48th International Conference on Environmental Systems
8-12 July 2018, Albuquerque, New Mexico
ICES-2018-153

Low-maintenance, consumables-free disinfection by UV-C LEDs

Richard M. Simons[1], Jennifer Pagan[2] and Oliver Lawal[3]
AquiSense Technologies, Erlanger, Kentucky, 41808

Ultraviolet (UV) disinfection has long been known as a chemical-free disinfection process capable of producing a 6-log reduction effect. Conventional UV sources, often called germicidal lamps, consist of a mercury amalgam encapsulated within a quartz sleeve and function by a plasma discharge mechanism; critically, the low durability and mercury content of these devices have limited their application within space environments. UV-C LEDs can produce the same disinfection effect as conventional germicidal lamps without many of the key drawbacks. Based on semiconductor technology, UV-C LEDs provide a high durability, DC-powered, long lifetime, mercury-free, small footprint, and low maintenance solution to the disinfection of air, water, and surfaces. As semiconductor devices UV-C LEDs are ideal for integration into reactive and controllable systems with real-time feedback, and capable of response times as short as 10 ns. UV-C LEDs have already been deployed on-orbit within the Microgravity Science Glovebox (MSG), are included within the Advanced Closed Loop System (ACLS), and perform a key function of the BIOWYSE system breadboard. We present a background to the technology, the development of UV-C LEDs to their current capabilities, and how these devices may be integrated into next-generation disinfection systems.

Nomenclature

AlGaN = Aluminium gallium nitride
DNA = Deoxyribonucleic acid
GaN = Gallium nitride
HEPA = High efficiency particle air
HVAC = Heating, ventilation, and air conditioning
LED = light emitting diode
LRV = Log reduction value
POE = Point of entry
POU = Point of use
RNA = Ribonucleic acid
SMD = Surface mount device
UV = Ultraviolet radiation
UV-C = Electromagnetic radiation within the 100 – 280 nm range
UVGI = UV germicidal Irradiation
UVT = UV Transmittance
WPE = Wall plug efficiency

I. Introduction

UV-C LEDs shall be presented as an emerging technology for the control of microbial contamination. A background to the technology, its fundamental principles, and the state of the art shall be discussed; the aim of which is to furnish the reader with a good understanding of the technology and its operation, such to provide context for the subsequent discussion. Areas of application, being present, planned, and potential, shall then be reviewed in the context of this knowledge with a specific focus on scenarios relevant to life support systems.

---

[1] Product Development Scientist.
[2] Chief Technical Officer & Founder.
[3] Chief Executive Officer & Founder.

II. UV Disinfection

A. History

The germicidal effect of ultraviolet light was first discovered in 1877[1] following the inhibition of culture formation in growth solution left on a windowsill versus those stored in the dark. By 1910 it was understood that shorter wavelengths (UV-C) showed the greatest inactivation efficacy and effective UV-C sources were developed. Research into the inactivation of *E. coli*[2], showed the optimum inactivation wavelength for that microbe to be ~ 260 nm.

The technical difficulties in producing and maintaining a reliable UV disinfection facility, coupled with the introduction of chlorination during the 1920's, meant that several decades passed before the first water disinfection facilities using UV were introduced in Switzerland and Austria in 1955. The technology later spread to Norway in 1975, and by 1985 over 1500 installations existed in Europe[3]. Over a similar period, UV germicidal irradiation (UVGI) lamps grew in usage for air and surface disinfection applications. These devices are predominantly used in laboratory and medical facilities[4], and in HVAC systems for public spaces[5].

Implementation in Europe continued over the proceeding decades, but the technology did not reach mainstream usage for municipal water treatment in North America until the late 1990's, following the discovery of its effectiveness in treating the chlorine-resistance organism *Cryptosporidium*. In 2006 the United States Environment Protection Agency (US EPA) issued the Ultraviolet Disinfection Guidance Manual (UVDGM)[6], further increasing the application of UV systems.

Today, UV disinfection systems are widely used across large-scale water treatment for wastewater and potable water, in consumer products such as water coolers, building-scale HVAC systems, and laboratory equipment such as sterilisation chambers and fume hoods/gloveboxes.

B. Mechanism

UVGI generally refers to short-wavelength UV, approximately 250 – 300 nm. Photons in this wavelength range have sufficient energy to penetrate microorganisms and cause direct damage to their DNA/RNA. The predominant effect is the formation of pyrimidine dimers between adjacent Thymine bases, breaking the intra-helix hydrogen bonds and disrupting the local molecular structure[7]. As such, the majority effect of UVGI is the 'inactivation' of microbial species and not their destruction/removal.

C. Capabilities/Limitations

Microbial management systems employ multi-barrier, multi-stage processes, since all disinfection methods—filtration, heating, irradiation, chemical attack—have their associated benefits and drawbacks. By targeting different mechanisms for microbial control, each stage has a different impact on the microbial community. Selection of a suitable disinfection method must therefore be made from a position of knowledge of the upstream and downstream treatments. Broadly, the key benefits and drawbacks of UVGI are shown in Table 1.

Table 1. Attributes of UV disinfection technology.

Attribute	Impact	Further details
Footprint/Envelope	Variable	>50 cm^3
Consumables	Lamps, electrical power	(1000's hours operation)
Disinfection by-products	Minimal risk of adverse photoproducts	Conditions covered by regulation
Universality	High	Variation in organism susceptibility
Energy requirement	Low	$10 – 10^3$ J L^{-1} (water & air) $10^2 – 10^4$ J m^{-2} (surface)
Residual disinfectant	No	Some bacteriostatic effects
Scalability	Very high	Increased power, arrayed devices
Over-dosing risk	N/A*	*Within the typical UV disinfection range

III. UV-C LEDs

A. Theory of Operation

Light emitting diodes (LEDs) generate light by the radiative recombination of electrons and holes (vacant electron states) across an electron energy band gap: electron transitions from higher- to lower-energy states release energy, generating a photon according to the Planck-Einstein relation, as illustrated in Figure 1.

The energy band gap, and so characteristic photon energy, is defined by the material-specific quantised electron energy states and is a result of non-overlapping orbital energies described by Band Theory.

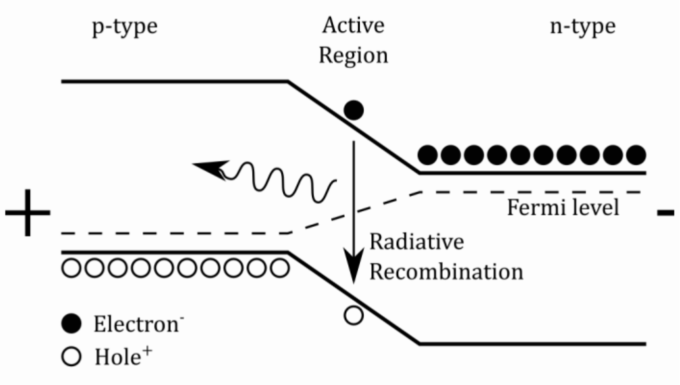

Figure 1. Illustration of the electron band structure across a p-n junction. Radiative recombination of an electron-hole pair within the active region under an applied potential results in the generation of a photon.

Manufacturing of adjacent nanoscale regions of electron-rich (n-type) and hole-rich (p-type) material manipulates the local band structure, creating a p-n junction where recombination is promoted. However, this process introduces an electrical potential across the junction which limits diffusion into the active region, and so recombination. Under an applied external electric field, the potential barrier across the p-n junction is reduced and diffusion of electrons and holes into the region may occur.

Transition of electrons from occupied higher-energy states to unoccupied lower-energy states (holes) releases energy. This energy release may be either radiative (generating a photon of energy equal to that of the transition) or non-radiative (generating heat energy equal to that of the transition). For an LED to function the case of radiative recombination is required, since an applied electric potential may thus be used to generate a radiative output.

The mechanics of radiative and non-radiative electron-hole pair recombination shall not be covered here, though in general radiative recombination is promoted in materials that exhibit a direct band gap, rather than those which exhibit an indirect band gap. Direct and indirect band gaps are determined by variations in electron energy and lattice momentum.

In the synthesis of LED structures, the minimisation of defects within the crystal lattice structure is imperative. Crystal lattice defects impact the efficiency of LEDs by affecting the local band structure in such a way to frustrate the radiative recombination process. Therefore, the concentration of atoms and their arrangement into a perfect structure is controlled at the level of parts per billion. Selection of the material system determines the wavelength of radiation emitted by and LED, as defined by the band gap. The AlGaN material system allows to the production of LEDs across the visible and UV spectral ranges.

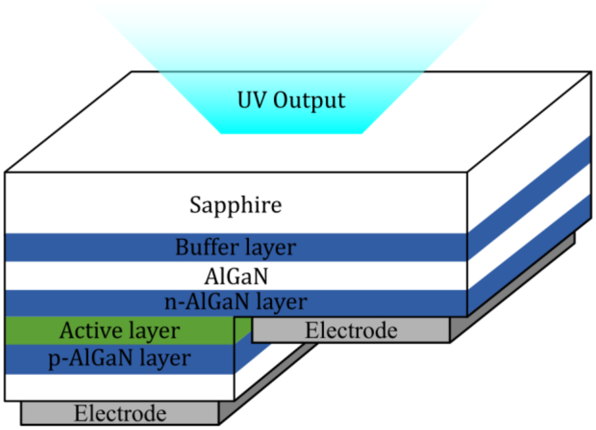

Figure 2. Schematic of the nanoscale epitaxial layers forming a typical UV-C LED.

UV-C LEDs are manufactured by epitaxial ethods, where thin films of material are deposited nto a substrate and the composition of deposited aterial is adjusted to control the resulting properties. n such methods, the structure of the devices may be inely controlled, adjusting composition across anometer scales. The structure of a typical flip-chip V-C LED is shown in Figure 2. A standard UV-C ED chip, once processed, is on the order of 1 mm^2. hese chips may be packaged into single-chip or ulti-chip devices incorporating a protective case and lectrical contacts; surface mount device (SMD) ackages are typically square in shape, measuring 3 – mm on edge and 1 – 2 mm in height.

B. Device Development

Advances in the production of GaN in the early-1990s, which led to high-power blue and white LEDs, spurred the development of UV emitters due to the relevance of such developments to similar AlGaN structures. Within the visible LED market, the association known as Haitz's law (analogous to the Moore's law in electronic devices) predicts a 20x increase in output power and a 10x reduction in cost per lumen for every 10 years of development[8].

Figure 3. a) tracks the single-chip LED output power from early UV-C devices (2003) to present-day. Devices emitting in the 260 – 285 nm range were purchased from ten manufactures and independent measurements made on their optical output power. A trend line representing Haitz's law for optical power is also shown, with the data tracking—and in recent years exceeding—this relationship. Similarly, the cost per unit output power was also recorded, based on the purchase price and measured optical output, Figure 3. b). In this case the measured data tracks closely to the predicted trend through the very early development stage, though a sharp change in gradient occurs around 2013, with a dramatic reduction in price occurring in the following 4 years.

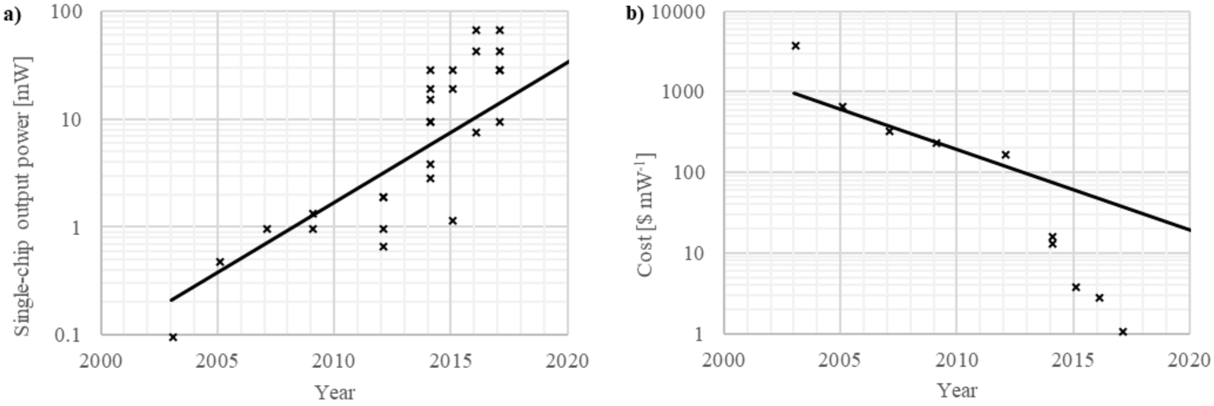

Figure 3. Independent measurement of optical output power, and b) Cost per UV output based on independent device measurements and purchase price, of commercially available LEDs. [Haitz's law relationship, solid line, fitted to early-stage development data spanning 2003 – 2009]

An increase in the number of manufacturers, an overall larger volume demand, and the transition to surface mount device packaging could be cited as a cause for the recent surge in UV-C LED development; particularly, new devices exhibit improved performance and reliability, essential qualities for large-scale commercial viability.

However, challenges remain to improve the efficiency of the devices which remains low (typically below 5% wall plug efficiency, WPE). Photon extraction efficiency—the likelihood of a photon leaving the LED crystal after being generated—is set as the greatest challenge for future improvement in overall device efficiency. This low efficiency is far from a purely academic concern, since it both limits overall device powers and its counterpart describes the heat generation during operation.

Despite ongoing challenges for device manufacturers, all indications point towards continued and even accelerated growth over the coming years, with 100 mW class devices predicted for 2018, and 1000 mW class devices expected before 2025.

C. Device Management

The evolution of UV-C LED output power with operating time is an important parameter which must be considered. Unlike traditional light source technologies, LEDs exhibit a gradual degradation in efficiency (and so output power) over their lifetime. The lifetime of an LED is therefore typically denoted as the time to reach a given relative output power, denoted as L_{70} for 70%, L_{50} for 50%, and so on.

As noted above, thermal control of UV-C LEDs is a significant concern for the system designer. A WPE of 5% equates to a 95% conversion of input electrical energy to heat. The finely controlled crystal structure of LEDs may be disrupted by excessive heat by the promotion of atomic diffusion and the formation of unfavourable structures. Though varying by manufacturer, the maximum safe LED junction temperature is approximately 100°C, and so moderate cooling is required to maintain safe operation; Figure 4 illustrates the effect of improper thermal control on the evolution of UV-C LED output power. The device with poor thermal control is unstable, dropping below 50%

initial output power (L_{50}) within 250 hours, whereas the device for which the heating is properly controlled a greatly reduced degradation is observed.

Historically, the rate of this degradation was a significant limiting factor for UV-C LEDs, with L_{70} values in the 100s of hours. Present-day UV-C LEDs in the 265 – 280 nm wavelength range achieve L_{70} values greater than 10,000 hours.

As discussed, the lifetime of a device is dependent on its temperature, determined by the heat generated by the device, and so the device efficiency and input power. The power requirements of UV-C LEDs vary between manufacturers, product lines, and application. However, a general guide for single-chip devices is a current range of 100 – 500 mA, and a DC potential of 5 – 7 V; thus, each device will consume between 0.5 and 3.5 W.

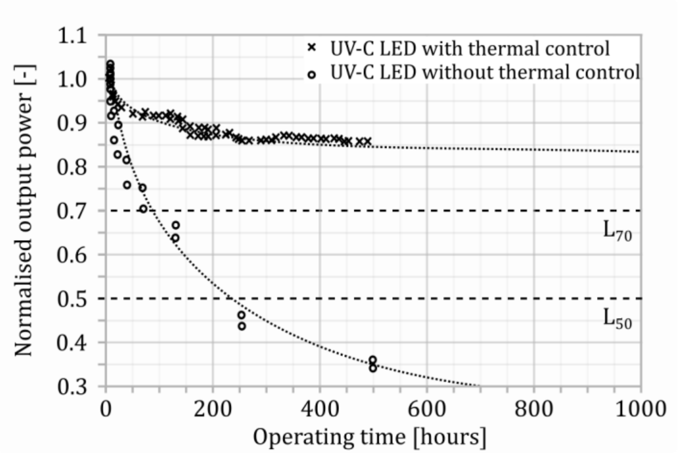

Figure 4. Impact of thermal management on UV-C LED power degradation.

D. Disinfection Effect

The first commercially available UV-C LED devices were produced in 2006[9,10], though the extremely low output powers largely limited their use to sensing applications. As the technology matured and performance improved, researchers were able to investigate the disinfection effect of these narrow-band UV-C radiation sources.

Early investigations aimed to confirm the comparability of disinfection efficacy of deep-UV LEDs (< 300 nm peak emission) to that of conventional UV sources[11-13]. This premise was supported by evidence of the wavelength-dependent germicidal effect of medium pressure Hg lamps[14], which emit radiation across the UV spectrum. A clear wavelength dependence was seen, with the peak efficiency (mW optical power per degree of inactivation) lying approximately within the range 265 – 270 nm, approximately following the action spectrum of DNA/RNA.

As UV-C LED performance improved, a bank of research developed supporting the efficacy of UV-C LEDs in microbial inactivation studies[15]. Compared to the available literature on disinfection by low pressure mercury lamp, the field of UV-C LED disinfection is still young. However, disinfection by UV-C LED has been demonstrated on numerous microorganisms, including: gram-positive bacteria[16], gram-negative bacteria[17,18], viruses[19], and spores[20].

UV-C LEDs differ greatly from traditional UV sources in shape, size, emission profile, power requirement, and more. As a result, dramatically different reactor designs are required to make best use the radiation output and maximise disinfection effect. Several researchers[21-24] have investigated LED-specific designs as well as numerous commercial entities, and research is ongoing to develop ever more efficient reactors.

IV. Implementation and Applications

Broadly, three distinct applications exist for UV disinfection systems: surfaces, air, and water. The compact form factor of UV-C LEDs opens possibilities for new devices in each of these areas.

A. Surfaces

As small DC-powered sources UV-C LEDs are well suited as components to systems for bespoke surface disinfection in semi-enclosed areas with high microbial contamination risk, such as laboratory benches, food preparation areas, and lavatories. In this case UV radiation may be an effective tool in reducing cross-contamination and improving human health, providing an automated, chemical-free solution. In 2014 UV-C LEDs were installed in to the Microgravity Science Glovebox, allowing microbiological studies to be conducted[25].

Another field within surface disinfection is that of the ‘UV autoclave’, such a device employs a closed cabinet into which small items—e.g. medical utensils, laboratory equipment—are exposed to a high dose of UV radiation. UV disinfection in this manner may reduce the risk.

B. Air

Air recirculation systems must manage microbial contamination to avoid the spread of airborne disease. Typically, this may be handled through HEPA (high efficiency particle air) filters, which act as a physical barrier to prevent redistribution of microbes. Though proven to be highly effective, filtration systems by their nature trap and concentrate contaminants; consideration of the lifetime risk reveals the problem of regeneration and/or disposal of the filter.

HEPA filters are presently installed as a magic-bullet device, filtering particles from the sub-micron (bacteria, viruses, and spores) to millimetre (dust, fibres) scales. Trapping microbial contaminants requires a very fine pore size, which increases the rate of clogging and performance degradation. The availability of alternative methods for microbial control within air handling systems would reduce the demand on filtration systems, opening possibilities for new designs with specific focus on particle separation, leading to greater regenerability and lower maintenance.

At present, UV-C LED-based air disinfection systems exist in prototype stage only, mainly as a result of limited LED output powers. As development of the UV-C LEDs continues it is expected that these devices will take a substantial share of the present market occupied by traditional vapour discharge lamp technology, as well as generating new application areas.

C. Water

Wet and humid environments present an inherent risk of microbial contamination, offering favourable conditions for a range of microorganisms. Within water distributions systems the primary rationale for microbial control is typically the preservation of human health. The use of UV-C LEDs for this purpose has been long anticipated, as they are ideally suited to applications such as point-of-use (POU) disinfection on potable water sources. A key benefit of UV-C LEDs is the ability to accurately scale the UV power according to system requirements coupled with long operating lifetimes a single device. The impact of small systems becomes apparent when integrating across their lifetime; a single UV-C LED manufactured today has the potential to disinfect in more than 180,000 litres of drinking water before failure.

Aside from introducing risks to human health, microbial contamination can damage components and reduce system efficacy: biofilm formation can clog filters, obscure sensors, and enhance corrosion. Control of biofilm within process water loops is therefore an important consideration for long-lifetime, low-maintenance systems. The selection of UV-C LED technology for such an application is seen in the ACLS project[26].

V. Drinking Water Systems

A. Background

UV disinfection is a photochemical process, where the target pathogen and UV photon must be coordinated in both space and time. It is necessary for a certain critical degree of damage to occur to induce the inactivation effect, though beyond this limit further irradiation has little impact: over-dosing of UV irradiation therefore constitutes a measurable reduction in energetic efficiency.

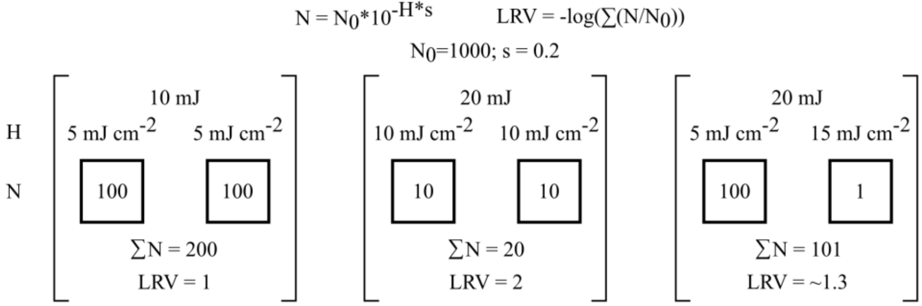

Figure 5. Demonstration of the impact of non-uniform fluence distribution on the overall efficacy of a UV disinfection system. N_0 = starting population, N = surviving population, H = fluence, s = microbial sensitivity, LRV = log reduction value.

The inactivation of microorganisms follows a logarithmic relationship with UV dose (more correctly UV fluence[27]). As such, small variations in fluence can have a dramatic impact on total inactivation. Consider the hypothetical case of two 'cells', each irradiated independently and uniformly, Figure 5. A doubling of the source power, applied equally across the two cells results in a doubling of the inactivation effect. However, if this increase is unequally distributed—non-uniform irradiation between cells—the net impact is significantly reduced. The logarithmic nature of the dependency of inactivation effect on the applied fluence is at the root of the difficulty in designing effective UV disinfection systems.

Practically, and with the aforementioned in-mind, the efficacy of flow-through drinking water systems incorporating UV disinfection relies on two key factors: the homogeneity of residence times and flow paths through the reactor, and uniformity of the irradiation (fluence rate) field, since together these determine the distribution of fluence delivered. A well-designed reactor therefore requires well controlled hydraulic optical characteristics.

Consider the Electrical Energy per Order (E_{EO})[28] as a measure of device efficiency. E_{EO} may be calculated by Eq. (1):

$$E_{EO} = \frac{P}{f \times \log_{10}\left(\frac{N}{N_0}\right)} \tag{1}$$

Where P is the input electrical power, f is the flow rate, and $log10(N/N_0)$ is the log reduction of contaminant. So defined, the E_{EO} was used to compare reactor efficacy as a function of flow rate for a range of reactor designs Figure 6. The E_{EO} decreases with increasing flow rate: greater volume treated with less electrical energy.

This behaviour can be explained through improved mixing of the water being irradiated and thus a more tightly constrained fluence distribution.

Optical and hydraulic design of UV disinfection reactors interact to determine overall reactor efficacy, with small alterations to UV source position, inlet diameter, water transmissivity, wall reflectivity, internal volume, etc. having a dramatic impact.

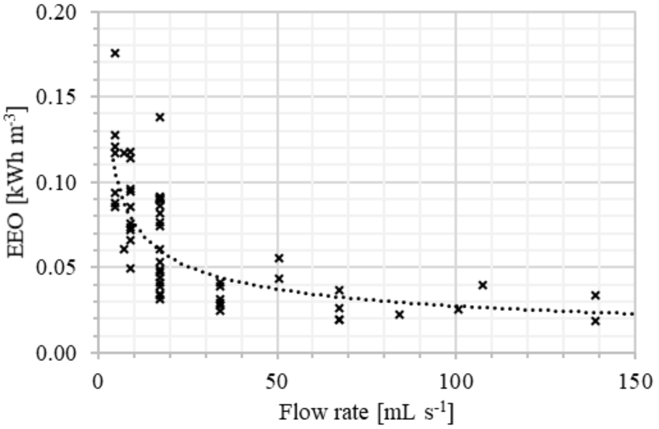

Figure 6. Dependence of the energy requirement on flow rate in aggregated data from a range of UV-C LED reactor designs.

The presence of numerous factors affecting performance limits the accuracy of generic statements on reactor performance. That said, the following guideline retains a degree of utility: for a drinking water treatment reactor using present-day UV-C LEDs and satisfying international standards for potable water disinfection, the electrical input power required will range from approximately 5 – 25 W per litre per minute delivered.

B. Usage Scenario: Generic POU Water Dispenser

The operating conditions of required for point of use (POU) water disinfection are well matched to the attributes of UV disinfection, as shown in Table 2.

User interaction with point of use systems means that utilisation is irregular, and the on-demand nature of water collections drives towards a system with low latency. In this area, UV-C LEDs have two key benefits:

- Near instantaneous power-up
    - UV-C LEDS have been shown to reach full output power within 10 ns
- No impact on performance resulting from power cycling
    - UV-C LEDs have been operated through 500,000 power cycles and have not shown degradation beyond that expected under continuous operation

Table 2. Implications for POU water disinfection applications of several UV disinfection attributes.

UV disinfection attribute	Implication for POU application
No change in taste, odour, or colour of water	No post-processing required
Water temperature is not affected (UV-C LEDs)	No cooling required before consumption
Immediate effect, not requiring any soak time or chemical reaction	Ready to consume on delivery
Small reactors can be positioned at point of delivery (UV-C LEDs)	Reduction of ‘last mile’ contamination risk
UV disinfection attribute	Implication for POU application

C. Usage Scenario: Treat and Store

As noted above, the primary application of interest for UV in drinking water treatment is In POU systems, where the UV irradiation occurs directly before delivery. Such a method is always recommended in the first instance, where possible, as it provides the greatest assurance of water security.

A key criticism of UV disinfection is the lack of residual biocide; since it is a photochemical process occurring only within the irradiation chamber the water stream is susceptible to recontamination events after the disinfection stage. Usage immediately following irradiation is therefore often recommended.

However, recent research has shown that UV irradiation induces a bacteriostatic effect which persists for a period of days after treatment. Though still an active area of research, this behaviour indicates the potential suitability of UV disinfection for ‘treat and store single-pass’ and ‘microbial suppression in recirculation’ modes of operation.

Through the BIOWYSE project[29], microbially biodiverse diluted surface water samples were irradiated by UV (150 mW at 100 mL min^{-1} flow rate single-pass, < 90% UVT$_{254\ nm}$) and the effects monitored over a period of 6 days afterwards using culture-based methods—R2A, 22°C. Samples were stored in dark, sealed containers at room temperature for the period between exposure and culturing.

In-line with comparable studies in the literature, an immediate inactivation effect was observed. Over a period of 1 – 2 days following irradiation the maximum reduction effect was maintained, indicating an extended bacteriostatic effect. Following this period of reduced microbial activity, a ‘regrowth’ phase is observed through to the end of the test period.

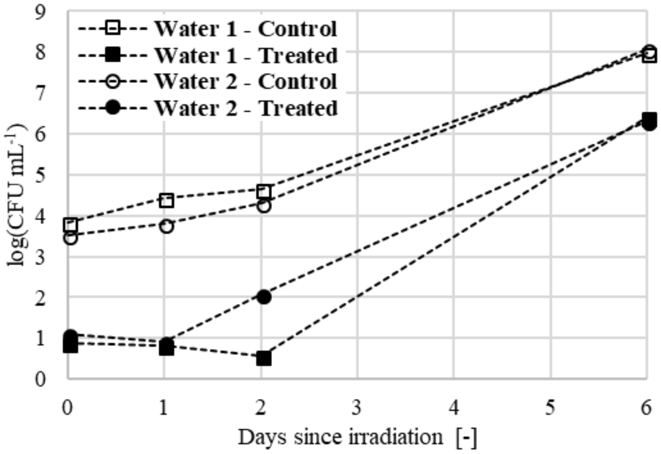

Figure 7. Time dependency of UV disinfection effect on two diluted surface water samples, measured using HPC culture methods. Credit: *GL Biocontrol* (BIOWYSE)

A full investigation of the processes governing this behaviour has not been conducted and so a complete description of the mechanisms at play cannot be provided. However, based on current information the following theory is proposed:

- Initial reduction in culturability follows UV-induced damage to genetic material, microbes are metabolically active but sterile,
- A bacteriostatic effect is maintained as the population remains stable, die-off of inactivated microbes does not affect culturability; reproduction of non-inactivated organisms is limited due to UV-stressed condition,
- Die-off of inactivated microbes provides nutrient source for remaining organisms; total microbial population recovers with reduced biodiversity.

This effect has further been independently observed in the literature in a study of the impact of UV irradiation on a dechlorinated tap water source[30]. Clearly, more research is required in this area to better determine the longevity of this effect and its impact on downstream/subsequent water handling.

VI. Future Systems

An improved understanding of the ability of UV to suppress, and maintain that suppression of, microbial communities within water distribution systems could lead to the expansion of UV photoreactors as tools for system-wide microbial control. A concept drawing of one such multi-stage UV potable water handling system sis shown in Figure 8. Here, UV-C LED disinfection systems have been employed in three distinct applications:

- Point of entry (POE) as a barrier to microbially contaminated influent water
- Recirculation (RC) to maintain suppression of microbial contaminants
- Point of use (POU) as a final barrier and safeguard

The concept does not constitute a complete processing system involving water recovery and recycling, though it could be used in downstream disinfection and storage stages.

Not shown are any system control elements, these may be simple, with programmed recirculation intervals etc., or advanced, incorporating microbial contamination monitoring—such as is applied in the BIOWYSE project.

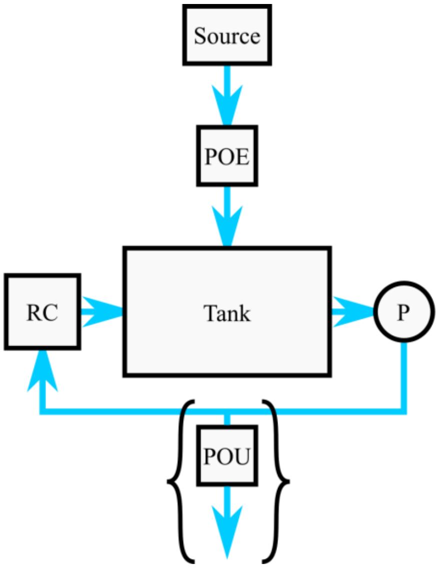

Figure 8. Schematic of a system concept for a multi-stage UV water handling system, capable of maintaining the microbial quality of potable water.

Where there is a mismatch between the instantaneous supply and demand conditions, safe water storage becomes an essential consideration. Challenging environments place additional demands on the systems employed to maintain safe water storage—chemical-free, consumables-free, low-power, small footprint, etc. Integrated multi-stage UV disinfection systems may prove a valuable resource in meeting these needs.

VII. Conclusion

The use of UV disinfection is well-known throughout a range of applications where chemical or physical methods have undesirable side effects and requirements. Though historically limited by the operating conditions, form factor, and fragility of mercury containing gas discharge lamps, recent developments in UV-C LED technology mean that next-generation UV disinfection systems are a realistic prospect.

In 2013 the global UV-C LED market entered a new phase of rapid development, exceeding the predictions of Haitz's Law—established for visible LEDs. Manufacturers are taking advantage of the great depth of knowledge gained in the visible and near-UV LED sector, to produce devices of rapidly improving quality.

Today, UV-C LED systems offer a viable solution to microbial control in air, surface, and water handling. The direct photochemical process requires no chemical resupply and has no consumable requirements beyond electrical power. The use of semiconductor technology means that such systems may be fully automated, digitally controlled, and provide real-time feedback on system status and operation.

Future use of miniaturised UV modules is envisaged throughout water and air handling loops of environmental control systems, providing a multi-stage barrier to microbial contamination.

Acknowledgments

The authors wish to acknowledge the support of the EC Horizon 2020 project (687447) BIOWYSE for the collaborative efforts of consortium members in the development of an integrated system and collection of the data shown in Figure 7.

References

---

[1] Downes, A., and Blunt, T. P. (1877) Researches on the effect of light upon bacteria and other organisms. Pro. Res. Soc. London, 26:488 – 500

[2] Gates, F. L. (1929) A study on the bactericidal action of ultra violet light: I. The reaction to monochromatic radiations. J. Gen. Physiol. 13 (2), 231-248.

[3] Bolton, J. R., Cotton, A. C. (2008) The Ultraviolet Disinfection Handbook, The American Water Works Association, ISBN 978-1-58321-584-5

[4] Memarzadeh, F., Olmsted, R. N., Bartley, J. M. (2010) Applications of ultraviolet germicidal irradiation disinfection in health care facilities: Effective adjunct, but not stand-alone technology. American Journal of Infection Control, Volume 38, Issue 5, S13 - S24 https://doi.org/10.1016/j.ajic.2010.04.208

[5] Robles, D., Kramer, S. W. (2017) Improving Indoor Air Quality through the Use of Ultraviolet Technology in Commercial Buildings. Procedia Engineering, 196, 888 – 894 https://doi.org/10.1016/j.proeng.2017.08.021

[6] United States Environmental Protection Agency, Office of Water (2006) Ultraviolet Disinfection Guidance Manual For The Final Long Term 2 Enhanced Surface Water Treatment Rule. [Online] Available from: https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=600006T3.txt

[7] Kowalski, W. (2009) Ultraviolet Germicidal Irradiation Handbook, Springer, ISBN 978-3-642-01998-2

[8] "Haitz's Law" (2007) Editorial, Nature Photonics, 1(23) http://dx.doi.org/10.1038/nphoton.2006.78

[9] Laser Focus World (2006) LIGHT-EMITTING DIODES: Deep-UV LEDs appear on the market. Available from: http://www.laserfocusworld.com/articles/print/volume-42/issue-5/worldnews/light-emitting-diodes-deep-uv-leds-appear-on-the-market.html [Accessed 1st January 2018].

[10] LEDs Magazine (2006) Seoul Optodevice teams with SET to produce deep-UV LEDs. Available from: http://www.ledsmagazine.com/ugc/2006/07/seoul-optodevice-teams-with-set-toproduce-deep-uv-leds.html [Accessed 1st January 2018].

[11] Bowker, C., Sain, A., Shatalov, M., & Ducoste, J. (2010). Microbial UV fluence-response assessment using a novel UV LED collimated beam system. Water Research, 45(5), 2011-2019.

[12] Chatterley, C. & Linden, K. (2010). Demonstration and evaluation of germicidal UV-LEDs for point-of-use water disinfection. Journal of Water and Health, 8(3), 479-486

[13] Vilhunen, S., Särkkä, H., & Sillanpää, M. (2009). Ultraviolet light-emitting diodes in water disinfection. Environmental Science and Pollution Research, 16(4), 439–442.

[14] Beck, S.E., Wright, H.B., Hargy, T.M., Larason, T.C., Linden, K.G., 2014. Action spectra for validation of pathogen disinfection in medium-pressure ultraviolet (UV) systems. Water Res. 70C, 27–37. doi:10.1016/j.watres.2014.11.028

[15] Song, K., Mohseni, M., and Taghipour, F. (2016). Application of ultraviolet light-emitting diodes (UV-LEDs) for water disinfection: a review. Water Res.94, 341 – 349, doi: 10.1016/j.watres.2016.03.003

[16] Gross, A.; Stangl, F.; Hoenes, K.; Sift, M.; Hessling, M. (2015) Improved Drinking Water Disinfection with UVC-LEDs for Escherichia Coli and Bacillus Subtilis Utilizing Quartz Tubes as Light Guide. Water, 7, 4605-4621.

[17] Green, A., Popović, V., Pierscianowski, J., Biancaniello, M., Warriner, K., Koutchma, T., Inactivation of Escherichia coli, Listeria and Salmonella by single and multiple wavelength ultraviolet-light emitting diodes, Innovative Food Science & Emerging Technologies, Volume 47, 2018, Pages 353-361, https://doi.org/10.1016/j.ifset.2018.03.019.

[18] Rattanakul, S., Oguma, K. (2018) Inactivation kinetics and efficiencies of UV-LEDs against Pseudomonas aeruginosa, Legionella pneumophila, and surrogate microorganisms, Water Research, 130, 31 – 37, https://doi.org/10.1016/j.watres.2017.11.047

[19] Oguma, K., Rattanakul, S., and Bolton, J.R. (2015) Application of UV Light–Emitting Diodes to adenovirus in water, J. Environ. Eng., 142(3): 1–6.

[20] Sholtes, K.A., Lowe, K., Walters, G.W., Sobsey, M.D., Linden, K.G., Casanova, L.M. (2016) Comparison of ultraviolet light-emitting diodes and low-pressure mercury-arc lamps for disinfection of water. Environ. Technol. 37(17), 2183 - 2188 Online: DOI: 10.1080/09593330.2016.1144798

[21] Jenny, R. M., Simmons III, O. D., Shatalov, M., Ducoste, J. J. (2014) Modeling a continuous flow ultraviolet Light Emitting Diode reactor using computational fluid dynamics. Chemical Engineering Science 116, 524-535.

[22] Oguma, K. Kita R., Takizawa, S. (2016) Effects of arrangement of UV light-emitting diodes on the inactivation efficiency of microorganisms in water. Photochemistry and Photobiology 92(2) 314–317.

[23] Simons, R., Gabbai, U. E., Moram, M. A. (2014) Optical fluence modelling for ultraviolet light emitting diode-based water treatment systems. Water Research. 66, 338-349.

[24] Würtele, M. A., Kolbe, T., Lipsz, M., Külberg, A., Weyers, M., Kneissl, M., Jekel, M. (2011) Application of GaN-based ultraviolet-C light emitting diodes – UV LEDs – for water disinfection. Water Research 45, 1481-1489.

[25] NASA (2014) Decontamination System to Up Research on Space Station, viewed on 1 January 2018, < https://www.nasa.gov/mission_pages/station/research/news/decontamination.html>

---

[26] Bockstahler, K., Hartwich, R., Matthias, C., Witt, J., Hovland, S., Laurini, D. (2017) Status of the Advanced Closed Loop System ACLS for Accommodation on the ISS, Proceedings of the 47th International Conference on Environmental Systems ICES-2017-135.

[27] Bolton, J. R. & Linden, K. (2003) Standardization of Methods for Fluence (UV Dose) Determination in Bench-Scale UV Experiments. J. Environ. Eng. 129(3), 209-215.

[28] Bolton, J.R., and Stefan, M.I. 2002. Fundamental photochemical approach to the concepts of fluence (UV dose) and electrical energy efficiency in photochemical degradation reactions. Res. Chem. Intermed. 28: 857–870.

[29] BIOWYSE (2016) Biocontamination integrated control of wet systems for space exploration, viewed on 1 January 2018 < http://biowyse.eu>

[30] Oguma, K., Kanazawa, K., Kasuga, I. and Takizawa, S. (2018), Effects of UV Irradiation by Light Emitting Diodes on Heterotrophic Bacteria in Tap Water. Photochem. Photobiol. doi:10.1111/php.12891 [Epub ahead of print]