

UV LED Disinfection 101

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Synopsis

Light is fascinating. It can be harnessed by solar panels to supply electricity to a building; it can be reflected off a land surface to create high-resolution topographical imagery; and it can be used to inactivate harmful pathogens and prevent the spread of airborne and waterborne diseases. The concept of using light to kill (or, “inactivate”) a living being is straight out of science fiction, and yet scientists have been doing it intentionally for public health reasons since the late 1800s.

What is ultraviolet disinfection? How has it evolved over time? How can we take advantage of recent advances in the technology to make it even more effective?

This article gives a high-level overview of light-based disinfection, the evolution of UV technologies over time and the potential of UV light emitting diodes (LEDs), a tiny light source at the tip of our fingers, to transform water disinfection and contribute to solving critical public health problems on a global scale.

Discovering the bactericidal effects of light

Solar disinfection was first discovered in the mid- to late 19th century, at a time when contaminated water led to waterborne disease outbreaks and pandemics across Europe, Asia and the Americas. Two English scientists investigated the effects of light on microorganisms in 1877 by exposing test tubes of a brown sugar solution to sunlight and monitoring for bacterial growth. Within days, bacteria began growing in the shaded samples, but growth was inhibited for up to a month in the samples exposed to sunlight. These early experiments revealed that the disinfection was dependent upon how long each sample was exposed, as well as the intensity of the sunlight. (Downes and Blunt, 1877).

A decade later, while working with bacillus anthracis (anthrax!) spores and other bacteria, French researchers discovered that the light sensitivity varied among microorganisms (Duclaux, 1885; Arnaud, 1890). This is also when the famous German microbiologist and epidemiologist who developed our standard laboratory practices, Robert Koch, linked the spread of disease to disease-causing microorganisms called pathogens. Koch was the first to use sunlight specifically against tuberculosis (Koch, 1890). His work,

awarded the Nobel Prize in Medicine, set the stage for modern UV systems – used in hospital wards, for example – which prevent the spread of tuberculosis and other airborne diseases.

Before the end of the 19th century, researchers began to understand the importance of the different wavelength ranges of light. Using prisms and colored glass screens to separate sunlight into distinct wavelengths, they showed that the inhibition of bacteria was wavelength-dependent and caused by the blue, violet and ultraviolet (UV) segments of the light spectrum (Geisler, 1892; Ward, 1892).

Introducing large-scale UV disinfection of water

These first experiments primarily used solar disinfection, called SODIS, which is used today with plastic bottles as a low-cost water treatment method; however, UV lamps were not far behind. The first large-scale water disinfection system (Figure 1) to use UV lamps was set up in 1910 (and taken down soon thereafter) to treat filtered river water in Marseilles, France (Henri et al., 1910). Chlorine outpaced UV disinfection in the 1920s, so it wasn't until 1955 that large-scale UV systems were consistently operational in Switzerland and Austria (Bolton and Cotton, 2011).

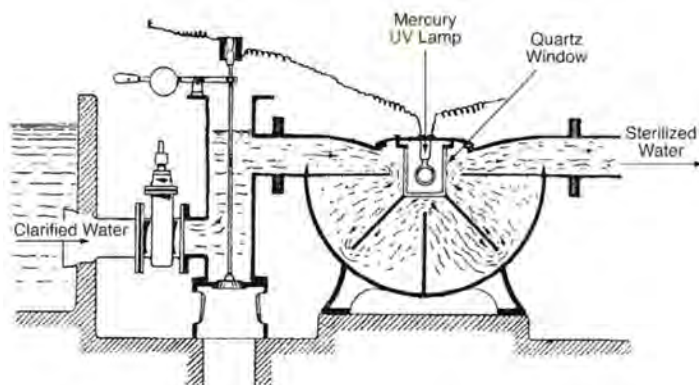


Figure 1. Schematic of the first large-scale drinking water disinfection system to use UV, in Marseilles, France in 1910 (Henri et al. 1910)

In the following decades, UV technology did not change as much as the reasons for using it. UV was introduced to Norway in 1975 due to concerns over carcinogenic disinfection byproducts from chlorination (Paidalwar, A. and Khedikar, I., 2016). At the turn of the century, UV continued to dominate in Europe for drinking water treatment (Sommer et al., 2002). In the United States, UV was used mainly for

wastewater. That began to change after scientists discovered that ultraviolet light was not only effective against bacteria and viruses, it also could prevent the spread of *Cryptosporidium* and *Giardia*, protozoan pathogens that are highly resistant to chlorine (Clancy et al., 1998 and Bukhari et al., 1998). By 2006, the U.S. Environmental Protection Agency required a secondary barrier, in addition to chlorine, to prevent *Cryptosporidium* and *Giardia* outbreaks (USEPA, 2006). This led to the largest UV disinfection system in the world, which treats the water for New York City. The Catskill-Delaware UV Water Treatment Facility, commissioned in 2013, uses a network of over 11,000 UV lamps to disinfect 9 billion liters of water daily from the highly protected Catskill and Delaware County watersheds (Catskill-Delaware Ultraviolet Water Treatment Facility).

Traditional UV lamps

These large-scale systems use what are called “traditional” UV lamps, also known as gas-discharge or arc lamps, which contain a gas mixture enclosed in a glass tube, or sleeve. When a voltage is applied across the gas through a light filament, it excites the electrons to a higher energy state. As they fall back to their original state, they release that excess energy in the form of light. The color – or wavelength – of the light released depends on the element of the pressurized gas inside. Excited neon gas used in neon signs emits red-orange, for example. Excited xenon gas emits blue or gray.

The lamp of interest to those in the water disinfection industry is the mercury vapor lamp, which emits in the visible and UV ranges. Mercury lamps are common in office buildings – they are the fluorescent lamps hanging above people’s desks. The primary difference between a fluorescent lamp in the office and UV lamps used to disinfect water is the type of glass surrounding the lamp and the phosphor coating that fluoresces on the inside of the glass. Lamps enclosed by glass tubes absorb the UV light; those with tubes made of quartz – a special type of glass – transmit it.

DNA damage

So how do these high-energy UV wavelengths damage microorganisms? To answer that, it is necessary to revisit history: Frederick Gates inferred that “It seems more probable that it is the effect of ultraviolet energy on a single vital and sensitive structural and chemical unit that results in subsequent failure in cell multiplication” (Gates, 1930). In other words, UV-induced damage to something within the cell causes microorganisms to become inactive.

What is that vital unit he referred to which prevents cell multiplication? In principle, it’s DNA: the double helix containing genetic instructions for growth, development and reproduc-

tion. UV photons, which are essentially little packets of energy, hit – or are absorbed by – the chemical bonds holding this complex helical structure in place (Figure 2). Bonds are broken; new bonds are formed.

UV-induced damage to the DNA prevents it from being replicated. As the DNA polymerase enzyme replicates the DNA strand, creating a complement, it gets stuck at the site of damage, kind of like a zipper that gets stuck on a winter jacket. The DNA replication cannot be completed. Since the organism cannot reproduce, it cannot infect. Although it has not been killed, per se – it has been rendered inactive. This holds true for RNA-based organisms and single-stranded DNA and RNA as well.

Gates used an instrument called a monochromator, a black box with prisms, mirrors and other optics, to separate UV light into individual wavelengths along the spectrum. At each wavelength, he determined where the inactivation of bacteria – in this case staphylococcus, the cause of staph infections – was

the strongest. Not surprisingly, the UV wavelengths that had the strongest effect at preventing the bacterial growth were those that were absorbed by staph the strongest.

This and later works showed that inactivation of bacteria, viruses and other microorganisms occurs along the UV spectrum, but is strongest in the UV-C range between 260 to 270 nm and below 230 nm (Rauth, 1965; Beck et al., 2015; Bolton, 2017). Some of this inactivation is due to DNA damage, some due to damage to vital proteins and some due to the transfer of energy in between (Besaratina et al., 2011; Beck et al., 2018). Mercury vapor lamps enclosing the gas at low pressure (<10 torr) emit near-monochromatic light primarily at 254 nm, which is conveniently close to the peak of DNA absorbance near 260 nm. This is great from a disinfection standpoint. UV light-emitting diodes (LEDs), on the other hand, offer an even wider range of wavelength emissions.

Light-emitting diodes

Light-emitting diodes (LEDs) are different than conventional lamps. They’re semiconductors consisting of a stable structure or substrate, such as silicon or sapphire, covered (or



Figure 2. Artist rendering of UV-induced damage to DNA (source: ledinside.com)

doped) in precise materials, which are alternatively missing or supplying electrons from their outer shell. As a voltage is applied, the free electrons flowing through the circuit “fall” into the microscopic holes – or spaces in the electron ring – due to impurities in the doped substrate. By falling into a lower energy state, they release their excess energy in the form of light. The wavelength or color released depends on the bandgap, or drop in energy, between the materials.

LEDs were initially developed in the 1950s by German, British and American researchers working in parallel to advance the electronics, phone, TV and lighting industries. These early LEDs, which used a gallium phosphide (GaP) substrate solo or doped in nitrogen or zinc oxide, emitted visible light in the red to green ranges (Grimmeiss and Koelmans, 1961; Gershenson and Mikulyak, 1961; Starkiewicz and Allen, 1962). The blue LED, which would complete the color wheel, proved elusive for three decades. It wasn’t until the 1980s that a trio of Japanese researchers developed the high-output blue LED by growing high quality crystals into a multi-layer gallium-nitride (GaN)-based substrate. This feat of engineering (Figure 3), and its subsequent impact on the lighting and electronics industries, earned Isamu Akasaki, Hiroshi Amano and Shuji Nakamura the Nobel Prize in Physics in 2014 (Scientific Background on the Nobel Prize in Physics 2014).

Blue LEDs generate white light either by combining with red and green LEDs or by illuminating a phosphor coating. The breakthrough of the white LEDs transformed the electronics industry with the advent of computer screens and smartphones. White LEDs also surpassed incandescent light bulbs with higher energy efficiencies and longer lifetime.

UV light-emitting diodes

In the disinfection field, the blue LED paved the way for the inevitable ultraviolet LED, which was developed through several iterations of manufacturing and material improve-

ments. Constructing multi-layer substrates from indium gallium nitride, diamond, boron nitride, aluminum nitride and aluminum gallium indium nitride, for example, led to LEDs in the UV range emitting at wavelengths as low as 210 nm.

As with traditional UV sources, LEDs in the UV-C and UV-B range are effective at inactivating bacteria and viruses (Bowker et al., 2011; Oguma et al., 2013; Beck et al., 2017; Rattanukul and Oguma, 2018) and helminthes eggs as well (unpublished). These UV LEDs currently are used in small reactors for batch experiments (Figure 4). LEDs in the UV-A range can degrade harmful organic pollutants like pharmaceuticals, insecticides and dyes, with the help of photocatalysts like iron, titanium-oxide and persulfate (Matfanova and Batoev, 2018).



Figure 4. 16W unit with 280 nm UV LEDs used for batch disinfection experiments

From a health and environmental impact standpoint, the primary advantage of UV LEDs over other UV lamps is that they are mercury-free. Mercury has toxic effects on human health and the environment. As a result, The United Nations Environmental Programme (UNEP), through the Minamata Convention on Mercury, is controlling mercury waste and working to eliminate the release of mercury into air, water and land by 2020 (Minamata Convention on Mercury).

As semiconductors, LEDs can be turned on and off instantaneously without requiring the 20- to 30-minute warmup time

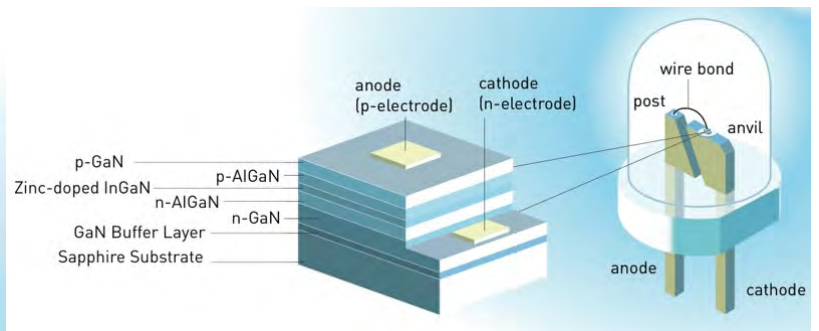
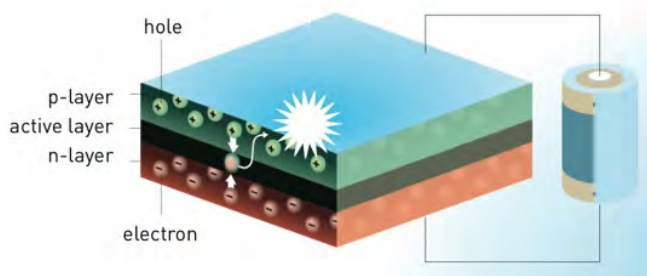


Figure 3. Illustrations of a light-emitting diode by Johan Jarnestad at The Royal Swedish Academy of Sciences

required by gas vapor lamps. This opens the door for smart sensor-based UV disinfection technologies that can be powered on-demand. From a power standpoint, UV LEDs can operate from less power than conventional lamps and can be powered by remote or photovoltaic power supplies (Lui et al., 2014). On the other hand, an equally important fact is that UV LEDs are considerably less efficient than traditional UV sources. As such, they must be powered for a longer time in order to reduce the spread of harmful pathogens by the same amount as mercury-based lamps.

From a design standpoint, the primary advantage of UV LEDs is their compact size, less than 1 mm². With this incredibly small footprint, multiple diodes can be arranged in unique

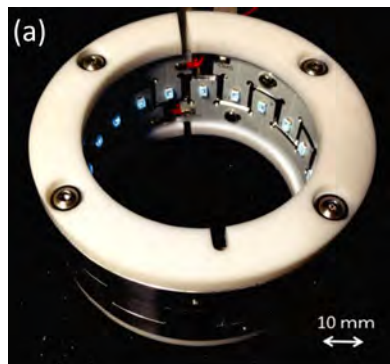


Figure 5. Ring-shaped apparatus for a flow-through reactor composed of two rings with 10 UV LEDs each

reactor designs as shown in Figure 5 (Oguma et al. 2016). LEDs of different wavelength outputs can even be combined to optimize inactivation of specific microorganisms. Ideally, a tailored UV LED disinfection system would target microbial and chemical contaminants by combining wavelengths from the dominant DNA damage region (260 to 280 nm),

the protein damage region (below 240 nm) and the UV-A region where external sensitizers (like catalysts or organic matter) are activated and cause indirect chemical degradation.

Commercially available UV LED reactors on the market currently range in scale from small hand-held devices to large-scale municipal treatment units capable of treating 2000 m³/day. The hand-held units include the option to select LEDs from up to three different wavelengths, including as low as 254 nm.

Potential applications of UV-C LEDs

Just as computers evolved from the size of a room in 1941 to the size of a smartphone in 2007, ultraviolet sources and LEDs have been evolving over the last century. LEDs in the visible range transformed computer and television monitors and brought electricity to remote environments, for example, by providing photovoltaic lighting to an estimated 5% of Africans who otherwise lacked electricity (“Solar Lighting Products Improve Energy Access for 28.5 Million People in Africa,” 2014).

LEDs in the UV-A range have already made their way into everyday life. For instance, getting a manicure or pedicure may involve drying (or “curing”) the shellac nail polish under an array of UV-A and visible LEDs. Other coatings, adhesives and inks are cured through UV-A LED technology, like ink used for high-resolution graphic imagery or posters, for example.

These technology trends are just now extending to the UV-B and UV-C range as well, as Figure 5 shows. For UV-B and UV-C LEDs to be as effective as traditional UV lamps from a microbiology perspective, they must reach wall plug efficiencies of 25 to 39 percent, meaning that 25 to 39 percent of the energy input through the wall plug is output in the form of light (Beck et al. 2017). Given the current state of technology, the wall plug efficiencies of these LEDs is closer to 4 percent. However, they are on an upward trend and well on pace with the development of red, blue and UV-A LEDs (Figure 6).

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Another exciting trend, as reported by Pagan and Lawal 2017 is the number of manufacturers of UV-C LEDs worldwide. What started with one company in 2003 has grown to 10 companies based primarily in the United States, Japan, Taiwan, China and South Korea, each working to improve their products' efficiencies and durability.

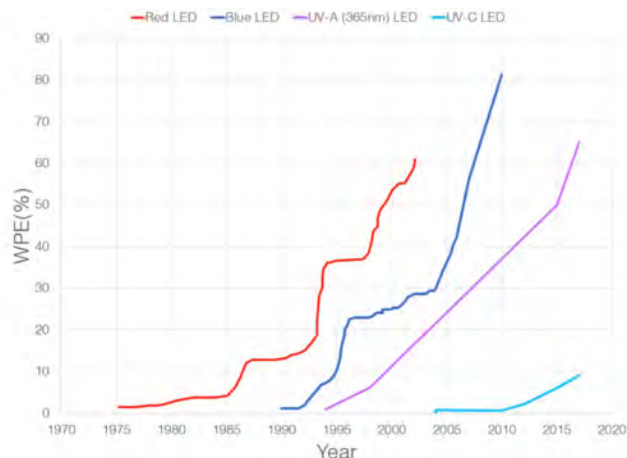


Figure 6. Technology trends of red, blue, UV-A and UV-C LEDs as measured by wall plug efficiency (Lawal et al. 2017)

UV-C LEDs are already being incorporated into point-of-use units to serve the defense and outdoor industries. They're being designed into airplanes to disinfect air in the passenger cabin, and they're being tested for water treatment in small towns in the United States.

What's next? This tiny robust light source at the tip of our fingers has the potential to transform water disinfection in developed and low- to middle-income countries alike. In developed countries, UV-C LEDs can be incorporated into showerheads to prevent outbreaks of Legionnaires' disease in hospitals and hotels. They can be introduced into pipe systems to prevent biofilm formation. In low- to middle-income countries, UV-C LEDs can be designed into hand-pumps to disinfect groundwater or studded in bottle caps to treat single bottles of water and prevent disease outbreaks.

As with every exciting new technological development, the broad array of applications cannot yet be foreseen; however, it is exciting to watch the transformation unfold. ■

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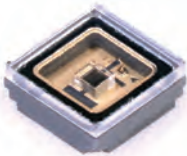
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