

Advancing the Science of Water: AwwaRF and Ultraviolet Disinfection

After almost a century of disinfecting water supplies with chlorine or chlorine-based compounds, US water suppliers in the 1980s and 1990s began to look for alternative disinfection schemes that would minimize the formation of chlorinated disinfection by-products (DBPs) and inactivate the difficult-to-kill *Cryptosporidium* oocysts found in many surface water sources. AwwaRF research has led the way in exploring the use of alternative disinfectants in the United States, including ultraviolet (UV) light.

From 1990 through 2006, AwwaRF funded more than 30 UV-related projects with a total research value of approximately \$14 million. “AwwaRF is without question the largest funder of drinking water UV research, starting early on and continuing through the present day,” said James P. Malley Jr., of the University of New Hampshire.

“AwwaRF took the initiative and funded some early studies that helped utilities understand how UV could be a viable water treatment technology,” said Christine Cotton, an associate with Malcolm Pirnie, Inc. “It’s a funding agency that looks into the future, and its studies have given utilities confidence that UV disinfection is here to stay.”

The process of UV disinfection inactivates microbial pathogens by irradiating them with UV light. The UV light disrupts the metabolic activity of the microorganisms, rendering them incapable of reproducing or causing infection. In order for the irradiation to reach the organisms effectively, the water to be disinfected should be filtered or otherwise relatively free of particles and UV-absorbing dissolved compounds such as natural organic matter. Unlike chlorine-based disinfectants and ozone, UV disinfection has not been shown to produce significant concentrations of regulated DBPs or to change a water supply’s biological stability.

Although UV disinfection has a history of use in wastewater applications and in small drinking water supplies in Europe, US water suppliers traditionally used chlorine, or ozone followed by chlorine, because it provided a residual disinfectant in the distribution system. It was not until the discovery that UV inactivates protozoa such as *Cryptosporidium* that the technology caught the attention of water utilities on this side of the Atlantic.

“UV has been a breakthrough technology,” says Stig Regli, a US Environmental Protection Agency (USEPA) policy analyst who has had primary responsibility for

developing a cluster of water quality regulations designed to control pathogens and DBPs in drinking water. “It’s a low-cost way of inactivating protozoa.”

The drinking water profession has embraced UV technology uncommonly quickly. “The length of time it took for UV to be recognized as an effective way to control *Cryptosporidium* (circa 1998) and to be incorporated in drinking water regulations (circa 2003) is incredibly short,” said Jennifer Clancy, president of Clancy Environmental Consultants. “One could say it happened at the speed of light,” she puns.

Understanding UV Technology

AwwaRF-funded UV projects have focused primarily on three areas of study: determining UV’s effectiveness as a water treatment technology, optimizing the design and operation of UV facilities, and integrating the technology into existing treatment plants. Within these three categories, AwwaRF’s fundamental contributions to the understanding of UV technology include:

- Verifying that UV does not form or affect the rate of formation of any regulated DBPs either during or after water treatment,
- Discovering UV’s effectiveness at inactivating protozoan cysts, particularly the chlorine-resistant *Cryptosporidium*,
- Documenting the relationship between UV dose and inactivation of selected pathogens,
- Demonstrating that UV disinfection can be applied successfully and relatively inexpensively in water treatment facilities,
- Quantifying practical information such as long-term operations and management costs, lamp life, fouling, cleaning requirements, and the effects of water quality,
- Determining that variations in power quality generally are not serious enough to undermine the effectiveness of UV systems,
- Examining UV’s use in advanced oxidation processes for controlling drinking water contaminants such as endocrine disruptors, synthetic organic chemicals, and compounds that cause taste and odor problems,
- Creating a decision-making tool to help utilities identify optimal *Cryptosporidium* control strategies under site-specific water quality conditions,
- Generating guidelines to help utilities retrofit existing water treatment plants with UV technology, and
- Providing data that helped enable USEPA to specify UV disinfection as an available technology for inactivating *Cryptosporidium* and other pathogens in the Long Term 2 Enhanced Surface Water Treatment Rule.

Determining UV’s Efficacy as a Disinfectant

Avoiding DBP Formation. In one of the earliest studies on UV disinfection of drinking water, Malley confirmed that UV did not cause precursor material to form regulated DBPs and did not influence post-disinfection formation of the DBPs that were regulated at the time (“Evaluation of the By-products Produced by the Treatment of Groundwaters With Ultraviolet Radiation,” Project 809, funded 1992, published 1996, order number

90685). Funded by AwwaRF and USEPA, the study was the first in a trilogy of bench-scale, pilot-scale, and full-scale projects Malley conducted during the 1990s. In this bench-scale study, the researchers examined a cross-section of groundwater and surface water supplies from 50 US utilities of various sizes (the largest was New York City, and the smallest was a 1-million gallons per day [mgd] groundwater system) and showed that UV irradiation produced no significant concentrations of regulated DBPs in groundwater, filtered surface water, or simulated distribution systems.

The second project in the trilogy determined the UV dosages required to kill several human pathogenic viruses (polio, rotavirus, and hepatitis A) as well as the surrogate MS-2 virus in on-site groundwater pilot-plant studies (“UV Inactivation of Viruses in Natural Waters,” Project 180, funded 1994, published 2000, order number 90773). The third (AwwaRF Project 474), a full-scale study, is discussed under the subhead Integrating UV Technology Into Existing Treatment Plants.

Inactivating *Cryptosporidium*. In addition to UV’s value as a way to avoid the formation of regulated DBPs, the most significant factor in assuring its acceptance as a primary disinfectant was the discovery that it inactivates *Cryptosporidium* oocysts. In a landmark study funded by AwwaRF and the Electric Power Research Institute (EPRI), Clancy demonstrated that high doses of UV light could inactivate crypto (“Innovative Electrotechnologies for *Cryptosporidium* Inactivation,” Project 282, funded 1995, published 1998, order number CR-111090 available from EPRIAMP Customer Assistance Center, 800.432.0267). But a follow-up study, conducted at Clancy’s lab and Charles Sterling’s lab at the University of Arizona, showed that low-pressure UV is also extremely effective at inactivating crypto (“*Cryptosporidium* Viability and Infectivity Methods,” Project 395, funded 1996, published 2000, order number 90799).

“None of the electrotechnologies worked except UV,” Clancy said. “We looked at two UV technologies. The first was a big inactivation device that captured the oocysts by filtering them out with a metal screen and subjecting them to long exposures of UV as they sat on the screen. This device never took off because the high doses it delivered weren’t required to kill *Cryptosporidium*. The second UV technology we looked at was pulsed UV. We moved down to 1900 milijoules of UV, which of course is laughable now that we know 5 milijoules will do it.”

In the follow-up study, designed to examine methods for determining crypto viability and infectivity, Clancy and her research team began investigating lower UV doses, using the mouse assay to measure inactivation. “That’s when we found out that lower doses also inactivated crypto,” she said.

For more details about these two studies, see the documentation on *Giardia* and *Cryptosporidium*.

Determining Required UV Doses. In 1999 AwwaRF funded three groundbreaking UV projects—one evaluating the effectiveness of two UV disinfection systems, one

examining the practical aspects of UV use, and one addressing both fundamental and practical considerations.

Karl G. Linden at Duke University evaluated the disinfection efficacy of high-intensity polychromatic UV radiation from medium-pressure lamps and pulsed UV systems (“Disinfection Efficiency and Dose Measurement of Polychromatic UV Light,” Project 2668, funded 1999, published 2003, order number 90931F). This study also compared methods of measuring UV dose and provided data on the relationship between UV dose and inactivation of selected microorganisms.

The project that addressed both fundamental and practical UV issues was a large pilot-scale study whose scope prompted Malley to call it “the mother of all UV projects” (“Inactivation of Pathogens with Innovative UV Technologies,” Project 2593, funded 1999, published 2004, order number 91024). Co-sponsored by AwwaRF, the Water Environment Research Foundation, and USEPA, the study had five principal investigators, involved three pilot plants, and produced two final reports. Malley was lead author of the report dealing with pathogen inactivation. Erin Mackey of Carollo Engineers was lead author of the report covering practical concerns (“Bridging Pilot-Plant Testing to Full-Scale Design of UV Disinfection Systems,” order number 90991).

On the fundamental side, the study examined the inactivation of bacteria and viruses by several UV technologies used in drinking water and wastewater applications. “Picture a medium-pressure UV lamp putting out energy in many different wavelengths,” Malley explains. “Some wavelengths are more effective at inactivating microorganisms than others.”

Malley, along with co-principal investigators Linden at Duke and Alex Mofidi at Metropolitan Water District of Southern California, looked at how specific wavelengths inactivate certain organisms in order to determine what wavelength the organisms are most susceptible to. When these data are plotted, the curve is called the action spectra. Researchers at Duke and the University of New Hampshire generated the action spectra for adenovirus, which has become the standard for virus inactivation because this virus has been identified as the most resistant of the waterborne pathogens to UV disinfection. “The cellular repair mechanisms of this virus make it much harder to kill than protozoa,” Malley said. “*Giardia* and *Cryptosporidium* are wimpy by comparison.”

Improving UV Design and Operation

On the practical side, this giant study laid much of the early foundation for UV implementation, according to Malley. “We had pilot plants in Atlanta, Georgia; Orem, Utah; and Austin, Texas. We examined long-term operations and management costs, lamp life, fouling of the quartz sleeves that enclose the lamps, cleaning requirements, and the impact of water quality. We asked questions such as: Where does UV fit into the process flow in a water treatment plant—i.e., where should we put it? What happens if we add chlorine before UV?”

Also focusing on the practical aspects of UV use, Gil Crozes of Carollo Engineers directed a pilot study that assessed design and operation issues such as lamp performance and fouling (“Practical Aspects of UV Disinfection,” Project 2623, funded 1999, published 2001, order number 90875). This study, a tailored collaboration with the North Shore Water Commission in Wisconsin, also organized the key features of UV disinfection, membrane filtration, and ozonation into a decision-making tool to help utilities identify optimal *Cryptosporidium* control strategies under site-specific water quality conditions.

Joel Ducoste at North Carolina State University studied UV reactor design to determine whether reactors contained “dead spots” where microbes were not exposed to UV irradiation (“Hydrodynamic Characterization of UV Reactors,” Project 2682, funded 2000, published 2005, report available only in electronic format, order number 2682). The study addressed this question by modeling the distribution of UV light and the hydraulic residence time of target microorganisms using a technique called computational fluid dynamics.

Applying UV as an Oxidant

In the past few years, AwwaRF projects have investigated another application of UV—not as a disinfectant but as an oxidant used in combination with hydrogen peroxide in a process known as advanced oxidation. “This is cutting-edge work,” said Malley, explaining that advanced oxidation may be helpful in controlling emerging drinking water contaminants such as pharmaceutically active compounds, endocrine disruptors, and *N*-nitrosodimethylamine (NDMA), a synthetic organic chemical found in certain industrial applications and sometimes formed during water and wastewater treatment through the reaction of nitrite, acid, and organic nitrogen compounds called amines.

Linden served as principal investigator for an AwwaRF study of advanced oxidation involving UV (“Innovative UV Technologies to Oxidize Organic and Organoleptic Chemicals,” Project 2599, funded 1999, published 2004, order number 91033F). Focusing on UV technologies already shown to inactivate protozoan pathogens, this study examined the ability of these technologies to oxidize volatile organic compounds, synthetic organic chemicals such as pesticides and herbicides, DBP precursors, and organoleptic compounds that cause taste and odor problems.

“Advanced oxidation uses different reactor configurations and involves much higher doses than UV disinfection,” said Clancy. “AwwaRF projects showed how to make these applications work effectively.”

Integrating UV Into Existing Treatment Plants

The third study in the Malley trilogy was the first AwwaRF–EPRI project to retrofit existing groundwater systems with full-scale UV technology and to follow up with long-term performance monitoring (“Full-Scale Implementation of Ultraviolet Disinfection in Groundwater Treatment Systems,” Project 474, funded 1997, published 2001, order

number 90860). This study identified the importance of reactor hydraulic design, water quality evaluation, sensor calibration, and proper cleaning techniques to ensure optimal UV performance. By collecting full-scale data on design, operation, and costs, the study provided valuable information for utilities choosing to implement UV technology.

A study AwwaRF co-sponsored with the National Water Research Institute (NWRI) initiated the development of guidelines for UV disinfection of drinking water (“Protocol for Designing and Conducting UV Disinfection Studies,” project 2674, funded 2000, published 2003 by NWRI as “Ultraviolet Disinfection Guidelines for Drinking Water and Water Reuse,” available from NWRI at 714.378.3278 or www.nwri-usa.org). The guidelines address field-testing before start-up, reactor design, reliability and redundancy, dose, performance monitoring, and engineering reports.

Results of a UV project funded jointly by AwwaRF and USEPA essentially constitute a handbook for utilities planning to incorporate UV disinfection into existing surface water treatment plants (“Integrating UV Disinfection Into Existing Water Treatment Plants,” Project 2861, funded 2002, published 2005, order number 91086). Carried out by Cotton and Doug Owen at Malcolm Pirnie, Inc., the study concentrated on basic design issues, emphasizing ways to minimize the risks and costs associated with installing UV technology. The researchers then built this guidance into an interactive Web tool.

“I think this project helped utilities understand some of the main issues they should take into account when they consider installing UV,” Cotton said. “We focused on practical information.” She and Owen also investigated the effects of power quality, a significant concern prior to this research, and concluded that power quality variations were not generally serious enough to cause utilities to be out of compliance with regulatory specifications.

Site-Specific UV Evaluations. As water suppliers began to accept UV as a viable water treatment technology and became interested in implementing it, a number of engineering studies ensued. Several of these projects, tailored collaborations partially supported by AwwaRF funding, examined the feasibility of UV use at specific water utilities.

William D. Bellamy of CH2M Hill and Malley directed a tailored collaboration with the city of Winnipeg, Manitoba (“UV Disinfection and Disinfection By-product Characteristics of Unfiltered Waters,” Project 2747, funded 2001, published 2004, order number 91039F). Examining the use of UV as a primary disinfectant followed by various secondary disinfectants, this study assessed the effects of source water turbidity, algal growth, and total organic carbon on UV disinfection and identified opportunities for controlling DBPs.

“The study involved a large demonstration-scale plant on Winnipeg’s reservoir,” said Malley. “The city now has a big UV disinfection facility with a capacity of approximately 165 mgd. The supply is currently unfiltered, but the city is building a filter plant.”

Another AwwaRF-funded tailored collaboration—involving major water utilities in Boston and Concord, Mass., Portland, Ore., and Las Vegas, Nev.—looked at integrating UV disinfection and ozonation. Led by Robert A. Hulse of Black & Veatch and Malley, this study won the 2005 Crystal Research Prize, the most prestigious research award in the engineering profession, conferred by the American Academy of Environmental Engineers (“Evaluation of Ozone and Ultraviolet Light,” Project 2749, funded 2001, published 2005, order number 91046F).

In this study, the research team compared the relative performance of two disinfection schemes—ozone followed by medium-pressure UV and medium-pressure UV alone—and investigated the synergistic effects of the two disinfectants on DBP formation, biostability, and corrosion. “This forward-thinking project showed both the fundamental and practical value of the synergy between UV and ozone,” said Malley. “There’s little doubt that it will set the stage for future full-scale treatment plant modifications in Boston, Las Vegas, and other cities. Boston has a 400-mgd ozone facility and a 30-mgd conventional chlorination facility and will be looking at installing UV at these two plants in the future.”

The nation’s largest city has also embraced UV technology. “New York City, working with the joint venture of Hazen and Sawyer and CDM, is now planning the biggest UV installation ever dreamed of in the industry—52 reactors, each with a 60-mgd maximum capacity,” said Malley. Harold Wright of Carollo Engineers is heading a tailored collaboration with the New York City Department of Environmental Protection to verify new tools for optimizing UV system size (“Optimization of UV Reactor Validation,” Project 2983, funded 2003, to be published 2006). Another of the project’s goals is to determine the effect of lamp and sleeve aging on dose delivery and monitoring.

“I’m confident that what New York City learned through AwwaRF-funded projects kept the city moving toward the conclusion that UV was the right way to go,” said Malley.

Malley also gives AwwaRF research part of the credit for Seattle’s decision to install UV. “Seattle’s Cedar plant—at 180 mgd—is currently the largest UV system in the United States; it treats two thirds of the city’s water supply. The AwwaRF work is one reason that a large, progressive utility like Seattle, working with its design–build–operate contractor, CH2M Hill, would go ahead with an installation of this magnitude. Before Cedar went on line in 2005, there was no UV installation of this size in the country, so it was a breakthrough,” he said.

The Cedar plant uses both ozone and UV to treat its unfiltered supply. Referring again to the award-winning study of these two disinfectants in Boston and Las Vegas, Malley claims these results “add validity to Seattle’s approach and to the forward-looking method of employing a multiple disinfectant barrier within the overall multiple barrier approach to providing safe drinking water.”

Providing Sound Science for Regulations

In April 1999 USEPA held a meeting to discuss the possibility of specifying the use of UV for *Cryptosporidium* control in the upcoming Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR). “The Clancy study showing UV inactivation of *Cryptosporidium* indicated the feasibility of using UV to control this protozoan in drinking water,” said Regli. “These results eventually led to criteria for unfiltered water systems to achieve *Cryptosporidium* inactivation levels not previously considered practical.”

The LT2ESWTR, promulgated in January 2006, specifies the level of crypto inactivation water utilities must achieve to lessen the likelihood of a cryptosporidiosis outbreak. “AwwaRF-funded UV work contributed significantly to the development of this regulation,” Regli said.

Michael J. McGuire, vice-president of McGuire Malcolm Pirnie Environmental Consultants, underscores Regli’s claim. In a March 2006 *Journal AWWA* article on disinfection, McGuire wrote that the LT2ESWTR “could not have been written” and the negotiating parties who participated in the rule’s development “could never have reached agreement if a viable, relatively inexpensive means of inactivating *Cryptosporidium* oocysts had not been available.”

In December 2006 USEPA issued a guidance manual on UV disinfection. Intended to help utilities plan, design, install, validate, and operate UV systems, the 400-page manual is the definitive source of information on UV disinfection of drinking water and is available on the Web at <http://www.epa.gov/safewater/disinfection/lt2/compliance.html>. The manual refers to the findings of several AwwaRF studies discussed in this document, including Malley’s early bench-scale study on treating groundwater with UV (Project 809), the so-called “mother of all UV projects” with reports written by Malley and Mackey (Project 2593), the collaborative study with NWRI (Project 2674), the Winnipeg study (Project 2747), and the Cotton and Owen project on integrating UV into existing facilities (Project 2861).

Coordinating International Research Efforts

In addition to funding specific projects to deepen our understanding of UV technology and contributing UV data used to develop US water quality regulations, AwwaRF has collaborated with other international organizations to establish an agenda for UV research. Participants in an expert workshop held in the Netherlands in 2002 set priorities for UV research related to drinking water applications and agreed to coordinate international UV research efforts. AwwaRF co-sponsored the workshop, along with the Dutch organization Kiwa Water Research, the UK Drinking Water Inspectorate, UK Water Industry Research Ltd., and the International Ultraviolet Association. Workshop participants—physicists, chemists, engineers, microbiologists, and modelers—were from Australia, Austria, Belgium, Canada, France, Germany, the Netherlands, the United Kingdom, and the United States.

Predicting UV's Future

The microbiologists and engineers who have conducted AwwaRF research on UV agree that this technology has a bright future with US water utilities. “Confidence in UV treatment for *Cryptosporidium* control is so high that systems in all size ranges are being installed across the United States,” said Clancy. “Now that LT2 has been finalized, more utilities are looking at implementing UV technology. Because UV is the best and cheapest technology for inactivating *Cryptosporidium*, I can’t imagine it won’t take off in a big way. I think UV will become a standard disinfection technology.”

Mark LeChevallier, director of innovation and environmental stewardship at American Water, concurs. “*Cryptosporidium* was the Freddie Krueger of water treatment—you couldn’t kill it!” he said. “You’d throw chlorine at it, but it kept coming at you. Finding its Achilles heel in UV was a real advance. We’ve only touched the tip of the iceberg in terms of UV’s application.”

LeChevallier thinks UV is likely to be more cost-effective than membranes for retrofitting large-volume surface water treatment plants. “It’s also a relatively easy retrofit,” he added.

Referring to a current AwwaRF project being conducted by Paul Rochelle, principal microbiologist at Metropolitan Water District of Southern California, LeChevallier said, “If Rochelle’s study confirms our published results showing that low concentrations of live *Cryptosporidium* are getting through the treatment plant, then UV may be installed in virtually every surface water plant. It will dramatically change the way we treat drinking water.”

Like Clancy, LeChevallier believes the LT2 Rule will move some utilities with poor source water quality toward using UV, but he thinks this is just the beginning. “I liken this process to chlorine use,” he said. “US utilities first started to use chlorine as a disinfectant in 1906. By 1920, most systems used chlorine disinfection. Now in 2006, I think we’re on the beginning of that curve with UV. I’m not sure how soon most utilities will be using UV—maybe by 2020.”

Noting that UV disinfection also has the potential to reduce DBP concentrations, LeChevallier describes UV as “a technology that solves the two major problems we’ve been battling over the past 30 years—the appropriate level of disinfection for controlling microbial pathogens and minimizing DBPs. AwwaRF has been instrumental in providing the basis of our understanding of both these issues.”