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REVIEW ARTICLE

# ULTRAVIOLET RADIATION AND ITS GERMICIDAL EFFECT IN DRINKING WATER PURIFICATION

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## SUMMARY

Microbial disinfection using ultraviolet radiation is a world wide technology for drinking water purification. The effectiveness of this technology depends on certain important parameters like the UV intensity, the exposure time, the area, clarity of the water etc. This technology is very convenient and fast, doesn't alter the taste of the water or adding chemicals into the water. The selection of UV wavelength is very important for the efficient disinfection process. The optimum microbial killing efficiency ranges from 254 to 260 nm wavelength probably varies with the type of organism. Viruses and bacteria in vegetative forms are most sensitive to UV radiation. It gives in-depth review of ultraviolet (UV) light for using as a disinfection technology in potable water supplies. This paper is intended to assist the reader in evaluating the disinfection capabilities of UV light to inactivate disease-causing bacteria, viruses, and cysts.

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## 1. Introduction

Water borne disease has been a concern to human being ever since its cause had discovered and the most appropriate treatment process adopted is microbial disinfection. Disinfection is necessary to destroy pathogenic (disease causing) bacteria and other harmful microorganisms that are present in water due to contamination. Over several years, Ultraviolet (UV) disinfection has developed into a viable technology for drinking water disinfection. UV disinfection systems inactivate protozoa, bacteria and viruses. Through all-embracing research and meticulous field experiences, UV disinfection has proven to be safe, reliable, and inexpensive and accepted this as a world wide technology for drinking water disinfection.

UV disinfects water without adding chemicals. It does not create any new chemical complexes, does not change the taste or odour of the water and does not remove beneficial minerals from the water. UV devices are the most effective when the water has already been partially treated for sediments and organic chemicals. Therefore UV disinfection devices are often combined with other treatment devices such as sediment filters and carbon filters.

The key factor of a UV treatment system is the UV dosage which can be measured from the known UV intensity, exposure time and water flow rate**.** The dosage is very important to disinfect the microorganism. This is again based on many factors like water clarity, water flow, flow pattern, UV intensity and quality of the quartz sleeve. The water quality of India is a real challenge to all water purifier manufacturers. There is a wide distinction in water quality from place to place like high turbidity, heavy microbial contamination, iron content, presence of other toxic chemicals etc. Surface water in river is the main drinking water source for urban and semi urban areas of India. Open Wells and bore wells also provides drinking water to the human community as well.

### Historical record of UV

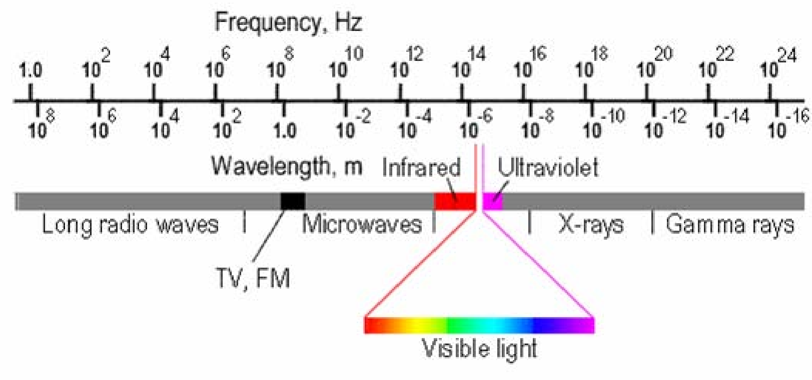
The germicidal properties of UV light were discovered in 1887. The first application of UV light in drinking water occurred in

1910 at Marselles, France. Since then, UV light is used in drinking water systems worldwide primarily for disinfection. Till 2006 there is only one Commercial water purification device using UV light for disinfection. Currently, several states have developed regulations that allow systems to disinfect their drinking water supplies with UV light. However, as UV research continues for bringing up more devices incorporating UV technology for its proposed germicidal effect. At present largest UV disinfection system is being constructed in the New York City. A total of 56 energy-efficient UV reactors will be installed to treat 2.2 billion gallons of water a day (8,300,000 $m^3/d$) to serve New York City.

**UV light description**

In drinking water, UV light is used for disinfection. The use of UV for disinfection involves: (1) The generation of UV light with the desired germicidal properties, and (2) The delivery (or transmission) of that light to microbial pathogens. As UV light lies between Xrays and visible light in the electromagnetic spectrum the UV spectrum covers the wavelength range from 100-400 nm (Figure 2). UV light at certain wavelengths can inactivate microorganisms. UV light with wavelengths from 200-300 nm inactivates most microorganisms, with the greatest amount of inactivation occurring around 260 nm.

Figure 1. The electromagnetic spectrum




**UV light generation**

Generation of UV light is similar to the generation of light in a fluorescent lamp. In general, a UV lamp contains an inert gas (e.g., argon) and a small amount of liquid mercury. When a voltage is applied to the lamp, some of the liquid mercury vaporizes. Free electrons and ions then collide with the gaseous mercury atoms, "exciting" the mercury atoms into a higher energy state. Excited mercury atoms have a tendency to return to their ground, or normal, energy state by discharging energy. The energy discharged is in the form of UV light. Mercury is advantageous for UV disinfection applications because it emits light in the germicidal wavelength range (200 – 300 nm). The UV light produced depends on the concentration of mercury atoms in the UV lamp, which is directly related to the mercury vapor pressure. Low pressure mercury vapor produces monochromatic (light at primarily one wavelength) UV light at a wavelength of 253.7 nm. Higher pressure mercury vapor produces UV light at several wavelengths (polychromatic).

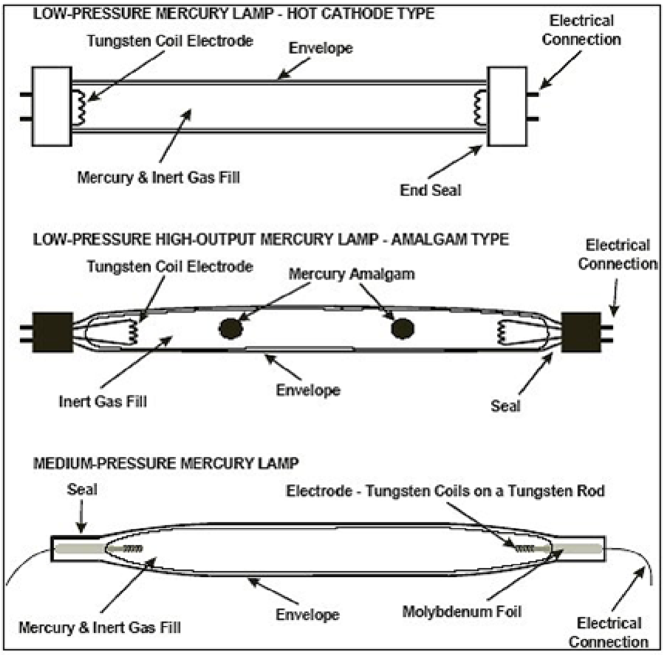
**UV lamps and its types**

For water treatment systems, there are three general types of UV lamps typically used; low pressure (LP), low-pressure high-output (LPHO), and medium-pressure (MP). These terms are based on the vapor pressure of mercury when the lamps are operating.

LP and LPHO lamps operate at mercury vapor pressures of $2x10^{-3}$ – $2x10^{-5}$ pounds per square inch (psi), thereby producing monochromatic UV light at 253.7 nm. MP lamps operate at much higher mercury vapor pressures of 2–200 psi and produce polychromatic UV light at a higher intensity. LP and LPHO lamps operate at temperatures of 40 – 200° C, while MP lamps operate at a much higher temperature range of 600-900° C. LP lamps have the lowest power requirements, while LPHO and MP lamps have higher power requirements. Subsequently, LP lamps have the lowest germicidal output (0.2 W/cm), while LPHO and MP lamps have higher germicidal outputs (0.5 – 3.5 W/cm and 5 – 30 W/cm, respectively). Figure 2 shows drawings of LP, LPHO, and MP lamps. There is generally no difference in disinfection capability between these lamps. But there are advantages and disadvantages to each. For example, compared to LP lamps, MP lamps have a higher germicidal output, typically require fewer lamps for a given applications, and would likely be a smaller reactor.

There are other types of lamps that can produce UV light such as metal halide lamps, electrode-less mercury vapor lamps, and eximer lamps. Most UV water purification devices use LP lamps due to lower operating temperatures and lower power requirements.

Figure 2. LP, LPHO and MP lamp drawings




**UV reactors**

In drinking water systems, UV lamps are contained in a UV reactor. UV reactors operate as either batch or continuous flow reactors. Several characteristics must be taken into account when designing, installing, and operating a UV reactor. Among them are water quality characteristics, distance between the lamp and the reactor wall, and the distribution of UV light. Additionally, continuous flow reactors must take into account hydraulic characteristics of water flowing through the reactor. Due to all these characteristics, all microorganisms will not receive the same UV dose. For example, UV lamp placement in a reactor influences UV dose delivery. If the distance between the lamp and the reactor wall is too large (i.e., a large amount of water between the lamp and the reactor wall), microorganisms furthest from the lamp will receive less UV intensity and subsequently a lower UV dose. Most UV-using water purification devices utilize a batch reactor system.

**UV dose and its estimation**

In drinking water applications, disinfection using UV light follows the familiar CT concept (disinfectant concentration times contact time). However, instead of using CT to describe UV disinfection, UV dose is used instead. UV dose is defined as the measurement of the energy per unit area that falls upon a surface. UV dose is the product of UV intensity, I, and exposure time, T (IT), similar to the CT concept. UV intensity is usually expressed as $mW/cm^2$ and exposure time is measured in seconds (s). So UV dose is reported as $mWs/cm^2$. However, UV dose is commonly expressed as millijoules per square centimeter ($mJ/cm^2$), because 1 mWs = 1 mJ.

When disinfection test data is not available models can be used to gain an understanding of disinfection capabilities of UV purification devices. Several complex models have been developed to estimate UV intensity delivered to a microorganism. With the estimated UV intensity, the UV dose can be calculated based on various exposure times and compared to UV doses determined in scientific literature. The simplest model used to estimate UV intensity is the radial model:

$$I(r) = (PL / 2\pi r) \times (e^{-aer})$$

Where: PL = UV power emitted per unit arc length of the lamp (mW/cm); r = Radial distance from the lamp (cm); ae = Base absorption coefficient of the water (1/cm). ae = 2.303*A254; I(r) = UV intensity ($mW/cm^2$) at a distance r from the lamp.

Using data provided by the manufacturer on UV power emitted (PL), dimensions of the purification device, UV reactor, and assuming water quality variables to develop an absorption coefficient (ae), UV intensity can be calculated. In the absence of good quality specific testing data, this radial model can be used to provide a rough evaluation of disinfection capability.

## 2. Mechanism of UV disinfection

When discussing UV light disinfection capabilities, a distinction must be made between inactivating and killing microorganisms. For chemical disinfectants (e.g., chlorine, chlorine dioxide, iodine), inactivating and killing can be considered synonymous terms since chemical disinfectants destroy and damage cellular structures which interferes with metabolism, biosynthesis, and growth. In contrast, UV light does not destroy or damage cellular structures. Rather, UV light prevents microorganisms from reproducing. Microorganisms that cannot reproduce cannot infect and are thereby inactivated. Subsequently, when evaluating UV disinfection capability, Giardia cyst and Cryptosporidium oocyst assays that measure infectivity, not viability must be used. Excystation assays measuring viability are not accurate indicators of UV disinfection capability.

UV light inactivates microorganisms by damaging deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). When DNA and RNA absorb UV light, dimers (covalent bonds between the same nucleic acids) are formed resulting in damage. Dimers cause faults in the transcription of information from DNA to RNA, which in turn results in disruption of microorganism replication. The microorganism continues to live, but it can’t reproduce and therefore is not infective. A microorganism that cannot replicate cannot infect a host. Microorganisms developed two mechanisms to repair damage caused by UV light. These mechanisms are termed light and dark repair.

It is possible for microorganisms to repair themselves to the extent where they will become infective again after exposure to UV light. Fortunately, however, most data indicates UV doses typically used in water treatment prevent most repairs. In general, microorganism inactivation by UV light follows first order reaction rates. However, inactivation rates can vary depending on microorganism type, and water quality conditions (e.g., turbidity, particulate matter, and clumping of microorganisms). Lastly, similar to chemical disinfectants and the CT approach to disinfection evaluation, data has shown that UV disinfection follows the law of reciprocity over an intensity range of 1-200$mW/cm^2$. For example, a UV dose of 1 $mW/cm^2$ for 200 sec (i.e., 200 $mJ/cm^2$) achieves the same level of inactivation as a

UV dose of 200mW/cm² for 1 sec (i.e., 200 mJ/cm²).

**UV radiation and its germicidal effect**

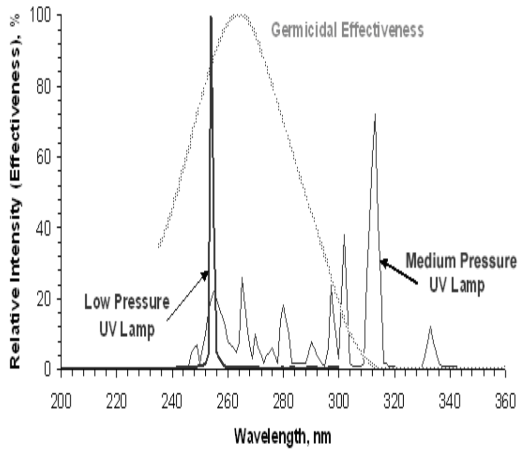
UV radiation actually destroys the genetic structure of microorganisms and inhibits its ability to reproduce and ultimately causing its death. UV radiation ranges from 200 nm to 400 nm. The radiation from 200 nm – 285 nm is called as UV C radiation and it is germicidal. In nature germicidal ultraviolet is a part of the sun's radiation however, most germicidal radiation (UV-C) does not reach on earth. State-of-the-art technologies can be used to convert electrical power into germicidal ultraviolet radiation in an effective mode. One of these technologies is a low pressure mercury vapor discharge lamp that generates UV-C radiation, which can be used to inactivate microorganisms by destroying its genetic material, DNA.

UV-C effectively kills airborne pathogens, surface and water living bacteria, viruses and cysts forms. Low doses of radiation may not produce any adverse affects on cells. If one lengthens the exposure time, or increases the intensity of the UV light, an increase in the number of unrepaired dimers and an increase in mutations probably occur. If a mutation occurs in an essential gene, the cell may die and is said to contain a lethal mutation.

Some viruses are resistant to conventional chlorination, which can be effectively destroyed by UV radiation. The selection of UV wavelength is very important for the efficient disinfection process. The optimum microbial killing efficiency ranges from 254 to 260 nm wavelength. Germicidal ultraviolet does not change the chemical composition and taste of water in contrast to reagent methods of disinfection (chlorination, ozonation). Viruses and bacteria in vegetative forms are most sensitive to UV radiation, for example, well known microorganisms such as Salmonella typhi, Vibrio cholerae, Shigella dysenteriae, Hepatitis virus, Mycobacterium tuberculosis etc.

More UV dose is required to inactivate cysts, while the largest UV dose is necessary to destroy spores. Since there is no negative overdosing effect, it is always possible to choose a UV dose that provides proper disinfection in any particular case.

Figure 3. Germicidal effectiveness of UV lamp




**Bacteria, virus, and protozoa inactivation capability**

The effectiveness of UV light on microorganism inactivation varies with different types of microorganisms. Generally, UV light is most effective at inactivating *Cryptosporidium* and *Giardia*, followed by bacteria and then viruses:

*Cryptosporidium* and *Giardia* > Bacteria > Viruses

Interestingly, UV resistance appears to follow microorganism size, with the smallest microorganisms being most resistant. The reason for this may be due to the amount of UV light absorption per cell. With microorganisms larger than 1 micron, the absorption of UV light by the cell can be significant, effectively reducing resistance to UV disinfection. The most UV resistant viruses of concern in drinking water are adenovirus Type 40 and 41. Because viruses are the most resistant to UV disinfection, dosing is controlled by log inactivation requirements for viruses, not protozoan cysts.

Table 1. Describes the UV dosage required to destroy the microorganisms

| Micro organisms: | Dosage of Ultraviolet radiation (UV dose) in mW sec/cm² needed to kill the selected micro organism. | |
|---|---|---|
| Bacteria | 90% (1 log reduction) | 99% (2 log reduction) |
| *Bacillus subtilis* | 5.8 | 11 |
| *Escherichia coli* | 3 | 6.6 |
| *Pseudomonas aeruginosa* | 5.5 | 10.5 |
| *Pseudomonas fluorescens* | 3.5 | 6.6 |
| *Salmonella enteritidis* | 4 | 7.6 |
| *Salmonela paratyphi* - Enteric fever | 3.2 | 6.1 |
| *Salmonella typhosa* - Typhoid fever | 2.1 | 4.1 |
| *Salmonella typhimurium* | 8 | 15.2 |
| *Sarcina lutea* | 19.7 | 26.4 |
| *Shigella dysenteriae* - Dysentery | 2.2 | 4.2 |
| *Shigella flexneri* - Dysentery | 1.7 | 3.4 |
| *Shigella paradysenteriae* | 1.68 | 3.4 |
| *Staphylococcus aerus* | 2.6 | 6.6 |
| *Vibrio comma* - Cholera | 3.4 | 6.5 |
| Virus | 90% | 99% |
| Bacteriophage - E. Coli | 2.6 | 6.6 |
| Infectious Hepatitis | 5.8 | 8 |
| Poliovirus - Poliomyelitis | 3.15 | 6.6 |

**UV toxicity**

A main chronic health concern with chemical disinfectants is the formation of disinfection byproducts. Trihalomethanes and haloacetic acids, the only regulated byproducts are not formed during UV disinfection. However, there are studies that show low-level (i.e., ug/L) formation of non-regulated disinfection byproducts (e.g., aldehydes). The health effects of non-regulated disinfection byproducts at the levels formed during UV disinfection has not been widely researched.

**Factors affecting the UV disinfection efficiency**

The effective UV disinfection process depends upon by several parameters. Prior to the UV disinfection, steps have to be taken to reduce the physical load like dust, dirt and mud particles from the water (sediment Filters). Also ensure and utilizes necessary treatment systems (activated carbon filter) to reduce the organic load from the water. Moreover UV intensity, water clarity, contact time, flow rate, surface area of the disinfection chamber, quality of the quartz glass etc., are very important to provide the adequate UV dosage for the microbial disinfection.

## 3. Evaluation of UV water purification system

There are several standards to evaluate the water purification system's microbial efficiency. Bureau Of Indian Standard - BIS 14724, covered this standard to evaluate the efficiency of UV water purification systems.

UV purification systems efficiency can also be tested by the following standards set by National Sanitation foundation. i.e. NSF/ ANSI 55 - Ultraviolet Microbiological Water Treatment systems. This Standard covers ultraviolet microbiological water purification systems and components for point-of-use and point-of-entry applications. The systems are intended to be used under the following specific conditions. There are two types of classes.

**Class A systems**

Class A point-of-entry and point-of-use water purification systems covered by this Standard are designed to inactivate or remove microorganisms, including bacteria, viruses, Cryptosporidium oocysts, and Giardia cysts, from contaminated water. It has been indicated that the water purification systems are intended to be installed on visually clear water (not colored, cloudy, or turbid).

**Class B systems or components**

Class B point-of-entry and point-of-use water purification systems covered by this standard are designed for supplemental bactericidal treatment of disinfected public drinking water or other drinking water that has been tested and deemed acceptable for human consumption by the state or local health agency having jurisdiction. In this class, the system is designed to reduce normally occurring nonpathogenic nuisance microorganisms alone. The Class B system is not intended for the disinfection of microbiologically unsafe water and may not make individual or general cyst claims.

**Advantages of UV disinfection technology**

1. UV disinfection refers to disinfecting drinking water with UV Radiation of 254 nm wavelength, a band of radiation located just beyond the visible light spectrum
2. UV radiation is absorbed by the cells of microorganisms and damages the genetic material
3. UV radiation damages the genetic material in such a way that the organisms are no longer able to grow or replicate, thus ultimately destroy them
4. No chemicals are added to the water, therefore the water retains its natural taste and odour
5. There are not hazards to health
6. The disinfection process is not affected by ammonia and pH
7. The disinfection process is rapid, and therefore a "detention time" is not required

## 4. Conclusion

Ultraviolet disinfection is a proven technology for disinfecting drinking water and is being used world wide since long time. UV light is most effective against *Cryptosporidium* and *Giardia* followed by bacteria. UV light is least effective against viruses. It does not create any new chemical byproducts, does not change the flavour or odour of the water and also does not remove any beneficial minerals. Its effectiveness depends upon many factors and it is very important to design the water purifier scientifically so as to deliver the safe & purified water. Turbidity, particulate matter, and natural organic matter are the most significant water quality parameters having the greatest effect on UV disinfection capability. Water temperature and pH have an insignificant effect on UV disinfection capability. Increasing levels of turbidity, particulate matter, and natural organic matter absorb more UV light, making less UV light available for disinfection. Similar to the CT concept, the IT concept [UV intensity (mW/cm2) times exposure time (s)], commonly referred to as UV dose (mJ/cm2), is used to describe UV disinfection capability. Increasing concentrations of turbidity, particulate matter, and NOM require higher UV doses in the form of increased UV intensity and/or longer exposure times to achieve the same amount of inactivation. Studies evaluating UV disinfection capability indicate UV doses of 120 mJ/cm2 are adequate to achieve 4-log virus inactivation of the most resistant viruses. They will ensure a 3-log *Giardia* and *Cryptosporidium* inactivation and likely ensure a 6-log bacteria inactivation. Most UV lamps used in drinking water applications contain mercury. There is concern of adverse health effects to the consumer as a result of mercury exposure from UV lamp breakage during operation. It is very convenient, instant and easy to operate is some of other important advantages.

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