Brief overview on the UVGI disinfection technology

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Summary

The information in this document is useful for HVAC professionals, facility engineers and specialists like employers and building owners and administrators seeking basic knowledge about ultraviolet germicidal irradiation (UVGI) technology.

This article explains the specific terms used in the UV field, reasons why UVGI is used for virus inactivation and the main features of UV-C lamps. UVGI device typology is presented, and some general rules and limitations for safe usage are provided.

Given the complexity of the UV transmission physics, specific software is needed for sizing UV systems. The sizing guidelines and design examples for different UV-C devices are not included in this document. This annexe scope is general and not limited to any specific building category (e.g., office buildings, educational buildings, shopping areas, sports premises, hospitals, healthcare settings, even residences). However, considering the negative effects on human health and some materials that UV-C radiation could generate when the design is defective, the most important rule is to use only certified products that are properly sized and tested.

Key words: covid-19, coronavirus, uvgi, uv-c, dose, disinfection

1. Short history and terminology

Germicidal lamps with UV-C radiation have been used since the 1950s to inactivate or destroy microorganisms like bacteria, mould, yeast, and viruses that severely affect indoor air quality (IAQ). Niels Ryberg Finsen was the first scientist to discover UV rays for treating diseases and was awarded the Nobel Prize for Medicine in 1903. He invented the Finsen curative lamp, which was used successfully during the 1950s. Westinghouse co-developed the first commercial UV-C germicidal lamps during the 1930s. They were used mainly in hospitals.

The applications for UV-C lamps grew after the Second World War when they were used anywhere microbiological contamination was a concern: for sterilising air and

surfaces in hospitals, pharmaceutical plants and animal labs. Eventually, they were incorporated into air handling equipment.

Many studies run under the Integrative Emergency Services (IES) or the Center for Disease Control and Prevention (CDC) in the United States **[1]** proved that UV-C irradiation could easily inactivate or kill different pathogens. UV-C became a major component in the control and eradication of tuberculosis in the 1950s **[1]**.

Recently, many researchers have proven that UV-C technology can be safely utilised in many fields of applications **[2]**, and scientific reports **[3,4]** have shown that UV-C can successfully be used in HVAC and the fight against COVID-19.

A portion of the **electromagnetic spectrum** is shown in Figure 1. Table 1 shows the five types of UV radiation defined according to their wavelength range in nm: vacuum UV, far UV-C, UV-C, UV-B and UV-A. Table 1 gives information regarding the safety of use, the plastic degradation speed (photodegradation) and the practical uses for each UV radiation type. The most powerful germicidal effect is obtained at around 265 nm, as the graph shows. UV-C lamps emit radiation at 253.7 nm.

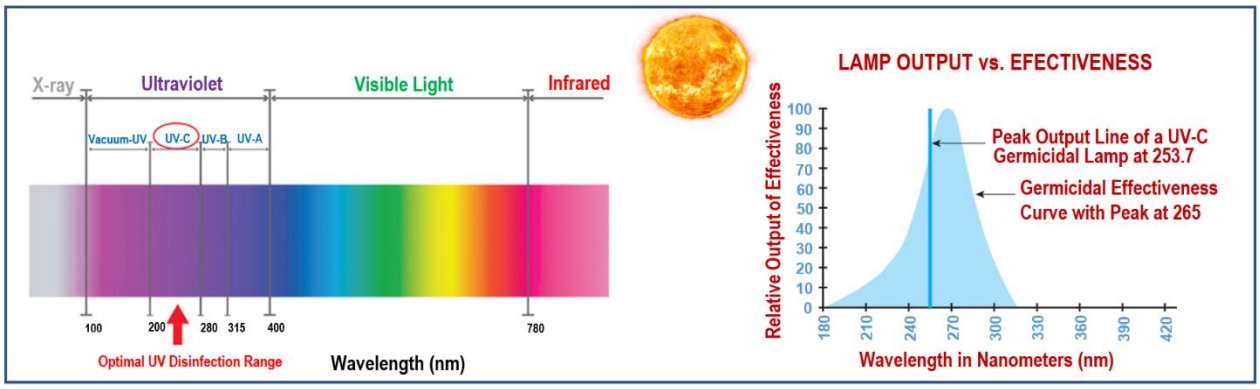

Figure 1 – electromagnetic spectrum and germicidal effectiveness of a UV lamp

Table 1 types of UV radiation

UV type	Wavelength (nm)	Safe for skin&eyes	Degradation of plastic/rubbber	Practical uses
VUV Far-UV	100-200	YES	rapid	Medical equipment
Far-UVC	207-222	YES	rapid	Germicidal desinfection
UV-C	200-280	NO	rapid	Germicidal desinfection
UV-B	280-315	NO	rapid	Tanning, medical treatment
UV-A	315-400	NO	very slow	Curing, printing, lithography, sensing, medical applications

UV-C is a low-penetrating form of UV radiation compared to UV-A or UV-B (Figure 2). Measurements on human skin exposed to a wide range of UV wavelengths, from 250 to 400 nm, showed that a small amount of UV-C is transmitted through the epidermis. Only 4 to 7% of UV-C is absorbed in the first 2 μm of the outer, dead layer of the human skin **[2]**. However, because UV is far more energetic than visible light and invisible to humans, exposure to UV-C may result in inflammation of the cornea (photokeratitis) or inflammation of the conjunctiva, called photo-keratoconjunctivitis. Other symptoms, like the sensation of sand in the eyes, tearing, and even eye pain, can occur 6 to 12 h after UV exposure. Acute overexposure to UV-C radiation leaves no permanent damage to human eyes, and generally, the symptoms fully disappear within 24 to 48 h. Cutaneous damage consists of erythema, a reddening of the skin without tanning. The maximum effect of erythema occurs at a wavelength of 296.7 nm in the UV-B band. Erythema produced by UV-C radiation at a wavelength of 253.7 nm is less likely.

Ultraviolet radiation, in general, is carcinogenic, and even if the radiation from germicidal lamps does not penetrate the eyes and the skin over short time intervals, health and safety measures are compulsory in the case when the exposure to the irradiation is long. Human skin and eyes must be protected against UV-C by using shielded or enclosed UV-C lamps.

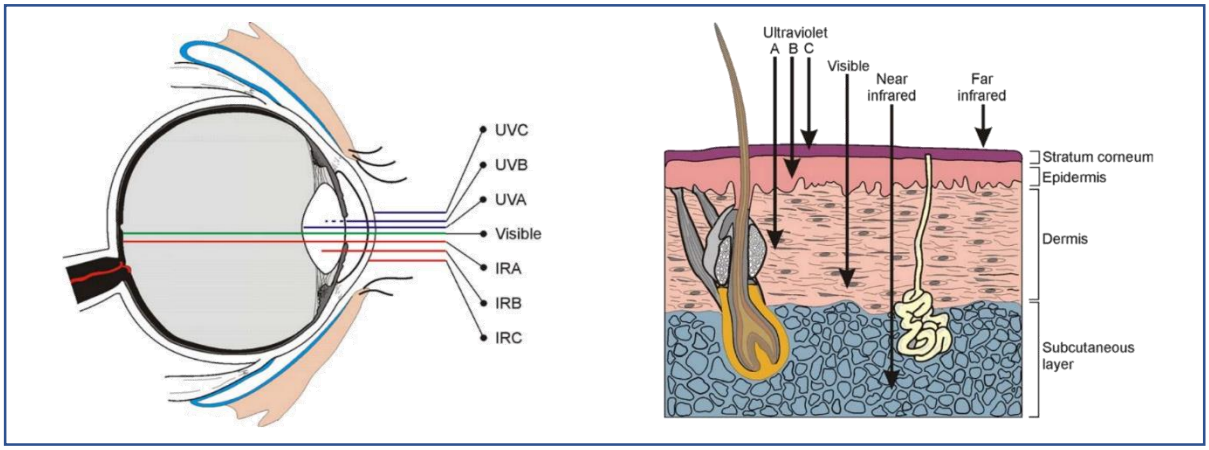

Figure 1 penetration power of different UV types for the human eye or skin [5]

An **exposure dose** in general, or a particular **UV dose**, D, represents the amount of radiant energy absorbed by an organism living in a droplet nucleus; it is calculated as (UV irradiance) times (t – the time of exposure); a UV dose is usually expressed as $\mu W \cdot s/cm^2$ or $\mu J/cm^2$.

$$\mathbf{D} = \mathbf{I} \times \mathbf{t} \ [\mu J/cm^2] \quad (1)$$

The term **fluence** (total radiant energy incident on the outer surface of an infinitesimal sphere) is linked to a UV lamp. It differs slightly from **UV dose** because the latter implies total absorption of UV energy received, whereas fluence represents irradiation energy transmitted over a given duration. Those two are, however, considered to be equal ($\mu J/cm^2$).

The dose-response correlates with the amount of energy received by a population of microorganisms and the resulting effect. For example, the UV-C dose-response of the SARS-COV-2 is the inactivated fraction or the survival fraction among that coronavirus population.

If one exposes a microbial species to an increasing UV irradiation, then the number of inactivated or killed pathogens will increase, or the number of surviving ones will

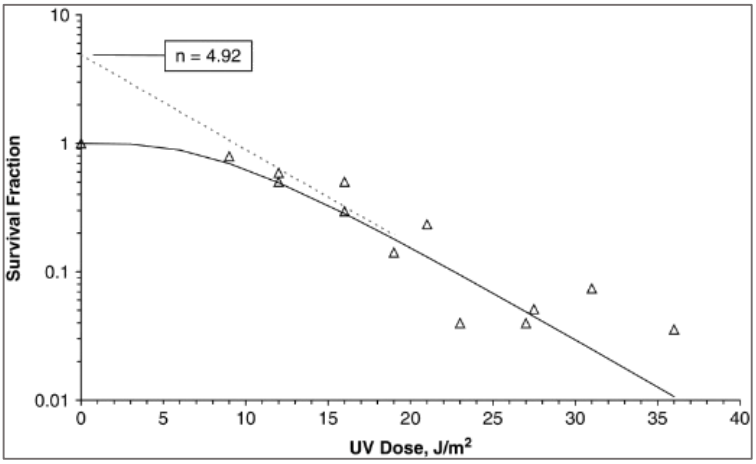

Figure 2 dependence curve of the survival fraction to UV dose [6]

decrease, and the result is a curve whose shape and slope will depend on the microbial species' susceptibility or sensitivity to UV. **The inactivation rate constant (k)** is the slope of this survival curve (Figure 3). k has a unique value for each species (Table 2). k is also called UV rate constant, or decay rate constant and is measured in cm^2/mJ. Its value is used to size UV-C devices.

Table 2 k values for different pathogens [17,18]

UV-C Dose Required	Dose in mWs/cm²	
	90% (Log 1)	99.9% (Log 3)
Bacteria		
Bacillus anthracis	4.5	13.5
B. megatherium Veg	11.3	33.9
Bacillus pumilis spores	5.0	15.0
B. subtilis	7.1	21.3
B. subtilis Sporen	11.2	33.6
Campylobacter jejuni	1.1	3.3
Corynebacterium diphteria	3.3	9.9
Enterobacter cloacae	6.4	19.2
E. coli	5.5	16.5
Legionella pneumophila	2.5	7.5
Listeria Monocytogenes	7.7	23.1
Micrococcus candidus	6.1	18.2
Micrococcus sphaerroides	10.0	30.0
Mycobacterium tuberculosis	1.1	3.3
Neisseria catarrhalis	4.4	13.2
Proteus vulgaris	3.0	9.0
Pseudomonas aeruginosa	5.5	16.5
Pseudomonas fluorescens	3.5	10.5
Salmonella enteritidis	1.0	3.0
Salmonella typhimurium	2.1	6.3
Seratia marcescens	2.2	6.6
Shigella sonnei	1.8	5.4
Spirillum rubrum	4.4	13.2
Staphylococcus aureus	5.0	15.0

UV-C Dose Required	Dose in mWs/cm²	
	90% (Log 1)	99.9% (Log 3)
Bacteria		
Streptococcus lactus	6.2	18.5
Streptococcus aureus	5.5	16.5
Streptococcus viridans	2.0	6.0
Yeasts		
Sacch. spp	4.4	13.2
Sacch. ellipsoideus	3.3	9.9
Sporotrichum schenkii	28.0	84.0
Virus		
Hepatitis A	4.5	13.5
Influenza Virus	2.0	6.0
Polio Virus	4.4	13.2
Rotavirus	10.5	31.5
Mould Spores		
Aspergillus flavus	60.0	180.0
Mucor racemosus	17.0	51.0
Oospora lactis	2.8	8.4
Penicillium expansum	13.0	39.0
Penicillium roqueforti	13.0	39.0

There are no standard methods for the determination of k. Furthermore, k values depend, on the one hand, on the conditions under which the UV dose is transmitted, for example, in air, in water, on surfaces; on the other hand, k depends on the measurement methods of the number of the microorganisms surviving.

The survival fraction of a microbial population that was not inactivated after UV-C exposure is determined by one of two similar equations:

$$\ln\left(\frac{N_0}{N}\right) = k \times D \text{ or } \frac{N}{N_0} = e^{-k \times I \times t} \quad (2)$$

where

N_0 = initial concentration of active microorganisms before disinfection

N = concentration of active microorganisms after disinfection, for example, after applying an exposure UV-C dose over the virus population
D = exposure dose or UV irradiation dose (or fluence, mJ/cm^2)
k = UV inactivation rate constant as explained before
t = time of the exposure measured in seconds
I = irradiance measured in μW/cm^2

These equations are valid only if the shoulder effect and the second stage effect that may affect the disinfection process are neglected. The shoulder appears because there is a delay in response of a microorganism exposed to UV, similar to a threshold dose. This effect could appear when the air velocity is too high and the dose becomes insufficient. Studies **[6]** showed that most microbial species are characterised by two-stage inactivation curves in which each stage has a different rate constant (k_1 and k_2, according to Figure 4).

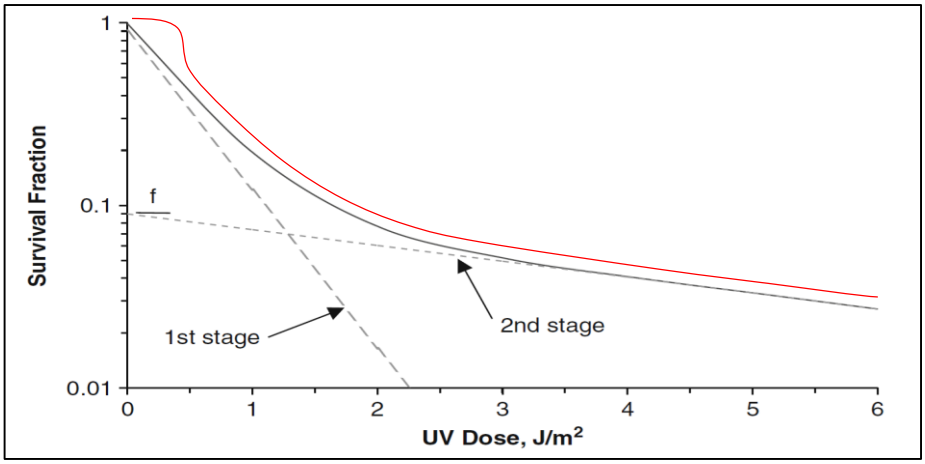

Figure 3 two-stage inactivation curve [adapted by CL from 6]

During the first stage, the decay rate is higher than that of the second stage, when the most resistant fraction will be finally inactivated. For some viruses, this resistant fraction could reach even 10%; for others, it is only 0.01%. The more complex inactivation process can be modelled by the equation below, where F is the fraction of the total initial population subject to fast-decay response:

$$\frac{N}{N_0} = F \times e^{-k1 \times I \times t} + (1-F) \times e^{-k2 \times I \times t} \quad (3)$$

In 1972, the CDC and the National Institute for Occupational Safety and Health (NIOSH) published the **UV REL value**, which is the recommended exposure limit to UV-C, defined to prevent adverse effects on human eyes and skin. In the United States, this value is 6000 μJ/cm^2 for a wavelength of 254 nm.

According to *Artificial Optical Radiation Directive 2006/25/EC European*, the maintenance operators of the UV-C devices shall not exceed 3000 μJ/cm² for a wavelength equal to 253.7 nm and for a working day of 8 hours, which means that irradiance equals 0.1 μW/cm^2.

The permissible exposure time PET (sec) for EU workers in healthcare can be calculated with the equation:

$$\mathbf{PET(seconds)} = \frac{\mathbf{REL\ (3000\frac{\mu J}{cm^2}at\ 254nm)}}{\mathbf{Measured\ irradiance\ level\ at\ 254nm\ (\frac{\mu W}{cm^2})}} \quad (4)$$

The PET values can be then computed if the irradiance values are known (measured). The permissible irradiance level can be determined if the exposure time is limited to a certain level (Table 3).

Permissible exposure time * (seconds)	**Effective irradiance** (μW/cm2)
28800	0.10
14400	0.21
7200	0.42
3600	0.83
1800	1.67
900	3.33
600	5.00
300	10.00
60	50.00
30	100.00
10	300.00
3	1000.00
1	3000.00
0.5	6000.00
0.3	10000.00
0.1	30000.00

Table 3 PET values for different irradiance (measured) values

In ventilation ducts, for example, due to very short exposure time, UV lamps shall generate between 1000–10,000 μW/cm^2 to ensure the needed exposure dose for at least a 99.9% inactivation rate, meaning at least 30 mJ/cm^2, according to the maximum values displayed in Table 2 for viruses. The permissible exposure time is less than 3 s for 1000 μW/cm^2 or 0.3 s for 10,000 μW/cm^2.

The average effective life of a UV lamp is measured between the first use (usually after a 100-hour break-in period) and the moment when the UV output is 50% of a specific

level based on testing the lamps from the same production lot. For example, Phillips considers that the effective UV-C lamp life is 9000 h with a 20% decline in the UV output, determined for a specific bulb. Normal values for the average effective lamp life depend on the gas in the glazed balloon and can vary between 5000 and 20,000 h.

2. Types & technical features of UV-C lamps

Modern UV-C lamps (Figure 5) are like fluorescent lamps found in the ceiling or wall fixtures. The similarities of UV-C and fluorescent lamps offer several benefits to producers: the same type of production machine, same shapes, diameters and lengths, the same manner of storage and recycling. UV-C lamps require reduced manufacturing, packing, and shipping costs that compensate for much higher material costs.

Figure 4 UV-C lamps [7]

Both types of lamps operate using identical electrochemical processes: an electric discharge inside the glazed tube strikes argon gas and mercury vapour particles and generates photons in visible and UV-C spectrum (Figure 6).

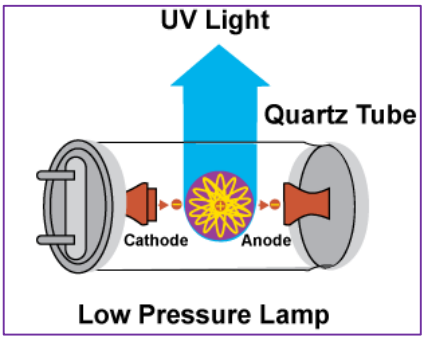

Figure 5 main operating principle of a UV-C lamp [8]

The phosphors that coat the inner surface of the ordinary glass in fluorescent lamps totally absorb UV radiation. The transparent glass envelope of a UV-C lamp is highly

engineered, allowing unfiltered transmission of the 253.7 nm wavelength (UV-C radiation is invisible).

A typical UV-C lamp streams about 90% of its radiative energy in the whole UV-C range, from 200 to 280 nm. About 4–5% of absorbed electric energy is given up as heat, and the rest (approx. 5%) is in the visible light range – mainly blue light.

Low-pressure UV lamps are also called germicidal lamps because UV-C inactivates or destroys microorganisms in both air and water. About 25–35% of their electric energy absorbed is converted directly into UV-C radiation with monochromatic emission at 254 nm for germicidal applications. Approximately 2% of the input power is converted into irradiation at 185 nm, used mainly for ozone generation **[20]**.

UV low-pressure amalgam lamps contain solid amalgam inside the envelope that is an alloy of mercury with titanium, gallium, iron, or lead. The low-pressure amalgam lamps have a very long operating life (up to 20,000 hours) and a UV-C efficiency of up to 45% at 254 nm, compared to the average value of 30% for traditional low-pressure lamps. The efficiency of a UV-C lamp is the ratio between the UV-C power in watts, after 100 hrs burn-in period, and the lamp wattage.

Medium-pressure lamps have the advantage of a much higher power density than traditional low-pressure or amalgam low-pressure lamps.

All lamp technical features are based on measurements performed under laboratory conditions in air, at ambient room temperature, on a high-frequency current, using limited electronic ballast and with average values measured at a 1 m distance from the light source.

The glazed tube of a UV-C lamp is generally made of highly thermal, mechanically stable quartz; quartz glass has high transmission efficiency and is highly transparent to UV radiation. Three different kinds of quartz glass are used, according to the type of ultraviolet lamp to be produced: synthetic quartz, natural quartz and Ti-doped quartz (Figure 7). The latter has the advantage of blocking the 185 nm wavelength radiation that generates ozone, so Ti-doped quartz lamps are ozone-free UV-C lamps. Note that O_3 is at least irritating for occupants if its concentration exceeds the safe level of 120 mg/m^3.

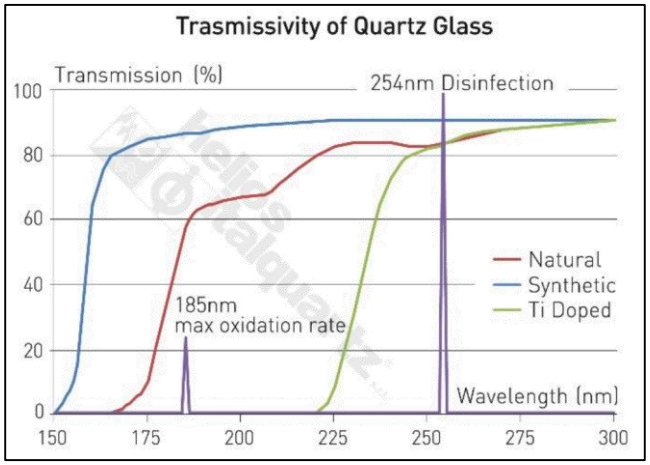

Figure 6 Different quartz glass transmissivity of UV radiation [8]

Generally, UV-C lamps can provide more than 80% of their initial output over a 20,000-hour period (minimum 8000 hours). The average effective life of a UVGI lamp depends on the location temperature, the lamp surface temperature, the number of on-off cycles (or switching rate) and the air velocity. The first three graphs in Figure 8 show the correlations between a UV-C lamp's percentage output and the number of operating hours, the switching rate, and the lamp surface temperature. The fourth graph shows the correlation between three parameters: the air temperature around the UV-C lamp, the airspeed and the UV-C output of the lamp.

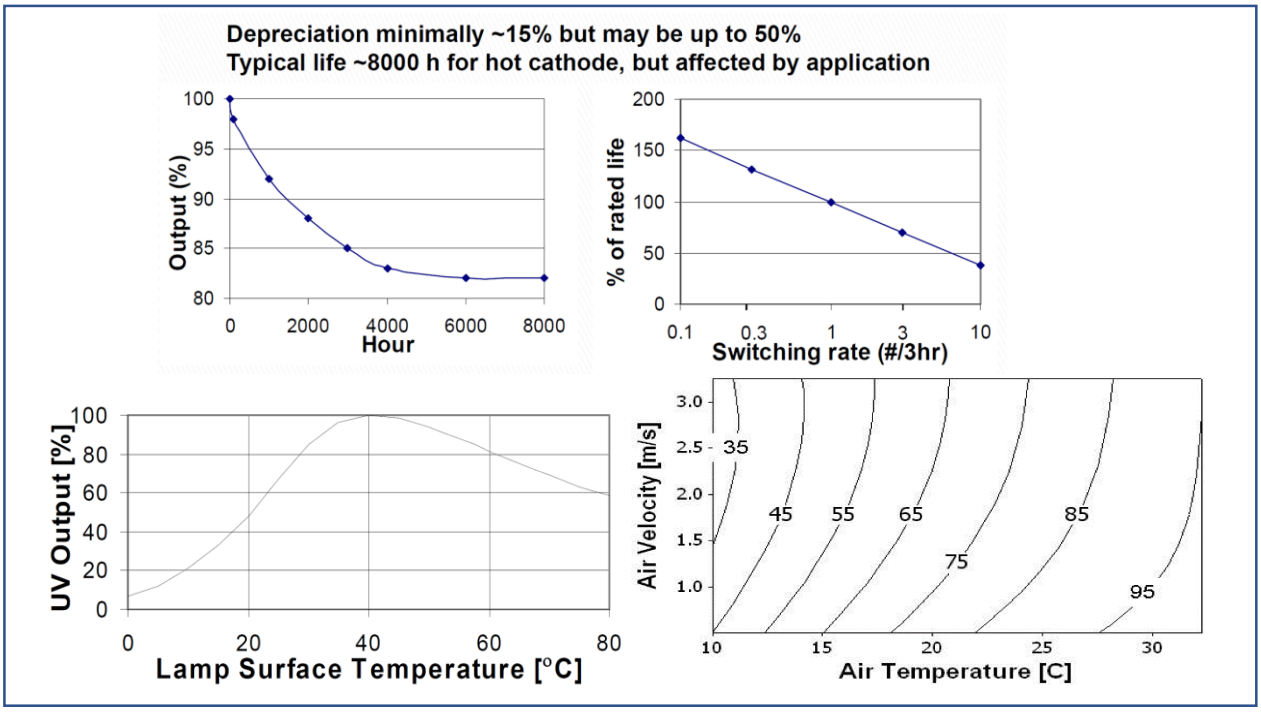

Figure 7 UV output change [%] with different parameters [10,16]

The temperature of the location where a UVGI system is mounted may affect the efficiency of the germicidal effect, depending on the lamp type. Firstly, higher or lower temperatures may decrease the UVGI output of low-pressure mercury lamps or decrease the microorganisms' susceptibility to UVGI. Second, the old (but still commonly used) mechanical/magnetic ballasts may be affected by high or low temperatures. A relationship exists between lamp operating temperature and output in all low-pressure mercury lamps. The UV efficiency of the lamp is directly related to the (saturated) mercury pressure, which, in turn, depends on the spot with the lowest temperature on the lamp. The decrease in UV output will be even greater if there is air movement around the lamp because air flow causes the lamp's mercury vapour to lose heat faster; in addition, low temperatures reduce the lamp's operating life.

One interesting use of a special lamp type using UV-C is the Wood lamp employed in the fight against the counterfeiting of banknotes. It is also used to search for cracks in metal structures coated with materials responsive to UV rays. A Wood lamp produces the so-called 'black light' used to illuminate materials that produce fluorescent and phosphorescent effects when illuminated with this light. Black light is so named because UV-C radiation is not directly visible to the human eye.

3. Why UV-C for air disinfection?

UV-C irradiation inactivates or even kills all viruses, including SARS-COV-2 that produces RNA and DNA mutations (Figure 9).

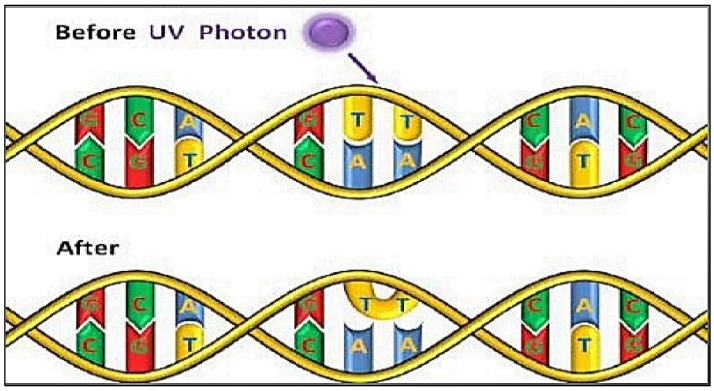

Figure 8 UV-C radiation effect on SARS-COV-2 [11]

The high energy photons of the UV-C radiation are absorbed by the cell proteins' DNA/RNA. The result is that the protein structure is damaged, causing metabolic disruption of the DNA and RNA, so microorganisms, or viruses in our case, can no longer metabolise and replicate.

In conclusion, UV-C is very useful for disinfecting water, building air, transportation, and the surfaces of different objects or products. UV-C is effective for all microorganism species: bacteria, viruses, and fungi. The germicidal effect of UV-C is simple, non-chemical and does not generate toxic by-products. UV-C technology requires low-to-medium investment, and UV-C devices are relatively easy to maintain. UVGI lamps do not affect the environment if they are collected correctly and recycled. If Ti-doped quartz glass is used, a UV-C lamp will not produce ozone.

This disinfection technology can be used practically anywhere infection risk is high: hospitals, retreat houses, sport facilities, in the food or pharmaceutical industry, in HVAC systems, and for transportation safety.

UV-C devices used in ventilation systems have two major advantages: 1) they reduce contamination of AHU elements, especially cooling coils and filters, and 2) they control infection transmission in ventilation systems with recirculation, implying major energy savings.

4. Types of air and surfaces disinfection devices using UV-C

There are three main categories of UV-C devices: in-duct systems, including those installed in AHUs, overhead devices, and stand-alone devices.

i. In-duct UV-C systems

For virus disinfection in AHUs, UV-C lamps shall be installed downstream of the mixing box and filtration section and upstream of the cooling coil in the direction of air

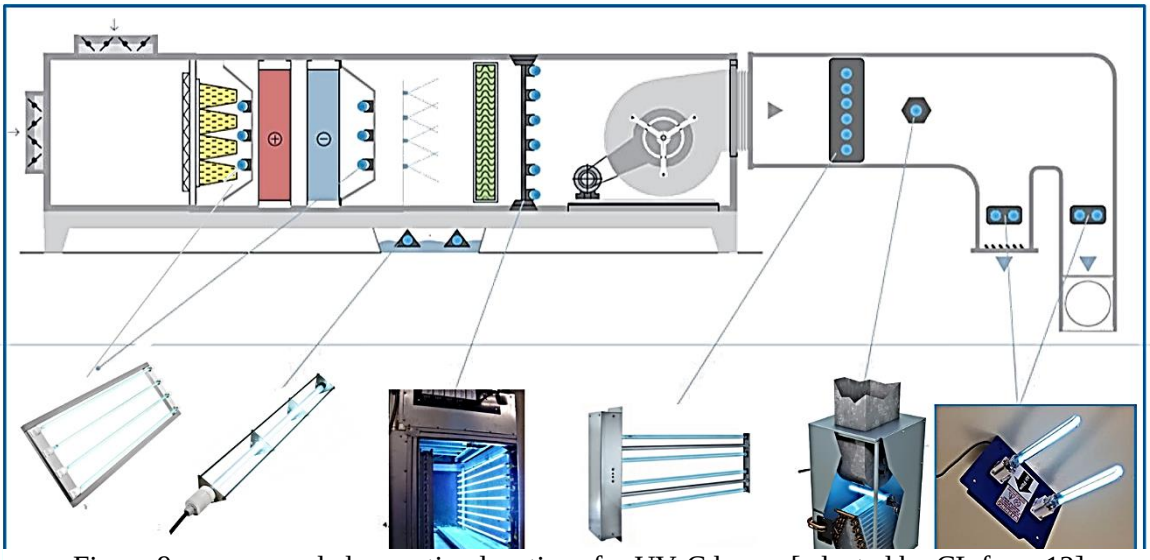

Figure 9 recommended mounting locations for UV-C lamps [adapted by CL from 12]

flow (Figure 10). Here, the low humidity level will not negatively affect lamp irradiation. The mounting position downstream of the cooling coil is preferred for the bacteria disinfection of surfaces because here the air approaches saturation, meaning that within this plenum, there could be raw water, damp insulation, and other conditions that are known to lead to the growth of mould and some forms of bacteria. Also, coil drain pans are often extended in this location to catch raw water carried over from the cooling coil. The lamps used must be resistant to water and or high levels of humidity.

Another mounting position can be even more downstream, between the droplet separator and the fan, or/and in the water collector pan. The in-duct mounting position presents the disadvantage of a higher airspeed that reduces the exposure time. However, the exposure time can be improved by using longer UV-C zones or multi-step exposure. Another countermeasure used to increase the dose is increasing the irradiance with the help of reflective materials or simply increasing the lamp's power. This last measure implies an increase in the electric energy consumed and in the UV-C system acquisition price.

No matter the mounting position of the UV-C lamps, the design engineers must consider at least three additional parameters that affect the lamps' number, size or power. These three parameters are airspeed, air temperature and air humidity.

ii. Overhead UV-C systems (fixtures)

Overhead UV-C devices are shielded units, with a special configuration, generating a band of UV-C radiation above the occupants' heads (Figure 11). Upper-room devices can be safely used when treated spaces are occupied, providing ongoing disinfection if pathogens carried from the occupied lower zone go through the upper irradiated zone near the ceiling. The disinfection effect is not 100% efficient, but it helps to reduce the virus concentration and reduces the transmission risk. Many positive results described in scientific papers were obtained in the past in TB hospitals. Different studies showed that the disinfection effectiveness depends not only on the lamp power but also on the

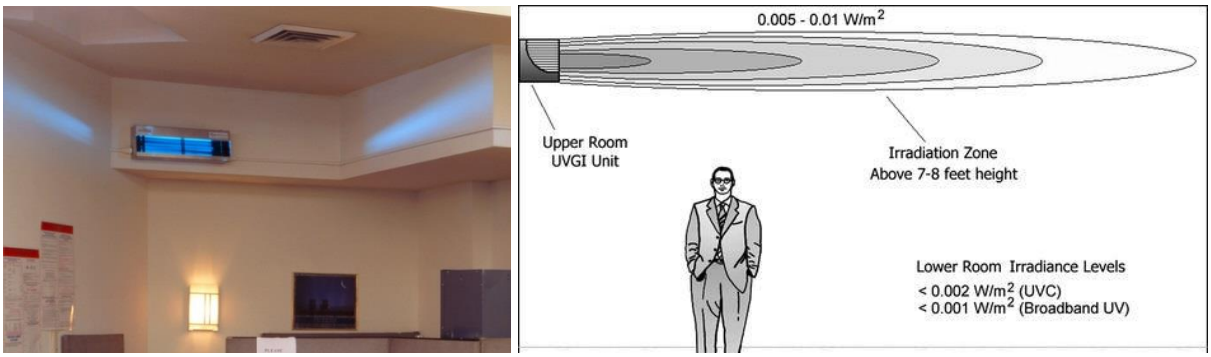

Figure 10 upper room (overhead) UV-C fixture [6]

lamp's position relative to the air flow pattern. The mixing degree of the air in the room can be improved by using mixing additional fans.

A complex model presented in 2015 using the Wells–Riley infection model showed that the impact of an upper-room UVGI device could be comparable to doubling the ventilation rate **[1]**. Other studies found that a UVGI overhead system could be equivalent to a ventilation system providing 2 to 6 ACH **[6]**. However, the infection risk in the 1–2 m range from the infection source will not be reduced substantially.

As displayed in Figure 11, the mounting height is very important related to the value of the UV irradiation at the occupant's eye level, which shall not exceed max 0.1 $\mu W/cm^2$.

iii. Stand-alone UV-C devices

Besides in-duct or overhead devices, other UV systems use enclosed lamps, like air-conditioner types or portable devices. Their disinfection effectiveness depends on the airflow rate they can recirculate, which, in turn, depends on the room size, the infection dose, and similar factors (Figure 12). These systems could be considered the equivalent of personal ventilation systems, and their sizing depends on many variables.

Figure 11 stand-alone UV-C devices [13,14]

5. Basics of UVGI sizing

There are four calculation situations according to each UV-C device type:
(1) UV-C lamps installed in AHUs,
(2) UV-C lamps mounted in ducts,
(3) UV-C fixtures mounted in the upper-room position (overhead type), and
(4) UV-C stand-alone (mobile) devices.

The first two cases cover surface or air stream disinfection, including microbial growth control. The last two refer only to inside rooms air disinfection situations.

The main parameters that must be calculated are:
- the UV-C dose needed to inactivate the microorganisms, in our case SARS-COV-2
- the lamp and ballast characteristics required to meet the individual application's operating conditions
- finally, one must determine how many UV lamps or UV-C devices are necessary and how are they placed in the AHU, in the duct or the room.

The parameters with known values used in the UVGI design refer to:

- AHU configuration and dimensions, or duct dimensions
- information about how much fresh air will be provided by the ventilation system
- air flow characteristics (temperature, RH, how much air flow, air speed ...)
- lamp(s) electric power (W) and lamp(s) technical characteristics
- distance between the lamp(s) and the surface treated
- virus type and concentration and possible infection sources.

In the case of overhead or stand-alone devices, it is also important to know the movement pattern of the virus particles in the room.

The output power of a UVC lamp can be calculated using the Keitz formula:

$$P = \frac{I \times 2\pi^2 \times x \times L}{2\alpha + \sin 2\alpha} \quad (4)$$

where

- P = UVC power [W]
- I = irradiance [W/m^2]
- x = distance [m]
- L = lamp arc length [m]
- a = the angle [rad]

The lamp electric power will be:

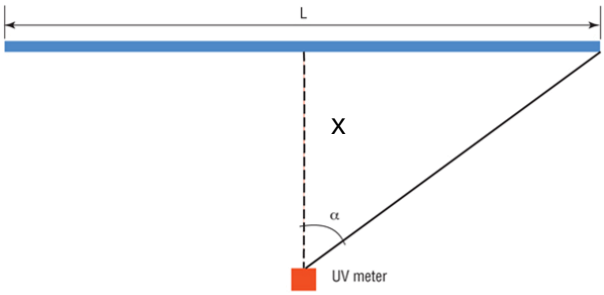

Figure 12 simplified calculation of the UV lamp power in a spot

$$W = \frac{P}{\text{UVC lamp efficiency}(\%)} \tag{5}$$

The radiation view factor from a differential planar element to a cylinder (the lamp), perpendicular to the cylinder axis **[6]**:

$$F_{d1-2} = \frac{1}{\pi H} ATAN\left(\frac{L}{\sqrt{H^2-1}}\right) + \frac{X-2H}{\sqrt{XY}} ATAN\left(\sqrt{\frac{X(H-1)}{Y(H+1)}}\right)\frac{L}{\pi H} - ATAN\left(\sqrt{\frac{H-1}{H+1}}\right)\frac{L}{\pi H}$$

$$\Rightarrow \begin{cases} H = x/r \\ L = l/r \\ X = (1+H)^2 + L^2 \\ Y = (1-H)^2 + L^2 \\ \text{where:} \\ \quad l = \text{length of the lamp segment, cm} \\ \quad x = \text{distance from the lamp, cm} \\ \quad r = \text{radius of the lamp, cm} \end{cases} \tag{6}$$

6. General rules

There is a set of rules that every UV-C user or engineer shall consider:

i. use only officially approved equipment and follow all safety rules indicated in the technical documentation.

ii. UV-C air treatment devices require safety measures and shall be installed only by trained personnel with appropriate risk assessment and controls in place; UV-C

installers and maintenance personnel must respect safety procedures to avoid exceeding occupants' exposure limit with non-enclosed lamps.
iii. UV irradiation level can sometimes be too high for the occupant's eyes, so the irradiation shall be measured immediately after the UV-C device installation and afterwards, periodically. The values shall stay under 0.1 $\mu W/cm^2$. Irradiance measurements are generally required for two reasons: (1) validation that the system provides a sufficient UVGI level to ensure microbial inactivation and (2) determination of compliance with occupational safety and health guidelines.

iv. Because ozone generation during UV-C lamps use could harm human health, only ozone-free UV-C lamps shall be considered for spaces occupied during the UV-C air treatment. The maximum allowed human exposure to ozone is 0.05 ppm, according to US Environmental Protection Agency **[21]**, 0.01 ppm according to ASHRAE Environmental Health Committee **[22,23]**, and 0.2 ppm for short exposures of less than 15 min, according to the UK Health and Safety Executive **[24]**. Therefore, UVGI disinfection equipment shall be tested to verify that the concentration of ozone generated during operation respects the maximum limits. Low-quality UV-C lamps and incorrect system design could generate a level of ozone that is higher than allowed.

v. UVGI lamps are typically mounted downstream from the mixing box and before the filtration section of an AHU; another usual mounting location is downstream from the cooling coil in the AHU or the air duct.

vi. if UVGI systems are installed, RH should be controlled to 40–60% for optimal efficiency **[15]**; if high humidity conditions are present, increased UV irradiation levels may be necessary to achieve equivalent effectiveness.

Note: Several studies have indicated that UVGI effectiveness decreases as RH increases. Other studies have shown that as RH increases, the ability of some bacteria or viruses to repair UVGI damage to their DNA increases.

vii. UV systems must be fitted with alarms to make the building operator aware of failure (if in duct UV fails, then the air is untreated, and the occupants are at immediate risk);
viii. Finally, UV-C lamps require periodic maintenance such as the irradiation level shall not go under 80% and, consequently, the dirty and dust on the lamps shall be eliminated periodically.

7. Conclusions

1. Germicidal UV-C radiation is a viable decontamination approach against SARS-COV-2 for the air inside buildings during occupying hours; all viruses and almost all bacteria (excluding spores) are inactivated by moderate levels of UV irradiation. Spores are filtered by high-efficiency filters and are not treated with UV.

2. UV-C air treatment is a disinfection, rather than sterilisation, measure; however, there are limited practical examples of the effective application of UV-C to remove respiratory viruses in real buildings.

3. The ozone concentration should be kept below 50 ppb (ideally, below 10 ppb) in indoor environments to protect human health.

4. UV-C is a complementary solution to filtration in mechanically ventilated buildings and a solution to poorly ventilated rooms, like offices and classrooms. Complementary means that UV-C technology is additional. It does not replace ventilation as the first option against air contamination, and proper ventilation to current local regulations must be provided.

5. UVGI is widely available as commercial technology because UV-C devices provide three levels of benefits when applied to HVAC systems:

- at the HVAC-system efficiency level, UV-C eliminates or prevents the build-up of organic material on filters and on cooling coils surfaces, in drain pans, and inside air ducts, keeping the air flow and the heat-transfer levels of cooling coils to ‘as-built’ conditions, reducing maintenance as well.
- At the **IAQ level**, by reducing pathogens and organic material on filters and cooling coil surfaces, UV-C improves indoor air quality (IAQ) delivered to rooms, with other benefits on occupants' satisfaction and productivity.
- At the **economic level,** UV-C's impact on mechanical systems and occupants translates into substantial economic benefits in energy consumption reduction, carbon footprint reduction, maintenance reduction, reductions in system downtime, and staff time needed for chemical or mechanical cleaning. On average, UV-C could reduce 10–25% of HVAC energy use.

6-. It is very difficult to assess the disinfection effect of a UV-C device; in fact, UV-C efficiency is affected by the distance from the UV-C device and by the ‘shadowing’ effect (UV radiation cannot penetrate solid material, and bacteria can easily ‘hide’ inside slightly larger solids). It depends as well on the lamps' state, usage time, and cleanliness.

7. UV-C radiation can produce fast photodegradation of plastic and other materials. From this point of view, materials can be ranked in *no effect* materials like inorganic materials (example aluminium), *minor effect* (copper, EPDM and silicone sealants), *moderate effect* (LPDE, polycarbonate, cast epoxy, paper, HEPA filters for high irradiance values) and *severe effect* materials (HDPE, polyester, cardboard, glass fibre insulation, foam insulation), depending on the damage that UV-C produces on those materials.

8. Commercial methods used to size and design UV-C air disinfection systems are quite empirical. Designers shall consider the room size, the virus dose, the interaction with the ventilation air flow and safety measures. The effectiveness of UV-C air treatment systems is also strongly affected by the type of microorganisms, the irradiation level/type (lamp power and wavelength), duration of irradiation (exposure time), air movement pattern (mixing degree), and temperature and relative humidity. High air speeds will reduce the lamp temperature and, sometimes, the UV output. High RH will reduce the germicidal effect on SARS-COV-2 (decrease the decay rate); however, there are contradictions. Temperature has a low impact on microbial susceptibility to UGVI, but it affects the power of the UVGI lamp.

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