PROGRAM ON TECHNOLOGY INNOVATION: State of the Art Assessment of UV-C LED Water Treatment Technology

Introduction

Ultraviolet (UV) technology is based on UV light, which is shorter in wavelength than visible light. UV light ranges from 100 nanometer (nm) to 400 nm and falls between visible light and X-rays on the electromagnetic spectrum. UV light is further categorized into:

- UV-A: 315-400 nm
- UV-B: 280-315 nm
- UV-C: 200-280 nm
- Far UV: 100-200 nm

UV-C light has been used for several decades for disinfection and is well-established as a means of controlling pathogens in water. Specifically, UV-C light penetrates the pathogen's cell and damages its DNA to prevent replication. Today, UV-C light is primarily generated with mercury vapor lamps. Much like light emitting diodes (LEDs) have revolutionized the general (visible spectrum) lighting industry, UV-C LEDs are set to rapidly replace conventional mercury vapor lamps and are now viewed as next-generation light sources in water disinfection and water reuse applications.

State-of-the-Art UV-C LED Water Disinfection Technology Overview

UV-C LEDs emit light in a continuous spectrum across a very specific, narrow band typically not wider than 20 to 30 nm. These types of LEDs are therefore considered monochromatic light sources. The peak emission wavelength within this narrow

band can generally be tailored for the greatest overlap with the most critical wavelengths required for targeted pathogen disinfection.

The first commercial-scale UV-C LED came on the market in 2008.[1] With modern UV-C LEDs, the intensity of the light, measured in mJ/cm^2, depends greatly on and decreases with the wavelength as it gets shorter. As a result, UV-C LEDs have lower wall-plug efficiencies (WPE)—the ratio of optical output to electrical input—than UV-B and UV-A LEDs. Typical WPE values for commercially available UV-C LEDs are 2-5%,[2] but research teams and LED manufacturers have reported WPE values of 10-12%.[3,4] To compensate for the lower WPE values of UV-C LEDs compared to those of conventional mercury vapor lamps, the UV disinfection reactor must be designed with a higher efficiency to improve the overall disinfection system efficiency. Improved UV reactor efficiency is often achieved with advanced optics and/or by creating rotational motion in the water using vanes, venturi tubes, and the like to effectively distribute the light.[5]

Key Flow-Through System Vendors and Research Organizations

While there are more than 60 manufacturers of packaged UV-C LED modules, there are currently less than fifteen vendors producing flow-through UV-C LED water disinfection systems; even fewer that offer larger-scale systems. Table 1 summarizes current vendors along with their primary target applications, system treatment capacities, and product status (e.g., commercially available, evaluation units available, or development/piloting). Treatment capacities are typically reported in liters per minute (lpm) for smaller flow-through systems, and in gallons per minute (gpm), cubic meter per hour (m^3/hr), cubic meter per day (m^3/day), or million gallons per day (MGD) for larger flow-through systems.

Most system vendors have developed point-of-use (POU) or point-of-entry (POE) systems with capacities less than 20 lpm. However, a few vendors have developed larger-scale systems for water disinfection. They include Typhon Treatment Systems (UK), MetaWater (Japan), and AquiSense Technologies (U.S.).

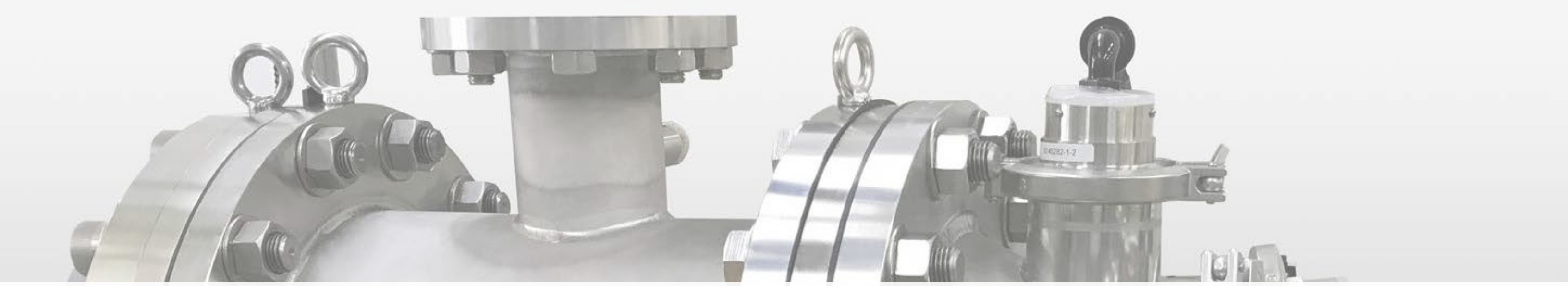
Figure 1 shows the 250 m^3/hr unit developed by Typhon Treatment Systems. This unit has been successfully field tested on drinking water by United Utilities in the UK, who recently ordered an additional six units to be combined into a large system for deployment at the Cumwinton Water Treatment Works in early 2020.[6] Metawater has developed three larger-scale flow-through units with treatment capacities of 300, 1,200, and 2,000 m^3/day.[7] One Metawater unit is currently being field tested on municipal wastewater at the Rock River Water Reclamation District, IL. (See Figure 2.) Finally, AquiSense Technologies has developed several pilot units with treatment capacities in the 10 to 30 gpm range that EPRI in collaboration with U.S. EPA has tested on both drinking water and municipal wastewater at the EPA Test and Evaluation Facility in Cincinnati, OH. (See Figure 3.)

There are more than 50 research organizations globally studying UV-C LED water disinfection. Notable organizations include the U.S. Department of Homeland Security, University of Colorado, University of Cincinnati, NASA/Jet Propulsion Laboratory, Fraunhofer IOSB, Sheffield University, and University of Tokyo.

Potential Applications of UV-C LED Water Disinfection Technology

Any applications where conventional mercury vapor lamps are currently used for disinfection are good candidates for UV-C LED technology replacement systems. Additionally,

1 Communication with Jennifer Pagan, CTO, AquiSense Technologies, October 2, 2019.
2 Ibid.
3 Ibid.
4 Khan, A., *UV-C LEDs and lasers: low-voltage light sources for killing germs*. April 8, 2016. URL: http://spie.org/newsroom/6373-uv-c-leds-and-lasers-low-voltage-light-sources-for-killing-germs
5 Communication with Jennifer Pagan, CTO, AquiSense Technologies, October 2, 2019.
6 Aqua Tech, World's Largest UV-C LED Installation Moves Forward, 2019-08-16. URL: https://www.aquatechtrade.com/news/article/worlds-largest-municipal-uv-led-installation-moves-forwards/
7 Ibid.



there will be many new applications where mercury-free operation and the smaller size of UV-C LEDs are highly valued. Table 2 summarizes potential UV-C LED water disinfection applications, categorized by end-use sector.

Table 1. Vendors with Flow-Through UV-C LED Water Disinfection Systems

Vendor (Country)	Primary Target Applications	Treatment Capacities	Product Status	URL
Acuva Technologies (Canada)	Residential, remote, mobile	1-10 lpm	Commercially available	https://acuvatech.com/
AquiSense Technologies (U.S.)	Residential, commercial, transportation, life sciences, mobile, emergency, research	0.5-40 lpm for commercial units, and 12-200 gpm for pilot units	Commercially available, except for larger systems which are under development/piloting	https://www.aquisense.com/
Canopus Water Technologies (U.S.)	Residential, commercial, industrial	25 gpm for standard unit, and 60 gpm for custom units	Evaluation units available	https://canopuswatertechnologies.com/
Crystal IS (U.S.)	Residential, commercial, healthcare, life sciences	0.4-2 lpm	Evaluation units available	https://www.klaran.com/
HCEN (China)	Consumer, residential	1-15 lpm	Commercially available	
Hytecon (Switzerland)	Residential, commercial	3-60 lpm	Evaluation units available	https://www.hytecon.com/
ITRI (Taiwan)	Residential, emergency	2 lpm (solar-powered)	Evaluation units available	https://www.itri.org.tw/eng/DM/PublicationsPeriods/1002343514337702341/content/spotlight3.html
Metawater Ltd. (Japan)	Industrial, municipal	300, 500, and 1,200 m^3/day	Development/piloting	http://www.metawater.co.jp/eng/news/detail/20181022diz.html
QD Jason (China)	Consumer, residential	N/A	Evaluation units available	http://www.qdjason.com/en/about.aspx?id=7
SleipnirLED (Taiwan)	Residential, commercial	0.6-8 lpm	Evaluation units available	http://www.sleipnirled.com/product_cg277844.html
Stanley Electric (Japan)	Residential, commercial, industrial	1-5 lpm	Evaluation units available	https://www.stanley-components.com/en/product
Typhon Treatment Systems (UK)	Industrial, municipal	250 m^3/hr	Development/piloting	http://www.typhontreatment.com/
Watersprint (Sweden)	Residential, commercial, mobile, emergency	2-20 lpm	Commercially available	http://www.watersprint.se/

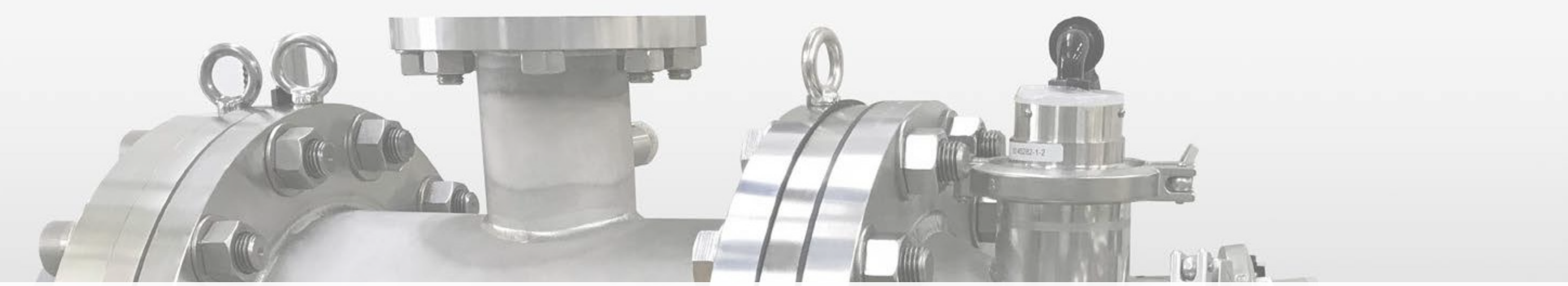


Table 2. Potential UV-C LED Flow-Through Water Disinfection Applications

Drinking Water & Municipal Wastewater Treatment Plants	Power Plants	Industrial Plants	Commercial Buildings	Healthcare Facilities	Homes	Emergency
• Disinfection of municipal drinking water • Disinfection of municipal wastewater	• Biofouling control for water intake pipes and water circuits (e.g., inactivation of mussels, clams, barnacles, algae) • Disinfection of cooling tower water (control of Legionella) • Surface water TOC destruction to inhibit steam turbine corrosion	• Point-of-use water disinfection for faucets, workstations • Disinfection of aquaculture water, process water • Clean-in-Place (CIP) procedures for process equipment, barrels, bottles • Disinfection of wastewater prior to discharge • Disinfection of wastewater, rinse water, chiller water for water reuse • Disinfection of cooling tower water (control of Legionella)	• Point-of-use water disinfection for faucets, showers • Disinfection of pools, spas, pump filters • Point-of-entry water disinfection • Point-of-exit water disinfection for water reuse • Disinfection of cooling tower water and water networks (control of Legionella)	• Point-of-use water disinfection for faucets, showers, medical instruments • Clean-in-Place (CIP) procedures	• Point-of-use water disinfection for faucets, refrigerators, showers, wells, remote communities • Point-of-entry water disinfection • Point-of-exit water disinfection for water reuse	• Emergency disinfection of drinking water after natural disasters • Emergency disinfection after environmental spills • Emergency disinfection after terrorist attacks, biological warfare

Technical Potential and Preliminary System Costs

In the last 20 years, municipal wastewater treatment plants have increasingly replaced chlorine gas with either sodium hypochlorite or UV light. Today, conventional mercury vapor lamp-based UV disinfection is used by an estimated 38%[8] of U.S. municipal wastewater treatment plants, ahead of both sodium hypochlorite (32%) and chlorine gas (23%). The UV disinfection share in U.S. drinking water facilities is smaller (7%)[9] but growing as more and more plants replace chlorine as a primary disinfectant with an alternative disinfectant to reduce the formation of harmful by-products.

The technical potential associated with the disinfection of municipal wastewater and drinking water using UV-C LED disinfection technology is significant. EPRI estimates the technical potential at 3.1 to 3.7 TWh per year. Because large-scale UV-C LED water disinfection technology is still undergoing field testing and reactor optimization, total system costs are unavailable. Preliminary assessments indicate these emerging disinfection systems will have total system costs of approximately $1,000 per gallon per minute.

8 Josh Goldman-Torres et. al. *Current and Historical Wastewater Disinfection Practices: A WEF Survey*. Presented at WEFTEC 2019.
9 American Water Works Association, 2017 Water Utility Disinfection Survey Report, April 2018. URL: https://www.awwa.org/Portals/0/AWWA/ETS/Resources/2017DisinfectionSurveyReport.pdf?ver=2018-12-21-163548-830

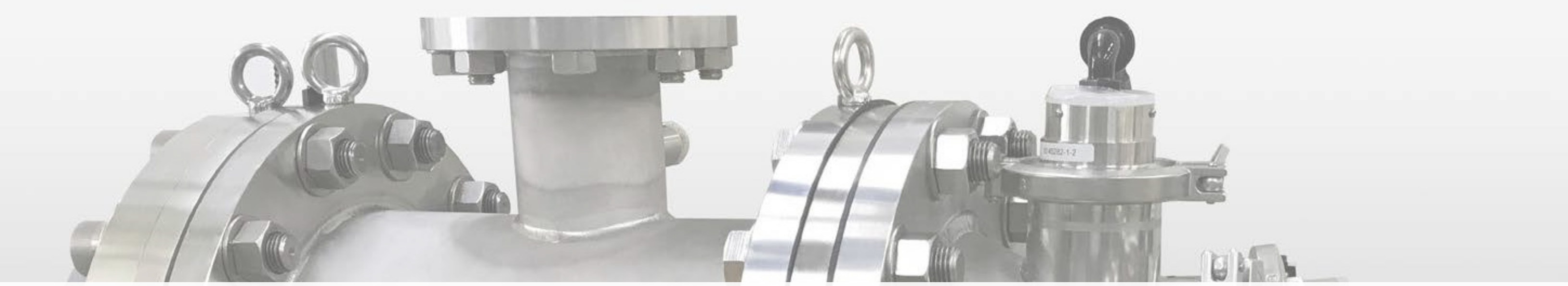


Figure 1. 250 m^3 per hour (~1100 gallons per min) UV-C LED Water Disinfection System
Courtesy of Typhon Water Treatment Systems Ltd.

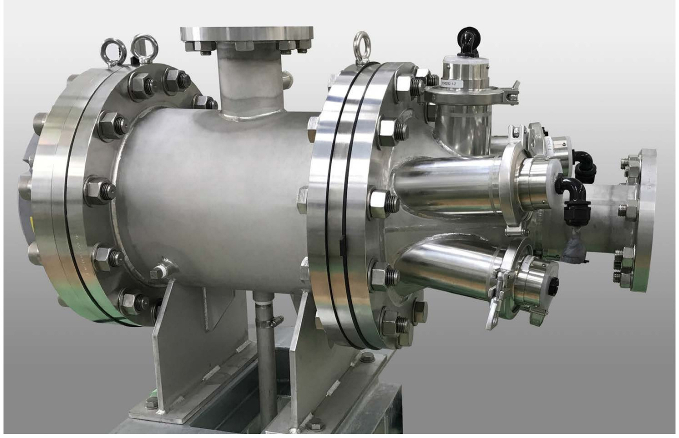


Figure 2. 300 m^3 per day (~55 gallons per min) UV-C LED Water Disinfection System
Courtesy of Metawater Ltd.

Figure 3. 20 gallons per minute UV-C LED Water Disinfection System
Courtesy of AquiSense Technologies

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY ITS TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY EPRI.

THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

APPLIED ENERGY GROUP,
500 YGNACIO VALLEY RD.,SUITE 250, WALNUT CREEK, CA 94546

PRINCIPAL INVESTIGATOR
C. ARZBAECHER.

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

Note

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI members represent 90% of the electricity generated and delivered in the United States with international participation extending to 40 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; Dallas, Texas; Lenox, Mass.; and Washington, D.C.

Together . . . Shaping the Future of Electricity

Contact Information

Baskar Vairamohan, Principal Technical Leader, Electrification Program
865.218.8189, bvairamohan@epri.com

3002017551 December 2019

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA • 800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

© 2019 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute, EPRI, and TOGETHER . . . SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.