-pumping of groundwater resources leading to salt water intrusion and/or extreme land subsidence. The use of UV technologies in water reuse applications increased in the 1980's and 1990's when systems needed to meet the stringent disinfection requirements embodied in the California Title 22 Water Reuse Standards. Guidance for the selection, design and validation of water reuse systems to comply with Title 22 requirements were published by NWRI in the 1990's and revised in 2003. When UV technologies are applied in reuse applications solely for disinfection all of the past, present and future issues previously discussed for wastewater and drinking water would apply.

More recently, UV based advanced oxidation processes (AOPs), in particular UV and hydrogen peroxide, have been applied in water reuse applications to provide a barrier to micro-pollutants such as NDMA and 1,4 dioxane. In a much smaller number of cases UV based AOPs have also been applied to conventional drinking water treatment plants for the purpose of seasonal taste and odor control and year round disinfection. It is very important to note that UV based AOPs are an entirely different technology than the conventional UV technologies used for the disinfection of wastewater and drinking water. UV based AOPs often apply UV doses in the range of 500 to 2,000 mJ/cm^2 along with chemical feed systems to deliver hydrogen peroxide concentrations of 3 to 20 mg/L. UV based AOPs because they has the joint actions of direct UV photolysis which is effective for NDMA and hydroxyl radical oxidation which is effective for 1,4 dioxane were adopted and installed in six very high profile projects and are being built in a seventh. The full-scale applications of this technology: first in the two PWN plants (Andijk and Heemskirk) in the Netherlands; the 70 MGD Groundwater Replenishment plant in Orange County, California; three plants in Southeast Queensland, Australia; and lastly the large plant under construction for Aurora, Colorado; has provided confidence that this technology will operate effectively.

UV based AOPs as well as non-UV based AOPs may also be an attractive technology for a wide variety of micropollutants including endocrine disrupting compounds (EDCs) as well as pharmaceutical and personal care products (PPCPs) that have been found at low levels (nanograms per liter) in many water resources and finished drinking waters around the world. Further discussion of non-UV based AOPs is beyond the scope of this paper but it should be noted that in any given application these processes may be favored over UV based AOPs and a careful comparison is needed.

In many ways, our knowledge of UV based AOPs is in its infancy and is quite similar to the level of understanding the profession had about UV disinfection prior to the 1990's when large amounts of research money was pumped into the field by the USEPA, WRF (formerly AwwaRF) and others to better understand its use as a barrier for *Cryptosporidium*. UV based AOPs have been pilot tested, selected, designed installed and are operating successfully as previously noted but there is a lack of standard guidance and approaches to the most efficient ways to select, design, validate, operate and maintain an AOP system. There is a growing need for an AOP guidance manual development effort that can build upon what is known. It is unlikely that an AOP guidance manual effort would need to be as intensive, length or result in as copious a document as the UVDGM.

As these full-scale UV based AOP facilities operate around the world it provides a good opportunity to benchmark their performance and the area that warrant improvement. In general, the area identified so far include: efforts to reduce power use perhaps through more optimized lamp systems; better understanding of the design basis for the systems so operational optimization can be performed;

improved ability to quantify free radical scavengers and how they change with time to adjust facility response to these changes; further study of byproducts produced by the UV based AOP process in terms of potential for toxicity or decreasing the biologically stability of the treated water; and alternatives to the use and quenching of hydrogen peroxide to initiate hydroxyl radical oxidation.

There is significant debate about whether AOP processes are sustainable and whether or not the water treatment profession is moving in the right direction by choosing them. Often in this debate, the energy use for the UV system is cited as well as the carbon footprint related to the production, transportation, storage, delivery and quenching of the hydrogen peroxide. UV based AOP technologies clearly use more energy than UV disinfection applications but this energy use is not the largest fraction of the treatment plants total energy use. As previously discussed in this paper rather than the concept of a "right" answer to this question of AOP process sustainability; it is better to approach this issue by determining what input variables and assumptions are the most important to the stakeholders in a given project and then based on those inputs and assumptions determine which technology emerges from the analysis as the most sustainable. It is a complex question and the answer is often site specific depending upon the treatment goals of the facility and many other variables.

Future

Population growth and water resource distributions around the globe both strongly suggest that water reuse will increase steadily in the next decade. This combined with the ability to measure low levels of organic micropollutants in water supplies and the related public concern about the presence of these compounds suggests that the number of UV based AOP facilities will grow during the next ten years. In many cases, these UV based AOP facilities may be built as part of advanced wastewater treatment plants prior to discharge to the receiving water if the goal is to prevent aquatic food chain impacts from EDCs and PPCPs.

However, UV based AOPs are a complex technology that is inherently energy intensive when compared to UV disinfection and presently it requires the addition of chemicals, normally hydrogen peroxide, to produce hydroxyl radicals. Therefore, the growth and overall number of facilities that will use UV based AOPs is predicted to be far less than the number of UV disinfection facilities. For example, if the number of new UV disinfection facilities for wastewater is projected to be 15,000 worldwide for conventional wastewater applications and 7,000 worldwide for conventional drinking water applications in the next decade the number of new UV based AOP facilities is likely to be in the 50 to 100 range worldwide.

UV based AOP research that has been initiated in this decade and should expand into the next decade will include several areas. Ongoing research to develop an optimized UV lamp with light output specifically to form hydroxyl radicals from hydrogen peroxide or some other initiator will continue. Efforts to develop other UV based AOPs that do not use hydrogen peroxide will continue and may include such things as nano-particle titanium dioxide, UV excited chlorine to form radicals or UV excited nano-iron to form radicals. Research into improved ways to assess the hydroxyl radical scavenging potential and real time online scavenging potential monitoring will continue. Better understanding of the potential human and/or aquatic food chain toxicity from waters treated by UV based AOPs (or other AOPs) will be developed from research projects during the next decade. It is well knows that AOP processes cannot cost effectively convert all constituents to their mineralized forms (i.e. carbon dioxide, water, nitrogen gas and chloride) and therefore byproducts will be formed. The potential for these byproducts to contribute to problems such as formation of regulated DBPs, increased biological re-growth and biologically unstable water and/or the potential for increased corrosion and the prevention of these potential problems will be the topic of many research studies during the next decade.

SUMMARY

The paper presents a 50,000 foot view of the UV technology field including where the field has been and where it may be going in the area of water treatment. Application of UV to wastewater was the initial and remains the most promising large long term market for the technology. Clearly the developing world will have numerous wastewater treatment challenges and UV will be widely used with a projection of up to 15,000 new facilities worldwide in the next decade. Challenges for wastewater UV includes much lower design UVT values; higher log inactivation requirements; and the need for tighter design requirements and validation. Applications of UV technology to conventional drinking water treatment should increase steadily in the next decade with projections of up to 7,000 new facilities worldwide. Challenges for drinking water UV include insuring that significant health effects resulting from currently unregulated DBPs are not produced; determining effectiveness of UV for emerging pathogens; development of mercury free lamps; and refinement of validation procedures. Application of UV to water reuse is likely to grow at a slower rate in the next decade due to the complexity and costs of UV based AOPs with a projection of up to 100 new facilities worldwide using UV based AOPs in the next decade. Challenges of UV for reuse applications include those mentioned for disinfection and also include UV based AOP applications. UV based AOPs need a much closer examination since they are a much more complex technology often intended to meet multiple treatment objectives. The need for validation protocols and a detailed guidance manual for UV based AOPs will become more and more apparent as the number of full-scale systems put into use increase.

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