UV-C LED Devices and Systems: Current and Future State

Oliver Lawal, Jim Cosman and Dr. Jennifer Pagan, AquiSense Technologies LLC
Contact: (859) 869-4700 or info@aquisense.com

Introduction

Light emitting diodes (LEDs) are semiconductor devices that produce photons based on an input current. Depending on the composition of the LED, it can produce photons at wavelengths anywhere from infrared, visible, and – since the turn of the century – in the deep UV (UV-C) range. The introduction of UV-C or germicidal LEDs that emit 240 to 280 nm will have a profound impact on the water, air and surface disinfection markets as society continues to seek more reliable, efficient, and environmentally friendly light sources for disinfection applications. Whether UV-C LEDs will eventually replace all traditional mercury-vapor based UV lamps for conventional disinfection applications is yet to be seen; however, it is clear they are already enabling the creation of entirely new disinfection applications due to a number of different characteristics, including:

1. Mercury-free – Conventional UV lamps contains up to several hundred milligrams of mercury in a liquid or amalgam form. However, UV LEDs are mercury-free and contain only tiny elements of metals held within a crystalline structure that has no ability to leach in case of breakage or disposal.
2. Compact footprint – High-power-density UV-C LEDs and advanced controls allow for a much smaller footprint compared to traditional UV sources and their electronic drivers.
3. Instant on/off – Unlike gas discharge lamps, UV LEDs can be switched on and off without any warm-up times. This enhances power savings and leads to prolonged lamp replacement intervals in batch process applications.
4. Unlimited cycling – Lamp life is not impacted by on/off cycles, allowing for unlimited lamp cycling.
5. Temperature independent – LED photon emission is from a different surface as the heat emission meaning they can be engineered not to transfer heat into the water, thus reducing fouling rates and ensuring a constant UV output, regardless of the water temperature.
6. Wavelength selection – The ability to select a specific output wavelength of an LED enables closer matching to peak absorption spectra of a target organism.

All the above incremental benefits associated with UV-C LEDs should be accounted for when comparing the viability of implementing a UV-C LED based system vs. a traditional

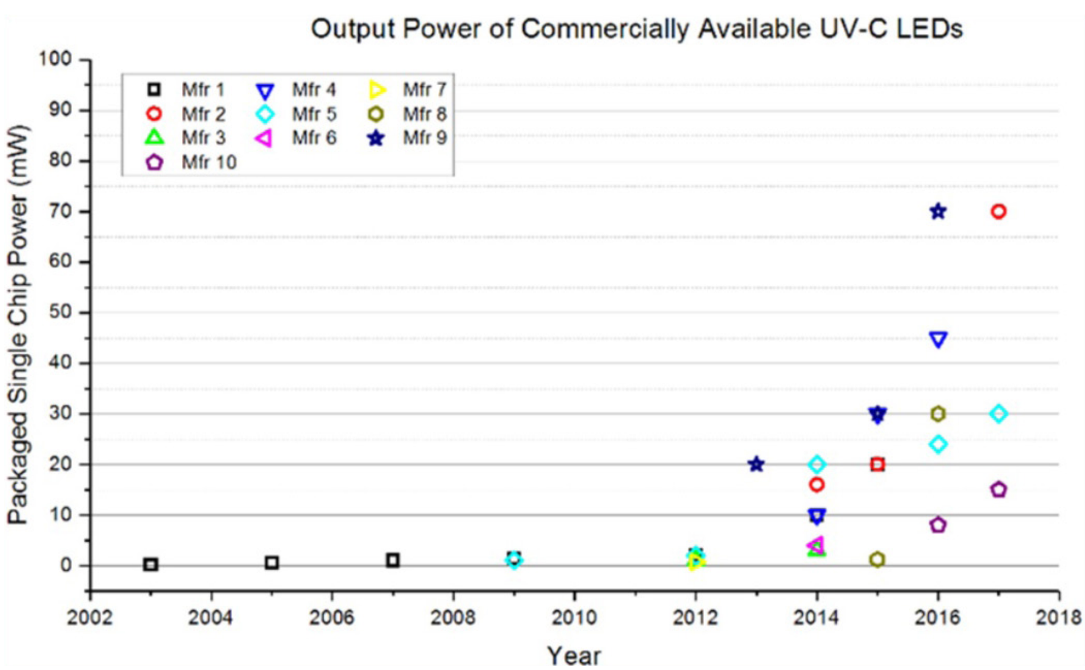


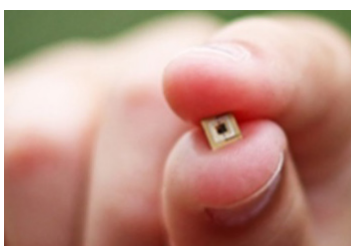
Figure 1. Measurement data of commercially available UV-C LED devices. Source: AquiSense Technologies

mercury lamp-based system. In some cases, these benefits create new applications for UV treatment technology and can even reduce the overall cost of implementation through the reduction of additional associated components.

Market development – UV-C LED devices

The first UV-C LED devices were developed primarily in Japan, Korea and the US, as extensions to LED devices emitting in the blue and then UV-A and UV-B wavelength region. As seen in Figure 1, the increasing output power of commercially available UV-C LEDs since 2002 has accelerated since 2012. This data is based on AquiSense internal test data of only commercially available devices and excludes "hero devices" reported in the literature and should not be considered exhaustive.

Early UV-C LED devices were primarily packaged in relatively expensive and thermally inefficient TO-type housings (Figure 2a). This mostly limited their application to analytical instrumentation as a replacement for laser, deuterium, and mercury-vapor light sources. However, as increased investments were made in manufacturing capacities, the first Surface Mount Devices (SMDs) (see Figure 2b) became available around 2013. This enabled lower costs and higher production volumes and were more suitable for integration into disinfection products.



Figures 2a and 2b. From left to right: (a) Early UV-C LED device in TO packaging. (b) Typical UV-C LED device in SMD packaging. Source: AquiSense Technologies

At least 12 corporations manufacture UV-C LED devices, although not all currently offer commercial products. Current best-in-class devices deliver UV-C optical output values in the 50 to 100 mW range, with lifetime to 70% of initial output (L70) of around 10,000 hours. It should be noted that there is a high degree of variability between the testing methods and, hence, specification reporting data of each device manufacturers. For example, UV-C optical output values are reported at a wide range of forward operating currents from 50 mA to 600 mA. This data does not always correspond directly to reported lifetime data and inherently makes datasheet like-for-like comparisons problematic. The IUVA have undertaken a project to standardize device output measurement methods, reported separately within this publication. Regardless, for a UV product designer, there should be no substitute for completing independent testing – ideally using identical conditions to those within the intended product.

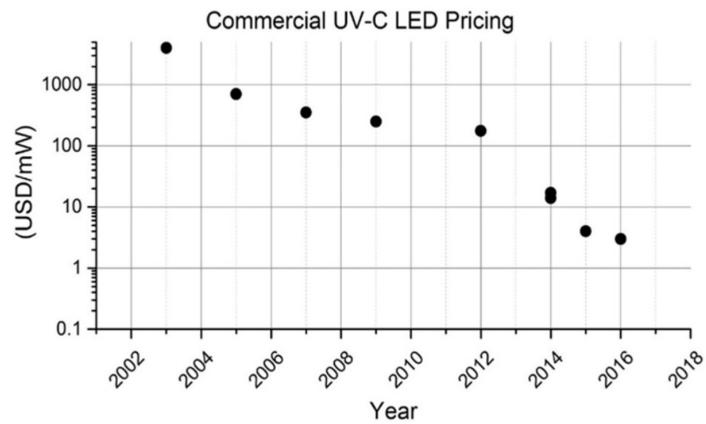


Figure 3. Commercial UV-C LED pricing. Source: AquiSense Technologies

Figure 3 illustrates historical UV-C LED device pricing on a per mW optical output basis. This trend is related to increased manufacturing capacity, improved manufacturing yields, refinements in packaging engineering designs, and increased manufacturer competition. In 2018, the lowest market price has fallen below US $1/mW for premium, higher powered devices and below US $0.5/mW for lower powered, lower lifetime devices[1].

Market development – UV-C LED systems

Early stage product development of UV-C LED-based UV disinfection systems has been challenging, due to the historical high cost of UV-C LEDs, coupled with low optical power output. Entirely new thinking and design approaches are required to fully utilize this new light source. However, despite this, some product and market development has occurred for water, surface and air disinfection products, particularly with start-up companies.

Figure 4. Selected examples of UV-C LED water disinfection systems

Commercially available systems are typically targeting flow rates below 20 lpm and specific applications that are chal-

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lenging for gas discharge lamps. For example, the extremely small footprint potential of UV-C LED-based systems has enabled them to be incorporated directly in faucets and appliances. UV-LEDs' mercury-free status has led to these systems being incorporated into medical devices and aerospace applications where conventional UV systems were often discounted due to potential breakage and contamination risk.

Table 1 highlights example applications within key market segments where UV-C LED-based water disinfection products are currently being evaluated by OEM manufacturers globally. The technical and market drivers for this evaluation work is related to the unique characteristics of UV-C LED-based products previously discussed, but are not equal, homogeneous or even initially obvious, across each application.

Case study 1: Space exploration and habitats

Currently, 88% of the water on the International Space Station (ISS) is reused, leaving 12% lost to waste, roughly 100 ml per person per day. Monthly resupply missions are needed to bring vital resources that cannot be recycled in-orbit. This delivery service uses a 3 million horse-power rocket to catch-up and dock with the ISS as it speeds around the Earth at 17,000 mph; this is a very expensive task, costing approximately $2000 per lb of cargo.

BIOWYSE, a European Union Horizon 2020 funded project, was launched to develop and test a new type of system that uses real-time microbial monitoring (ATPmetry) and UV-C LEDs for disinfection. The intent of the project is to develop an integrated, autonomous, chemical-free system to control and monitor biomass growth in potable water systems aboard the ISS. Two years in to the project, the consortium has devel-

Table 1. Key market segments that value UV-C LED solutions

Market segment	Example applications	UV-C LED system benefits: Top 3 important attributes valued by segment
Residential	POE Appliances Faucets	Ultra-compact footprint Plug and play (e.g. easy to retrofit) Low power draw
Commercial	Food and beverage service Water dispensers and fountains	Ultra-compact footprint Low power draw No heating of water
Health care	HAI control Dialysis Dental	Mercury-free Chemical-free Durable (e.g. vibration resistance)
Transportation	RV and boating Automotive Aviation Space	Chemical-free Durable Lightweight
Life sciences	Bio-pharma Ultrapure water	Point-of-use distribution Mercury-free Chemical-free
Defense/emergency response	Personal hydration Remote treatment	Ultra-compact footprint Lightweight Durable (e.g. vibration resistance)

oped the main components of the system, which include several advanced technologies, such as AquiSense Technologies' UV-C LED Decontamination Module. The next stage of the project will see integration followed by laboratory and field testing through to the end of 2018.

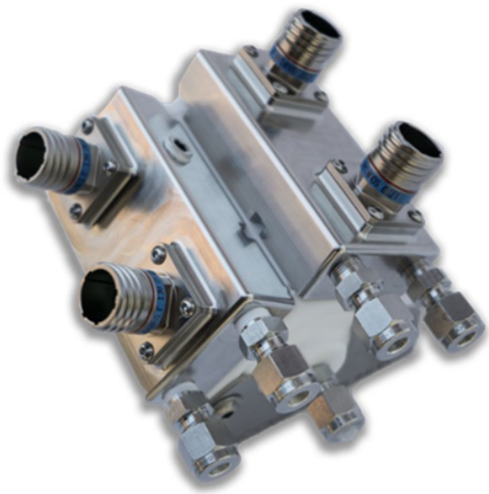

Figure 5. UV-C LED disinfection module used in BIOWYSE ISS project. Source: AquiSenseTechnologies

Case study 2: Biofilm control

Water cooler products for residential, commercial, and industrial applications are known to generate growth of biofilm in their static water storage components. UV-C LED lamp modules have been integrated into these products. A review of these solutions indicates that most are using very low optical output devices in the 1 to 3 mW range. While it is not clear that the level of applied fluence is homogenous or of a high level, the commercial introduction into high-production volume products shows a demand for such technology that is likely to have a positive impact on price reduction of UV-C LED devices.

Figure 6. Example of a low optical output stationary UV-C LED module. Source: LG Innotek

Case study 3: Commercial steam oven

Low-temperature steam ovens are used to cook food over long periods of time, at temperature ranges of between 30°C to 300°C. This warm, moist environment has the potential to propagate the growth of harmful pathogens such as *Listeria*, *Salmonella*, *Clostridium* and *E. coli*. To mitigate this risk, Disform Food Service Technology worked together with AquiSense Technologies to integrate a disinfection module into their MyChef product.

The key design parameters – intermittent flow, small envelope, high ambient temperature, and 4-log pathogen reduction – were used to specify the PearlAqua Micro system. Performance validation included microbiological bioassay, long-term aging, temperature and vibration tests, with volume production commencing in mid-2017.

Figure 7. UV-C LED disinfection module used in commercial steam oven. Source: Disform Food Service Technology

UV-C LED devices and systems: future state

The future of UV-C LED devices and systems is a hotly debated topic amongst the UV community. The current focus and discussion is on the relatively low efficiencies and optical outputs of the individual UV-C LED devices reported in the literature, compared to the largest available mercury-vapor UV lamps. However, it is more helpful to consider the product performance of commercial UV-C LED-based products in the sub-20 lpm range, to similar capacity conventional mercury-vapor lamp products. Already, market experience has demonstrated that users are demanding disinfection solutions with the unique benefits offered by UV-C LED sources and are willing to integrate these new solutions. In some cases, the cost is lower, and in other cases, users are prepared to pay a premium to do so. In most cases, however, UV-C LED solutions are creating new applications for UV tech-

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EXHIBITING COMPANIES
(As of January 28, 2018)

Aal Chem
Alberdingk Boley, Inc.
Allnex
American Ultraviolet
AMS Spectral UV - A Baldwin Technology Co.
BCH Brühl
BYK USA
Carestream Contract Manufacturing
CB Mills
CFCM Magazine
Changzhou Tronly Advanced Electronic Materials Co. Ltd
Chitec Technology Co, Ltd.
Clearstone Technologies
Colorado Photopolymer Solutions
Daicel ChemTech, Inc.
DSM
Dymax Oligomers & Coatings
EIT Instrument Markets
Energy Sciences Inc.
Evonik Corporation
Excelitas Technologies
GEW, Inc.
Gold Array Technology Beijing LLC
GURUN
Hampford Research
Hauthaway
Heraeus Noblelight America
Honle UV America
Hybrid Plastics Inc.
IGM Resins USA, Inc.
IMI
Innovations in Optics
IST America ITL
Jelight Company, Inc.
Jiangsu Tetra New Material Technology Co., Ltd.
Keyland Polymer Material Sciences, LLC
King Brother Chem Co., Ltd
Kopp Glass
Kowa American
Kromachem Inc.
LG Innotek
Melrob US, Inc.
Miltec UV
Miwon North America
Nagase America
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nology, rather than displacing existing gas discharge lamps. But, how do scientists assess the opportunity in the next two decades? How will this technology progress?

A good starting point is an examination of Haitz's Law, developed by Dr. Roland Haitz, who has been characterized as the "Godfather of LEDs." It states that every decade, the optical output of an LED will increase by a factor of 20, while the price per optical output will fall by a factor of 10.

A review of the progression of Output Powers of Commercially Available UV-C LEDs in Figure 1 and Commercial UV-C LED Pricing in Figure 3 suggests that UV-C LED devices development is following this predictable path. Based on this trajectory, the implication for 2026 is 1.4 Watt per LED at 0.1 $/mW. This position can be further validated by reviewing research literature of developmental UV-C LEDs, see figure 8. Internal Quantum Efficiencies (IQE) values of UV-C LEDs have long been shown to be comparable to visible LED devices, above 75%. Thus, research focus is centered on alternative light extraction techniques to increase the External Quantum Efficiency (EQE) yields of operational devices.

The future for UV-C LED systems lies at the intersection of multiple factors. Optical output levels of commercial devices have now been reported in the 100 mW range, and, inevitably, LED device efficiency will increase from current levels. Costs will continue to decrease as supply increases. In parallel, system engineering for UV-C LED-based systems is evolving as system designers are beginning to realize that entirely new thinking and design approaches are required to fully utilize this new light source. The result is that larger systems will be developed (see Figure 9 on page 28).

Will the Minamata Convention drive UV-C LED growth?

The Minamata Convention on Mercury was initiated by the United Nations Environmental Programme (UNEP) to protect human health and the environment from anthropogenic emissions and releases of mercury. The UNEP has set the goal for mercury to be phased out of production by the year 2020. In 2013 they asked organizations and governments to discourage the use of mercury starting immediately

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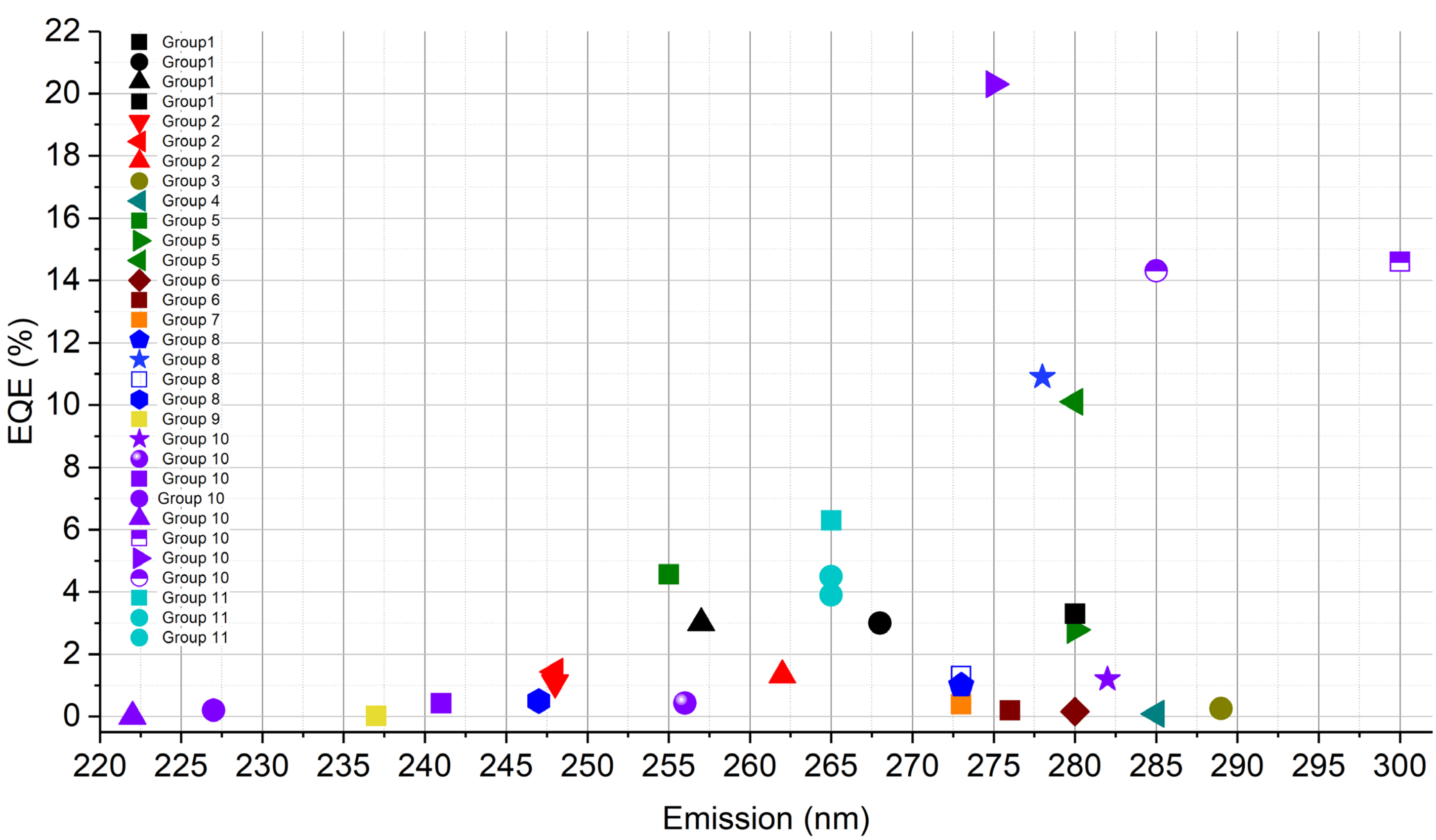

Figure 8. Reported external quantum efficiencies for UV-C LEDs. Source: AquiSense Technologies

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Figure 9. UV-C LEDs' path to commercially available larger systems

unless there is a substantial benefit to the environment and human health. As of August 2017, the convention has been ratified and has officially entered into force.

Although the Minamata Convention does not specifically prohibit the manufacture and sale of UV mercury-vapor lamps, it could provide a generally positive influence for the more widespread adoption of alternative technologies. For example, if UV-C LED systems can achieve disinfection performance, capital cost and operating cost values close to those of conventional technologies, then the following user groups may respond as follows:

1. Corporations that use UV systems in products or manufacturing processes (e.g. white goods, beverage, microelectronics, life sciences, etc) may implement best practices by selecting an LED option by influence of the Minamata Convention, not by enforcement. This may especially factor into decisions on new product development where 20+ year product lifecycles are considered.

2. Original Equipment Manufacturers that currently employ gas-discharge lamps may see a conflict with the use of mercury-based products to their own environmental policies and, based on Minamata regulations, might start a transition to develop new products using mercury-free light sources – again having consideration to long product lifecycles.

3. Municipalities may also follow suit in adopting UV-C LEDs, although it is more likely that they will require more time to adopt the new technology. Once a generalized mercury regulation takes place, states and municipalities will begin to critically review their processes for any potential violations and improvements.

4. There will always be a percentage of people that will look for "eco-friendly" product options. As the Minamata Convention raises awareness of the effects of mercury, it inherently effects the use of mercury-based lamps without banning the sale or manufacturing of these lamps. Because of this, end users may choose LEDs over mercury lamps, even if they are more expensive, just as can be seen in the visible light market with CFL and LEDs.

5. Regulators will likely have a slow transition from mercury to UV-C LED lamps. Regulators will always look for viable alternatives to mercury, as it is their mandate to steer technology to the most holistically sound solution.

Conclusion

The introduction of UV-C LEDs will have a profound impact on the water, air, and surface disinfection markets. They may not replace traditional UV lamps for disinfection applications but have already created new disinfection applications as a result of the numerous incremental advantages over traditional mercury lamps. While the optical output and efficiencies of UV-C LEDs remains relatively low, it is critically important to examine the full value proposition of a UV-C LED disinfection solution by fully monetizing the unique benefits of such a solution. As the price per mW lowers, more applications and markets will become available. While the inevitable replacement of mercury vapor lamps is eventually coming, UV disinfection technology has an exciting future, as it is working its way into markets and applications not previously possible. ■

References

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